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A grey-box identification case study: The Åström–Bell drum-boiler model

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Abstract

This report describes a case-study involving parameter identification of a family of physical models for a drum-boiler, as described by Åström and Bell. The models are based on first principles, but they also include some grey-box parts where there is not complete physical knowledge. The case-study uses a series of unique open-loop data from Öresundsverket in Sweden.

The object of the case-study is to study the interaction between the modelling tool, OmSim, and the parameter optimization tool, IdKit. A newly developed interface for equation export using Maple is used to tie the tools together. The case-study also adresses the question of which of a set of given model structures is adequate for capturing the dynamics seen in the data. The results show that a previously published fourth-order model is the most powerful unfalsified model. A newer fifth-order model including time-delays is rejected since it does not add any reproducibility with respect to the data in the six datasets.

Key words
modeling, simulation, nonlinear models, model validation, parameter estimation.

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Chapter 1

Introduction

At the outset, the goals of this project were loosely specified as follows:

- Prototype the code-generation interface between LTH's OmSim simulation environment and KTH's IdKit software for grey-box identification as proposed in [1].
- Use these tools to investigate what improvements can be gained via parameter optimization of the deterministic thermo-physical drum boiler model structures developed by R. Bell and K.J. Åström [2–5].

Results addressing the first point are presented in a companion report [6]. This report documents the results of the identification case study that ensued the second point. Additional motivation for the investigation came from the following desires:

- to demonstrate the utility of Omola in defining multiple models as proposed in [1],
- to gain practical experience using the identification tools with real industrial data.

In particular, the availability of six sets of open-loop data [7, see Figure 1.1] provides a unique opportunity to assess the structural fidelity of the deterministic models by considering parameter reproducibility.

Parameter Reproducibility

Bohlin [8, 9] discusses a number of approaches in gauging the performance of model structures. The most stringent is what he calls parameter reproducibility. This is a measure of the variation of parmeter optimization results derived from a number of independent datasets. A reasonable premise for such a comparison requires that we limit consideration to only those parameters which are expected to be constant.

A test of this severity is deemed appropriate for the family of model structures under consideration because of its deterministic, thermodynamic basis. Most of the parameters have physical meaning and several are physical constants, e.g. the metal masses. Furthermore, parameter reproducibility provides an analysis tool for assessing the validity of structural hypotheses. Through such an investigation, we can answer questions like: "Are we data modeling or actually modeling the system?"

1.1 Report Outline

The report tries to give a fair presentation of large body of work done over a long period of time, starting during the autumn of 1996. Chapter 2 gives a brief description of the drum-boiler model [5, 12], which is the subject of the case-study. Details are given about the different model structures and hypotheses used in the parameter optimization trials. Chapter 2 also gives information on how the equation export from OmolAto IdKitwas done and how the limitations in this export mechanism affects the model definition. Chapter 3 describes initial simulation trials to assess the quality of the hypotheses and the identifiability of the parameters. In Chapter 4 the results from the parameter optimization trials are explained and finally, Chapter 5 gives some conclusions on what was learned from the case-study.

Details on derivations, model definition and parameter optimization trials are given in the appendices.

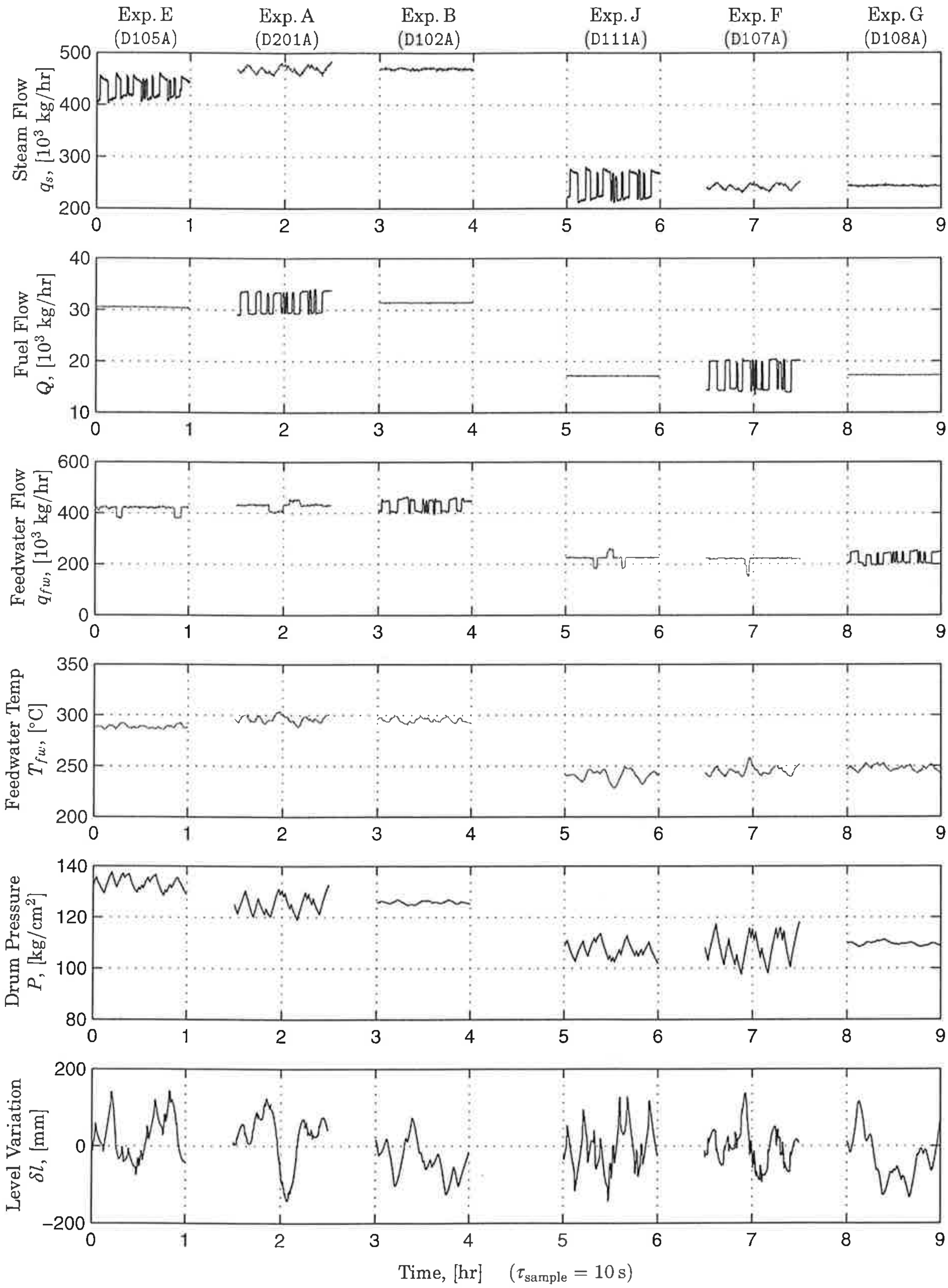


Figure 1.1: Six datasets from Eklund's Öresundsverk experiments [7]. Three controlled signals were perturbed separately under both full (90%) and partial (50%) load conditions.

1.2 Acknowledgment

The work was supported in part by Sydkraft AB under the auspices of Project 391, Modelling and Control of Energy Systems.

Chapter 2

Model Definition

The model structures studied in this report are a result of work by Professors Karl Johan Åström and Rodney Bell [2–5]. To verify their derivations, we used MAPLE (software for computer algebra) to rederive and study the modeling equations. The output of the MAPLE worksheets is presented in Appendix A. Appendix B provides an alternate summary of the modeling equations, i.e. the OMOLA definitions for the family of model structures.

The outline for this chapter is as follows: In the following section, we summarize Åström and Bell's results and suggest a few alternate hypotheses to some of their heuristic models. Section 2.2 surveys the model structures and how OMOLA simplified their definition and administration. Section 2.3 summarizes the parameterization of the model equations and the OMOLA simulation interface. The later defines collectively the calibration constants associated with the experimental data. Sections 2.4 and 2.5 discuss respectively the prerequisites and procedure of exporting the model equations from OMSIM [10] and generating C-code used by IDKIT [6, 11]. Finally, Section 2.6 makes some closing remarks regarding the model definition stage of this project.

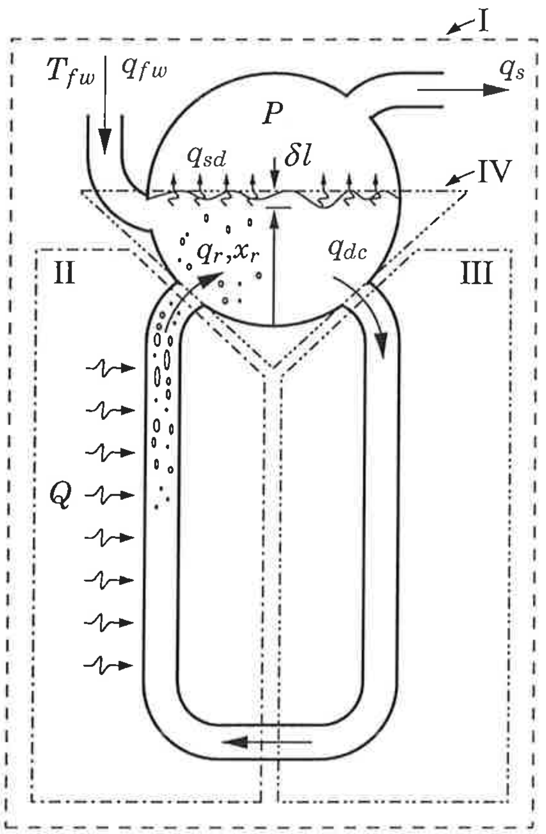


Figure 2.1: Ideal physical model of a steam generation process. Shown are the global control volume (I), and three component control volumes for the risers (II), the down-comers (III) and the liquid-zone of the drum (IV).

2.1 Model Equations and Hypotheses

An idealized physical model for the system is shown in Figure 2.1. Steam vapor is vented from the drum with flowrate q_s. Feed-water enters the drum in a sub-cooled liquid state with flowrate q_{fw} and temperature T_{fw}. Combustion of fuel gives rise to the heat flowrate Q into the risers. Steam vapor is generated by channeling the liquid phase from the drum through the down-comers/risers circuit. The flowrate into this circuit q_{dc} is driven by the density gradient caused by the phase change in the risers. At the risers outlet, the two-phase mixture is characterized by the mass flowrate q_r and vapor mass-fraction x_r.

The fundamental modeling simplification is that the two phases of water inside the system are everywhere in a saturated thermodynamic state. With this assumption, all thermodynamic properties can be characterized by one independent variable. The drum pressure P is chosen to be this key state variable since it is the most globally uniform variable in the system. Another key assumption is an instantaneous and uniform thermal equilibrium between water and metal everywhere. This simplifies including thermal capacitance effects.

Indicated in Figure 2.1 are the boundaries of four thermodynamic control volumes. Mass and energy balances for the global control volume (c.v. I) yield two state equations; see Section A.2. The state variables are pressure P and the total volume of liquid water in the system V_{wt}. By combining the mass and energy balances for c.v. II to eliminate the flowrate q_r, a third state equation is derived with the vapor mass-fraction x_r as state variable; see Section A.3. By considering fluid friction in c.v. III, a fluid momentum balance establishes the flowrate q_{dc}. A combination of the mass and energy balances for c.v. IV yields a fourth state equation with state variable V_{sd}, the volume of steam vapor below the liquid surface; see Section A.4. Assembled in matrix notation, the fourth-order model structure (i. e. a set of parameterized implicit differential state equations) is:

$$\mathcal{M}_4: \quad \begin{bmatrix} e_{11} & e_{12} & 0 & 0 \\ e_{21} & e_{22} & 0 & 0 \\ 0 & e_{32} & e_{33} & 0 \\ e_{41} & e_{42} & e_{43} & e_{44} \end{bmatrix} \begin{bmatrix} \frac{\partial}{\partial t} V_{wt} \\ \frac{\partial}{\partial t} P \\ \frac{\partial}{\partial t} x_r \\ \frac{\partial}{\partial t} V_{sd} \end{bmatrix} = \begin{bmatrix} q_{fw} - q_s \\ Q + h_{fw} q_{fw} - h_s q_s + \Delta_{\mathrm{I}} \\ Q - (h_s - h_w)\, x_r q_{dc} + \Delta_{\mathrm{II}} \\ \dfrac{V_{sd} - V_{sd}^0}{\tau_{sd}} + \dfrac{(h_{fw} - h_w)\, q_{fw} + \Delta_{\mathrm{IV}}}{\rho_s (h_s - h_w)} \end{bmatrix} \tag{2.1}$$

The elements of the coefficient matrix e_{11}, e_{12}, e_{21}, etc., are state dependent. They are all listed in Appendix A on pages 41 and 55. On the right, Δ_{I}, Δ_{II} and Δ_{IV} represent under-modeling, i. e. unmodeled energy interactions (nominally taken to be zero). The initial state conditions are parameterized $[V_{wt}^0, P^0, x_r^0, V_{sd}^0]^T$. In addition to these, the model involves seven physical parameters: metal masses m_d, m_r, m_{dc}, volumes V_d, V_r, V_{dc}, and a fluid friction coefficient in the down-comers k_f. Known constants are the specific heats C_{fw} and C_p for the feed-water and metal respectively. Finally, note that the third-order model structure $\mathcal{M}_3$ corresponds exactly to the first three state equations in Equation 2.1.

For the purpose of level control, Åström and Bell [5] proposed the following measurement model for the liquid level in the drum (see Section A.3.1):

$$l = \frac{V_{wd} + V_{sd}}{A_d} - L_0. \tag{2.2}$$

The level variation δl is caused by variations in the volumes of liquid in the drum V_{wd}[1] and the steam below the surface V_{sd}. This model introduces two additional physical parameters: A_d, the drum's cross-sectional area at the nominal level, and L_0, nominal level offset. The aim of including variation in V_{sd} is to capture the level dynamics known as the "shrink-and-swell" effect [5]. Note that we amend Equation 2.2 in Section 3.2.

To assess the necessity of including the fourth state equation in $\mathcal{M}_4$, we shall investigate parameter optimization of both third and fourth-order model structures. In the third-order structure $\mathcal{M}_3$, the state variable V_{sd} in equation Equation 2.2 is replaced with an instantaneous value. Engineering judgment suggests several approximations for its value:

$$V_{sd} = \begin{cases} b_1 & +b_2(q_{fw} - q_s) \quad \text{hypothesis 0,} \\ b_1 \alpha_r V_r & +b_2(q_{fw} - q_s) \quad \text{hypothesis 1,} \\ b_1 x_r q_r / \rho_s & +b_2(q_{fw} - q_s) \quad \text{hypothesis 2,} \\ b_1 \alpha_r V_r & +b_2 q_{ct} / \rho_s^0 \quad \text{hypothesis 3,} \\ b_1 \alpha_r V_r & +b_2 q_{ct} / \rho_s \quad \text{hypothesis 4.} \end{cases} \tag{2.3}$$

[1] $V_{wd}(t) = V_{wt}(t) - V_{dc} - (1 - \alpha_r(t))\, V_r$ where α_r is the total volume fraction of steam in the risers, i. e. $\alpha_r = V_{sr}/V_r$. An approximation with form $\alpha_r \approx \mathrm{fcn}(P, x_r)$ is given in [3, 4]; see also Section A.3.3.

The fourth-order structure $\mathcal{M}_4$ instead involves a similar set of hypotheses for the bubble-residence time-constant τ_{sd}. The heuristics for the values which have been tested are:

$$\tau_{sd} = \begin{cases} b_1 \rho_s (V_d - V_{wd})/q_s & \text{hypothesis 0,} \\ b_1 \rho_s (V_d - V_{wd} - V_{sd})/q_s & \text{hypothesis 1,} \\ b_1 \rho_s (2V_{sd}^0 - V_{sd})/x_r/q_r & \text{hypothesis 2,} \\ b_1 \rho_s^0 V_{sd}^0/x_r^0/q_r^0 & \text{hypothesis 3.} \end{cases} \tag{2.4}$$

These hypotheses are programmed in Listings B.12 and B.14 using the technique proposed in [1] for programming multiple realizations. Note that b_1 and b_2 are "grey-box" parameters to be optimized.

Bell and Åström have also proposed a fifth order model structure [12]. This was motivated by the desire to capture an additional "rapid-swell" phenomena present in some of the measured data (see the non-minimum phase behavior in the level variation of experiments A and F in Figure 1.1). The extra dynamics model the transport delay of steam vapor passing from the risers to the drum surface. The transport delay with time constant τ_{sd} is approximated by a Padé(0,1) approximation:

```
> with(numapprox):
> exp(-tau[sd]*s) = pade(exp(-tau[sd]*s),s,[0,1]) + O(s^2);
```

$$e^{(-\tau_{sd}\, s)} = \frac{1}{1 + \tau_{sd}\, s} + O(s^2)$$

Augmenting the state space representation of this approximation yields the following set of implicit differential equations:

$$\mathcal{M}_5: \quad \begin{bmatrix} e_{11} & e_{12} & 0 & 0 & 0 \\ e_{21} & e_{22} & 0 & 0 & 0 \\ 0 & e_{32} & e_{33} & 0 & 0 \\ e_{41} & e_{42} & e_{43} & e_{44} & 0 \\ 0 & 0 & 0 & 0 & \tau_{sd} \end{bmatrix} \begin{bmatrix} \frac{\partial}{\partial t} V_{wt} \\ \frac{\partial}{\partial t} P \\ \frac{\partial}{\partial t} x_r \\ \frac{\partial}{\partial t} V_{sd} \\ \frac{\partial}{\partial t} q_{sd} \end{bmatrix} = \begin{bmatrix} q_{fw} - q_s \\ Q + h_{fw} q_{fw} - h_s q_s + \Delta_{\rm I} \\ Q - (h_s - h_w)\, x_r q_{dc} + \Delta_{\rm II} \\ \frac{V_{sd} - V_{sd}^0}{\tau_{sd}} + \frac{(h_{fw} - h_w) q_{fw} + \Delta_{\rm IV}}{\rho_s (h_s - h_w)} + \frac{x_r q_r - q_{sd}}{\rho_s} \\ x_r q_r - q_{sd} \end{bmatrix} \tag{2.5}$$

The physical interpretation of the fifth state variable, q_{sd}, is the vapor mass flow rate crossing the liquid surface. Note the appearance of q_r in the right-hand side of equations. The mass balance for the risers (see Section A.3.2) gives the following expression:

$$q_r = q_{dc} - \tfrac{\partial}{\partial t} M_r \;=\; \mathrm{fcn}\left(\tfrac{\partial}{\partial t} P, \tfrac{\partial}{\partial t} x_r, \ldots\right).$$

In order to maintain compatibility with the definitions for the coefficients e_{42} and e_{43} in $\mathcal{M}_4$, we chose to leave q_r on the right-hand side (rather than bringing all time-derivative dependencies to the left-hand side). Consequently, derivation of *explicit* state equations (ODE's) is more complex than the bottom row of the coefficient matrix in Equation 2.5 suggests. Fortunately OMSIM automates this task using Cramer's rule, affording us the luxury of the more compact definition as implicit state equations.

2.2 Model Structure Administration

As alluded to above, OMOLA greatly simplified the task of defining and administrating model structures. Table 2.1 and Figure 2.2 on the facing page provide an overview of the model structures we have programmed. Besides the three model structures $\mathcal{M}_3, \mathcal{M}_4$, and $\mathcal{M}_5$, we defined and tested a number of alternative structures. Not all have been (or can be) used in parameter optimization. Listings for most are given in Appendix B.

2.3 Model Parameterization and Simulation Interface

The parameter definitions are concentrated in the OMOLA classes: `OresundSimIC` and `Boiler2FM` (see Listings B.11 and B.12 respectively). Table 2.2 on the next page summarizes the model parameterization and rates qualitatively our prior knowlege of the parameter values. Using a scale from

Model Structure	OMOLA Class	State Variables V_{wt}	P	x_r	V_{sd}	V_{wd}	Delay Var's q_{ct}	q_{sd}	Descriptive Note
$\mathcal{M}_2$	Boiler2FM	+	+						second order
$\mathcal{M}_3$	Boiler3FM	+	+	+					third order
$\mathcal{M}_4$	Boiler4FM	+	+	+	+				fourth order
$\mathcal{M}_{1r}$	Boiler1rFM		+						reduced second order
$\mathcal{M}_{2r}$	Boiler2rFM		+	+					reduced third order
$\mathcal{M}_{3r}$	Boiler3rFM		+	+	+				reduced fourth order
$\mathcal{M}_{3wd}$	Boiler3wdFM		+	+		+			alternate state realization
$\mathcal{M}_{3i}$	Boiler3iFM	+	+	+					iterative initialization
$\mathcal{M}_{3d}$	Boiler3dFM	+	+	+			+		multiple delay realizations
$\mathcal{M}_{4d}$	Boiler4dFM	+	+	+	+			+	multiple delay realizations
$\mathcal{M}_5$	Boiler5FM	+	+	+	+			+	Padé(0,1) delay approx.
$\mathcal{M}_{5a}$	Boiler5aFM	+	+	+	+			+	Padé(1,1) delay approx.
$\mathcal{M}_6$	Boiler6FM	+	+	+	+			+	Padé(1,2) delay approx.

Table 2.1: Overview of the model structures defined using OMOLA.

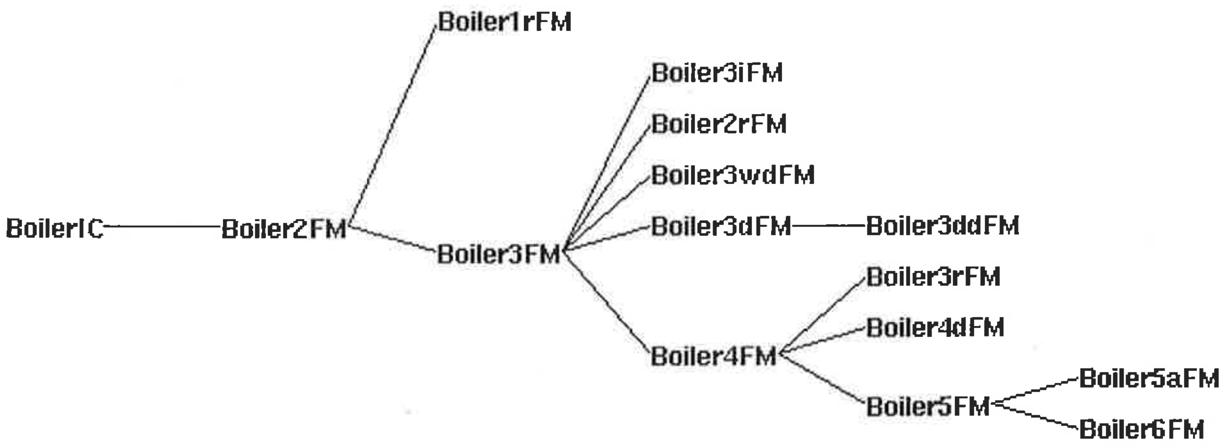


Figure 2.2: Inheritance hierarchy of the boiler model structures.

Parameter	OMOLA	Units	Description	Prior Knowledge
$q_{s_{cf}}$	qscf	kg/s/ton/hr	steam flow rate calibration factor	light grey
$q_{f_{cf}}$	qfcf	MW/ton/hr	fuel flow rate calibration factor	grey
σ_4	sigma4	kg/cm^2	standard deviation of pressure output error	–
σ_5	sigma5	mm	standard deviation of drum level output error	–
m_d	md	kg	metal mass of the drum	white
m_r	mr	kg	metal mass of the risers	white
A_d	Ad	m^2	cross-sectional area of the drum	light grey
k_f	kf	–	fluid friction factor in the down-comers	***black***
k_s	ks	kg/s/MPa	compressibility coefficient in the steam valve	grey
L_0	L0	m	slack factor in the drum level model	black
b_1	b1	–	slack factor in V_{sd} and τ_{sd} hypotheses	grey
b_2	b2	m^3/kg/s	slack factor in V_{sd} hypotheses; V_{sd}^0 in $\mathcal{M}_4$ & $\mathcal{M}_5$	grey
δV_{wt}^0	dVwt0	m^3	perturbation in the initial condition of V_{wt}	grey
P^0	P0	MPa	initial condition of the drum pressure P	white
x_r^0	xr0	–	initial condition of the vapor mass fraction x_r	black

Table 2.2: Overview of the model parameterization and prior knowledge.

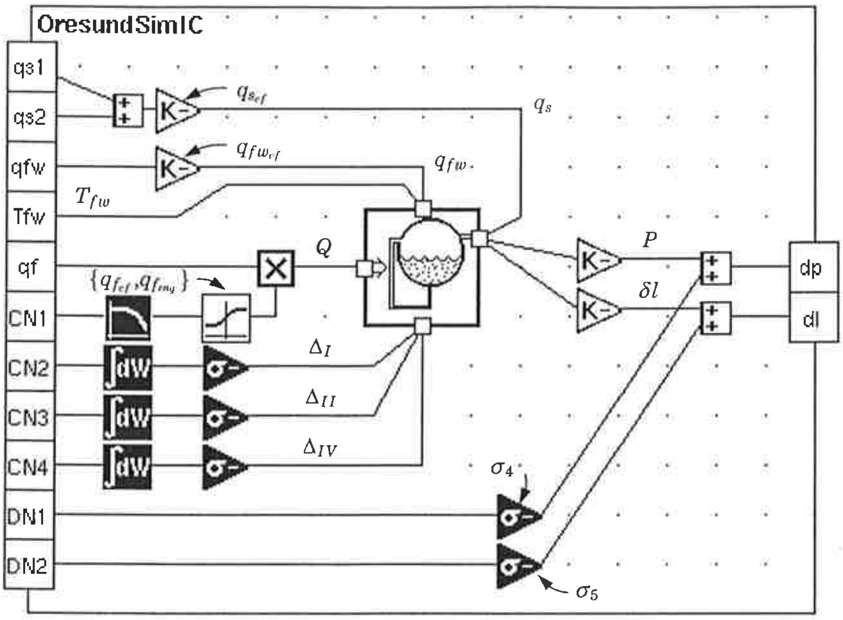


Figure 2.3: The OMSIM simulation interface to the experimental data; see Listing B.11. The interface includes stochastic black-box input- and output-error models.

black to white, black indicates little or no help from engineering physics. At the opposite end of the spectrum, white indicates a high degree of certainty.

Figure 2.3 shows the simulation interface to the five measured inputs: two steam flows, feed-water flow, feed-water temperature and fuel flow. The interface with real data necessitates conversion factors; the simulation schematic shows several. Most uncertain is the calibration of the heat input Q. Because the chemical energy content of the fuel is known to vary, this gain has been probabilistically modeled with a nominal value $q_{f_{cf}}$ and a known, bounded range $q_{f_{rng}}$. More certain are the calibrations of the steam mass flowrates $q_{s_{cf}}$ and feed-water mass flowrate $q_{fw_{cf}}$. We shall consider the later a known constant, assuming liquid flow measurements are more precise than vapor flow measurements. The conversion of steam flowrate is complicated by the fact that the measurements are volume flowrates, which need to be converted to mass flowrate. Since steam is a compressible medium, the conversion is pressure dependent. This can be compensated for by including a compressibility factor, k_s, which can also be seen as a "steam valve nonlinearity". Similar to [7] this has been modeled as

$$q_s = q_{s_{cf}}(\mathrm{qs1} + \mathrm{qs2}) + k_s(p - p^0) \tag{2.6}$$

The compressibility factor takes into account that at higher pressures the density of steam is higher and thus the mass flow rate is higher. These choices give $q_{f_{cf}}$, $q_{s_{cf}}$ and k_s as additional parameters for optimization.

In addition to the stochastic modeling of the gain $q_{f_{cf}}$, the simulation interface includes simple stochastic input and output-error models. The focus of this study is parameter optimization in a deterministic setting. Accordingly, only the instantaneous output-error models will be investigated here. In a possible continuation of this work, the input-error models could be used to investigate the effects of under-modeling, i. e. Δ_{I} etc.

2.4 Signal Model Specification

A requirement for the automatic code generation is a name mapping that defines inputs, outputs etc. For the OMSIM–IDKIT interface developed as part of this project (see [6]) this was solved by requiring a `SignalModelMapping` submodel be included in the simulation model. Listing B.9 provides the template. This class defines the vector variables and a parameter matrix of a standard nonlinear stochastic state space model structure (see [1, 11]):

$$\frac{\delta x}{\delta t} = f(t, x_t, u_t, \theta) + w(t, \theta) \qquad \text{and} \qquad y_t = h(t, x_t, u_t, \theta) + v(t, \theta).$$

The `SignalModelMapping` class is used by including it in the simulation model, and defining the vector dimensions and element-wise contents. This constitutes a name mapping from the models internal

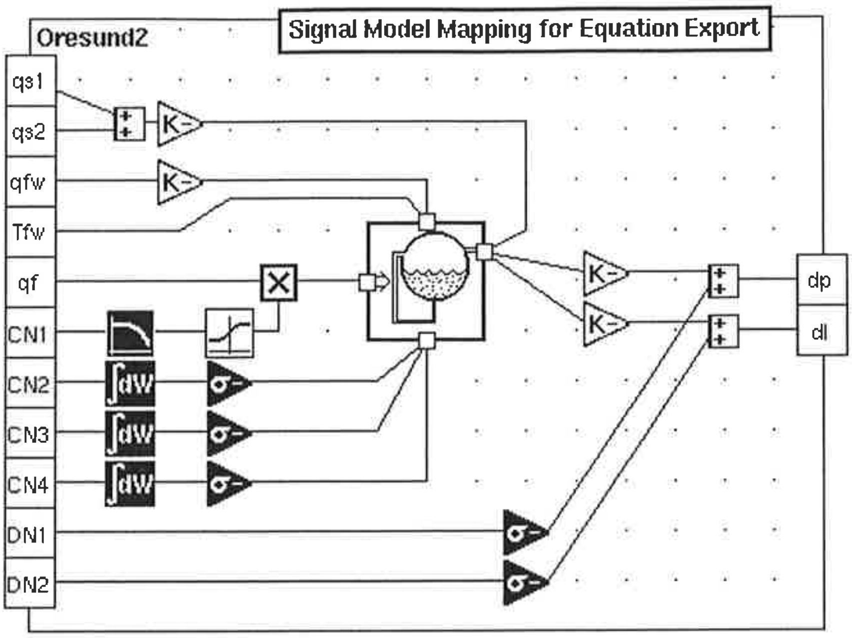


Figure 2.4: Each simulation model specifies: (*i*) a boiler submodel structure and (*ii*) a signal-model mapping for equation export.

hierarchical names to the standard state space vectors u, v, w, x and y, as well as the parameter matrix θ.

The row-by-row organization of the matrix θ is important. When using IDKIT, the user fixes or frees entire rows at a time—it is not possible to fix and free elements row-wise. Only parameters for which simultaneous optimization is essential should be grouped row-wise. Furthermore, IDKIT uses the same numerical scaling factor for all elements of a row.

The second-order simulation model `Oresund2` shown above and listed on page 77 provides an example of the signal model mapping. Lines 8–19 define the vector variable mappings. The first four rows of the parameter matrix mapping (lines 24–27) collect those parameters which we have no intentions of optimizing yet we do not wish to hard-wire their values into the automatically generated C-code. The remaining rows (lines 28–46) map the parameter names which we (potentially) wish to optimize. Note the correspondence between these lines of OMOLA code and Table 2.2. No parameters were grouped row-wise because of the need for distinct scaling factors.

2.5 Equation Export and Code Generation

The process of turning OMOLA model equations into C-code functions that can be used by the parameter optimization routines in IDKIT consists of two steps:

(*i*) exporting sorted model equations from OMSIM, and then

(*ii*) invoking a shell script that translates the equations and uses Maple to generate C-code.

These steps and also limitations concerning the use of conditional statements in the model are described fully in [6]. For the sake of self-containment, a short description follows.

Exporting Omola Equations

Th IDKIT model interface requires a set of nonlinear ordinary differential equations in explicit form. In our case we defined the model in an implicit differential equation form. By configuring OMSIM to use Cramer's rule during the instantiation the model is automatically transformed to explicit ODE form. This is set by choosing the "Config→Options" menu and marking the "Cramer's rule for manipulation" option before starting the simulator. We also need to mark "Log to file" option to create the log-file.

To generate the sorted equations we use the OMSIM simulators "Flat model" and "Event part" debug output. This writes all the continuous equations as well as parameter equations and event equations to the log-file. In the event part, only initialization events are allowed. This restriction is necessary since the code generation script (described below) is designed only to handle continuous time models.

Code Generation Script

The model equations captured in the log-file are processed by running the Unix shell-script CodeGen.sh in the same directory as the log-file. This shell-script automatically performs the steps of:

(*i*) OMSIM log file translation,

(*ii*) MAPLE post-processing of the equations, and

(*iii*) MAPLE code generation.

The script takes no arguments and, if successful, it creates two files in the working directory:

model.c — a subroutine module for use with IDKIT,

Smodel.c — a SIMULINK S-function for MATLAB.

Event Equation Limitations

It is important to note the limitations of the code generation script. With regard to the event equations, i.e. the "Event part" of the log-file, we mentioned that only initialization events are supported. A further limitation is that these events cannot form an iterative sequence of equations.

To convey this restriction, we compare the initialization programming in the model structures $\mathcal{M}_2$ and $\mathcal{M}_{3i}$. The latter is a special iteratively-initialized derivation of $\mathcal{M}_3$. The motivation behind this is discussed in Section 3.2.4. The sequence is derived in Section A.3.7. Note that $\mathcal{M}_{3i}$ inherits the events of $\mathcal{M}_3$.

Considering $\mathcal{M}_2$ first, observe that lines 124 and 142 in Listing B.12 involve the same equation:

```
new(Vwt) := 1/2*Vd + (1-ar0)*Vr + Vdc + dVwt0;
```

In contrast, the $\mathcal{M}_{3i}$ equations:

```
new(xr) := xr0;

new(xr) := -ar/dardx + xr/2
  + (1/2/hc/dardx/qdc)*sqrt( hc*qdc*(4*hc*qdc*ar*(ar-dardx*xr)
                           + hc*qdc*(dardx*xr)^2 + 8*Q*ar*dardx) );

new(xr) := -ar/dardx + xr/2
  + (1/2/hc/dardx/qdc)*sqrt( hc*qdc*(4*hc*qdc*ar*(ar-dardx*xr)
                           + hc*qdc*(dardx*xr)^2 + 8*Q*ar*dardx) );
```

programmed in lines 28 and 12–14 of Listings B.13 and B.22 respectively constitute an iterative sequence.

The cause of the restriction is simple. The code generation script translates the OMSIM equations into MAPLE assignment statements. For an iterative sequence, this results in repeated assignments to the same name (i.e. the same left-hand-side symbol). When loaded into MAPLE, no iterative substitution takes place. Instead, only the last assignment survives.

2.6 Closure

Since the definition of the model structures in OMOLA constituted a substantial amount of time, it seems relevant to recap some of issues raised in the process. Questions raised while programming the OMOLA model definitions are:

- How important is the thermal capacitance effects of the metal mass? Where is it most important to include these effects in the modeling equations?
- What are the consequences of using enthalpy instead of internal energy in deriving the energy balances? How valid is this approximation?

Answers to these questions can be found through simulation testing and parameter optimization, the topics of the following two chapters.

Chapter 3

Simulation Testing

More than anything else, this case study has demonstrated the importance of good simulation tools. When conceptualizing a methodology for grey-box identification (see e.g. [1, 13]) it is easy to over-emphasize the importance of statistical methods. One should not under-estimate what can be learned directly through iterative simulation and analysis. This synthesis of information is what we refer collectively to as "simulation testing." Indeed, the knowledge gained through simulation testing can be essential for achieving success with statistical methods. Conveying this lesson is one reason we include this chapter.

The outline for the chapter is as follows: Section 3.1 discusses the role that manual parameter tuning has played in this case study. As a tutorial example, we consider calibration of the model to the experimental data. Section 3.2 presents a qualitative assessment of parameter sensitivities, couplings and over-parameterization. Through simulation testing, we were able to identify where this occurs in the modeling equations. These findings are largely responsible for the iterative refinements of the model structures described in the preceding chapter. Section 3.3 demonstrates how simulation testing can answer questions of model structure, i.e. structure determination. Specifically, we answer the question concerning the validity of replacing internal energy with enthalpy in the derivation of energy balance.

3.1 Manual Parameter Tuning

Manual tuning of parameters is important for a number of reasons. Most obvious is the need to determine values for those parameters that cannot be established from construction data. To even begin a simulation let alone parameter optimization, we need a functional set of numeric values for the parameters. By functional, we mean in the sense that numerical integration is not driven unstable. In case study, manual experimentation was important for two reasons:

(*i*) to establish good "guesses" suitable for initializing computer-aided tuning, and

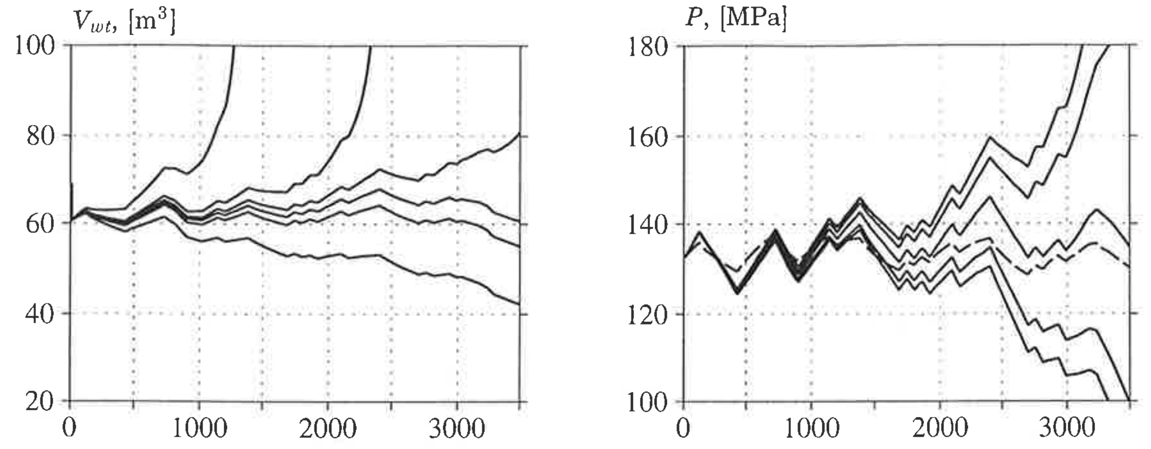
(*ii*) to "feel out" parameter sensitivities as well as couplings between parameters.

With *computer-aided* tuning, we mean of course parameter optimization. For iterative methods of parameter estimation, e.g. as implemented in IdKit, good initial guesses greatly aid in speeding convergence to the optimum. Prior knowledge of the parameter sensitivities, however rudimentary, guides the choice of which parameters to fix as constants and which to free for optimization. In fact one does this in stages, freeing more and more parameters sequentially. Ideally, the model becomes more "tuned" to the data at each stage. We will elaborate on this procedure in the next chapter. For now, we concern ourselves tutorially with manual tuning.

3.1.1 An Example: Balancing the Flux of Mass and Energy

To begin, recall the nature of the global mass balance. Accumulation equals the flux in minus the flux out i.e. the feed-water flow rate q_{fw} minus the vented steam flow rate q_s. In terms of Eklund's measured signals and calibration factors, we have:

$$\begin{aligned} \frac{dM}{dt} &= q_{fw_{cf}} u_3 - q_{s_{cf}} u_1 \\ &= \mathrm{fcn}(u, \theta) \quad \neq \quad \mathrm{fcn}(x, u, \theta). \end{aligned}$$



(a) Balancing mass flux via $q_{s_{cf}}$.

(b) Balancing energy flux via $q_{f_{cf}}$.

Figure 3.1: Typical results of iterative manual tuning.

Here x, u and θ represent generically the state variables, measured inputs and parameter respectively. The last line above emphasizes the *pure integral* nature of the system. System stability requires a net balance of the mass flux. The same can be said of the global energy balance, even though it is not purely integral in nature, i. e.:

$$\begin{aligned}\frac{dU}{dt} &= q_{f_{cf}} u_2 + h_{fw} q_{fw_{cf}} u_3 - h_s q_{s_{cf}} u_1 \\ &= \text{fcn}(x, u, \theta).\end{aligned}$$

Recall in Section 2.3 we chose based on the accuracy of liquid and vapor flow measurements (*i*) to fix $q_{fw_{cf}}$ and (*ii*) to leave $q_{s_{cf}}$ free for parameter optimization. Clearly this choice was essential for identifiability. Similarly, we left free $q_{f_{cf}}$, the calibration factor relating heat transfer to the measured fuel flow rate.

Engineering know-how guides the manual tuning of $q_{s_{cf}}$ and $q_{f_{cf}}$. We know Eklund's experiments were conducted under near-equilibrium operating conditions. Logically, one must first balance the inlet and outlet mass flows q_{fw} and q_s. This is done by adjusting $q_{s_{cf}}$. The state variable V_{wt} is fairly representative of the total mass in the system. Once the net mass flux is balanced, one can balance the energy flux by adjusting $q_{f_{cf}}$. The state variable P is a good indicator of the total energy in the system.

Figure 3.1 shows results of manually calibrating $q_{s_{cf}}$ and $q_{f_{cf}}$ to the dataset from experiment E. Starting with $q_{s_{cf}} = 0.26$ and $q_{f_{cf}} = 5.6$, the following adjustments are shown in Figure 3.1(a):

$$q_{s_{cf}}: \quad 0.26 \rightarrow 0.27 \rightarrow 0.265 \rightarrow 0.267 \rightarrow 0.266 \rightarrow 0.2665$$

With the mass flux more or less balanced, the following adjustments were made:

$$q_{f_{cf}}: \quad 5.6 \rightarrow 5.61 \qquad q_{s_{cf}}: \quad 0.2665 \rightarrow 0.267 \qquad q_{f_{cf}}: \quad 5.61 \rightarrow 5.62 \rightarrow 5.615$$

These are shown in Figure 3.1(b). In this plot, the measured pressure signal is shown as a dashed line. Note that manual tuning (by mortals) is best limited to tweaking one parameter at a time.

Regime	Experiment	$q_{s_{cf}}$	$q_{f_{cf}}$
full	E	0.267	5.612
load	A, B	0.253	5.575
partial	J	0.253	6.205
load	F	0.253	6.121
	G	0.257	6.121

Table 3.1: The manually tuned calibration factors used as starting point for optimization.

Table 3.1 summarizes the manually tuned values that were used as initial guesses in computer-aided optimization trials. Note that because of changes in Eklund's experimental conditions, e. g.

variations in the chemical potential of the fuel, each of the six datasets requires its own tailor-tuned set of calibration factors. Finally, readers curious about the batch processing may inspect the cs_setp0.cf command script listing on pg. 83 and its use in Listing C.7.

3.2 Parameter Sensitivities and Couplings

With nonlinear model structures, it is difficult to assess the global nature of a manually tuned parameter. As demonstrated in the preceding example, changes in one parameter affect the tuning of others. Nevertheless with a little ingenuity it is possible to get a qualitative feel for parameter sensitivities.

In tuning calibration factors for example, the effects of thermal capacitance were not included. This was done by setting the metal masses equal to zero. (see lines 80–82, and 117 in Listing B.12, lines 21 and 12 in Listings B.13 and B.14 respectively). This increases the models sensitivity to $q_{s_{cf}}$ and $q_{f_{cf}}$, and greatly affects the perceived results in manually tuning them. Including thermal capacitances effectively slows down the dynamics of the energy balance. Graphically one can imagine the numerical explosions (due to imbalance in mass flux) shown in Figure 3.1(a) on the facing page elapsing at a slower pace. That the thermal *energy* effects affect the *mass* balance is evidence of the implicit couplings between the global mass and energy balances; cf. page 33 in Section A.2.

3.2.1 Couplings with Fluid Friction in the Down-Comers

The most uncertain parameter in the model is k_f, the coefficient of the fluid friction. This parameter enters the modeling equations via q_{dc}, the mass flow rate entering the down-comers. In both formulations of q_{dc} proposed by Åström and Bell [3, 12], k_f enters functionally in the denominator under a square root:

$$q_{dc} \propto \frac{1}{\sqrt{k_f}}. \tag{3.1}$$

The precise relations are derived via momentum balances in Section A.3.4 and programmed in lines 154–170 in Listing B.12.

To establish qualitatively the model's sensitivity with respect to k_f via simulation testing, we perturbed k_f and looked for effects in the simulated response. Figure 3.2 shows the most notable signal couplings. These can be summarized as follows:

$$\downarrow k_f \quad \Longrightarrow \quad \uparrow q_{dc}, \quad \downarrow x_r, \quad \downarrow \alpha_r.$$

For a quasi-steady rate of heat transfer to the risers, increasing the mass flow rate through the risers (q_{dc}) decreases the vapor generation (x_r and α_r). Thus, the model agrees qualitatively with our physics-based engineering intuition.

The last coupling, between k_f and α_r, is significant in the third-order model structure proposed in [3, 4]. Recall in Equation 2.2 that to capture the shrink-and-swell effect, Åström and Bell incorporated the volume of vapor below the surface, V_{sd}. In order to decouple V_{sd} from k_f, we inserted the multiplicative grey-box parameter b_1 to Åström and Bell's instantaneous heuristic (see Equation 2.3 and Section A.3.1). In essence, we tested:

$$V_{sd}(t) = b_1 \alpha_r(t) V_r.$$

This adds an extra degree of freedom to the measurement model, allowing magnification of the dynamics contained in α_r, independent of the value of k_f.

3.2.2 Over-Parameterization of the Drum Level Measurement Model

When choosing what parameters to optimize, over-parameterization is an important issue. This is very common in model structures based on first principles. For example, thermal energy storage in metal depends on $m\,C_p$ i.e. a product of two constants. These parameters cannot be estimated independently. More subtle over-parameterizations are easily overlooked.

In this study we set out to estimate the friction factor, k_f. It was deemed impossible since k_f seemed mainly to affect the static offset in the drum level. To account for this static error, we introduced the parameter L_0 in Equation 2.2 on pg. 5. Further scrutiny of the original level model

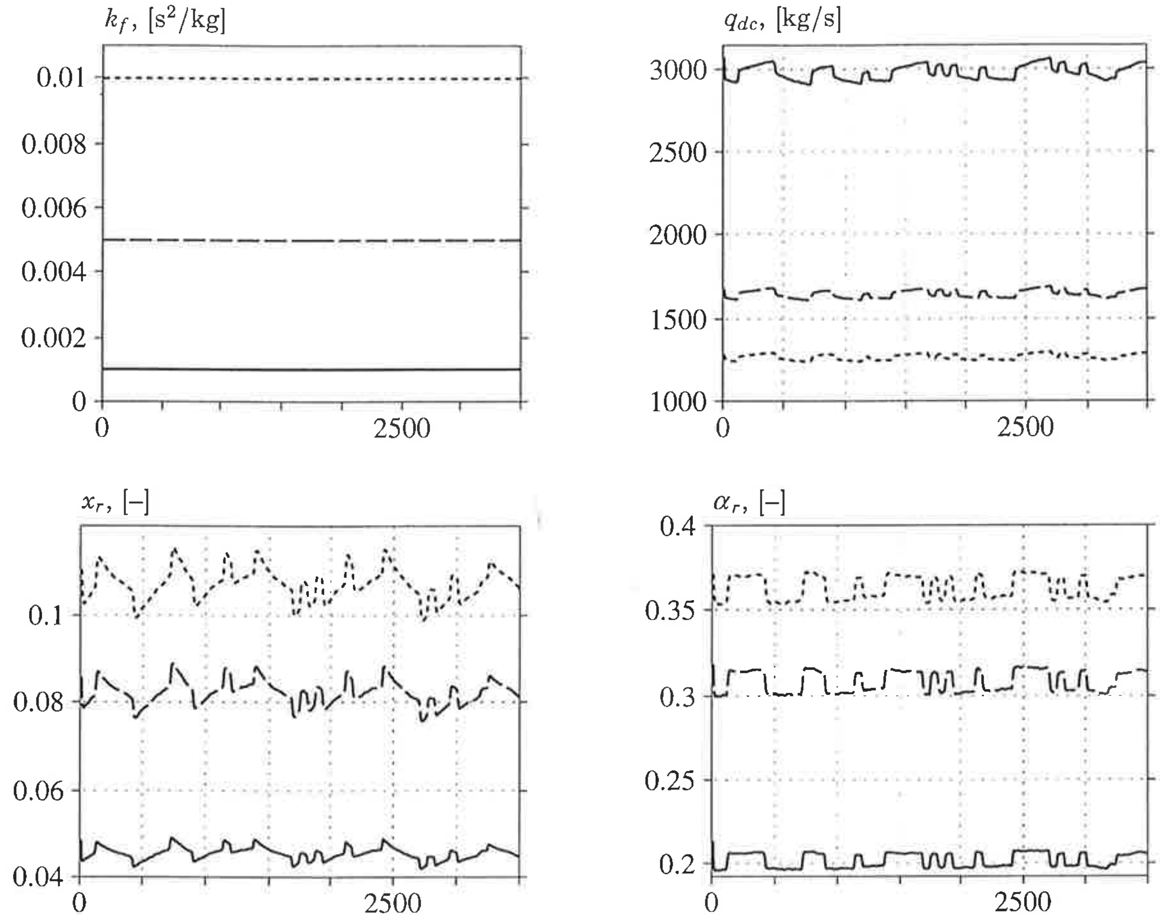


Figure 3.2: A simulation test that assesses the model's sensitivity to the coefficient of fluid friction. Note that k_f modulates not only the mean value, but also the peak-to-peak variation of the other signals.

revealed a subtle over-parameterization. Eliminating L_0 from the equation led to the following *variational* measurement model:

$$\delta l(t) = \frac{\Big(V_{wd}(t) - V_{wd}(0)\Big) + \Big(V_{sd}(t) - V_{sd}(0)\Big)}{A_d}. \tag{3.2}$$

In essence, we replaced the nominal drum level L_0 with a function of $V_{wd}(0)$ and $V_{sd}(0)$ which are themselves functions of the initial state conditions. This indirect parameterization of L_0 agrees logically with the physical assumption of near-equilibrium operation during the experiments. Unfortunately, the over-parameterization was only part of the problem and its elimination does not affect the identifiability of k_f. What the variational level model helped clarify is the dependency of the level model on the initial state conditions.

3.2.3 Couplings due to Non-Equilibrium State Initialization

Much to our chagrin, after switching from Equation 2.2 to Equation 3.2, drum level simulations still showed a static offset. More simulation testing revealed the source of the error: non-equilibrium initialization of the third state $x_r(t)$. Thus there is a coupling between k_f and the initial state condition x_r^0.

From Figure 3.2, we know the effect changing k_f has on x_r. Figure 3.3 shows the effect of perturbing x_r^0. Summarizing this later figure, we have:

$$\uparrow x_r^0 \quad \Longrightarrow \quad \downarrow V_{wt}(0), \quad \downarrow V_{wd}(t), \quad \uparrow V_{sd}(0), \quad \downarrow \delta l(t).$$

The initialization of x_r affects the state initialization of V_{wt} through the non-linear relationship for α_r. This is best explained by looking at the OMOLA code — look for `ar0` in lines 124 and 142 in

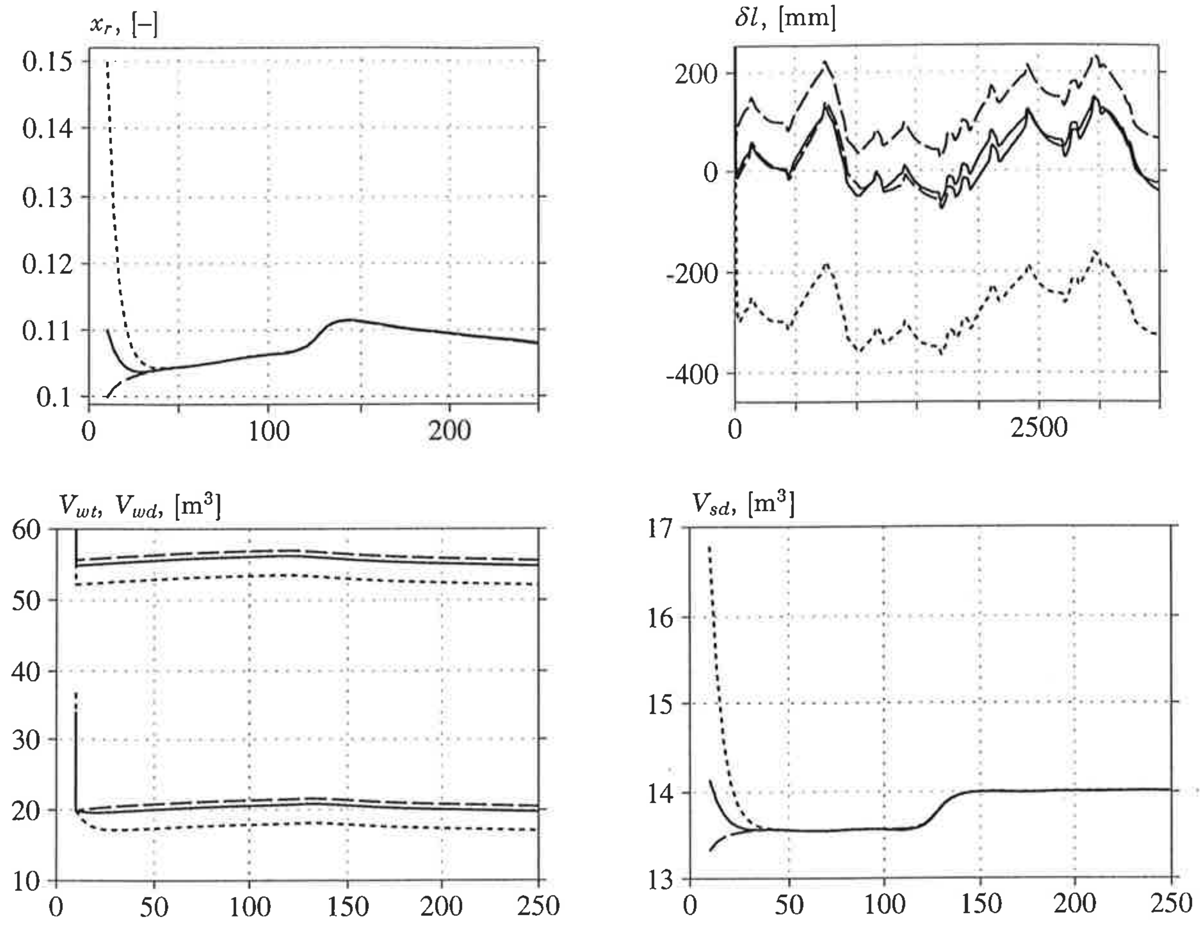


Figure 3.3: Effect of non-equilibrium initialization on the drum level model: For any *fixed* value of k_f, a non-equilibrium initialization of state $x_r(t)$ causes static error in $\delta l(t)$.

Listing B.12. The first-order transients seen in $V_{wd}(t)$ and $V_{sd}(t)$ are the dynamic response due to the non-equilibrium initialization of V_{wt}. As before this is best understood by examining the OMOLA code — the discrete initialization sequence programmed in lines 120–143 of the above mentioned listing. We note that repeating lines 130–137 in this sequence as a fourth event (timed after the `Start` event) has no effect on the simulation results shown in Figure 3.3.

The implication of the coupling is this: In order to maintain a near-equilibrium initialization, a change in k_f requires a corresponding change in x_r^0 i.e.:

$$\uparrow k_f \quad \text{requires} \quad \uparrow x_r^0.$$

The exact correspondence is analytically characterized by the equilibrium condition provided by the third state equation (see Equation 2.1 or Section A.3.2):

$$-h_c(0)\, x_r^0\, q_{dc}(0) + Q(0) = 0. \tag{3.3}$$

Including the parameter x_r^0 in a model is thus an over-parameterization. Any attempts at optimizing k_f require the simultaneous adjustment of x_r^0. Simultaneous unconstrained optimization of the coupled parameters is an ill-posed problem, hence k_f becomes unidentifiable. Finally, we note that because the coupling is transmitted through both V_{sd} and V_{wd} (see Equation 3.2), the problem does not go away by switching to the fourth-order model structure.

3.2.4 Iterative State Initialization and the Drum Level Measurement Model (*Revisited*)

The coupling between x_r^0 and k_f motivated us to investigate parameterized initializations for the state x_r. Theoretically, Equation 3.3 could be used to parameterize $x_r^0 = \text{fcn}(P^0, Q(0), k_f)$. The nonlinear

```
BEGIN
  Simulator s();
  s.reset;
  Model m(s);
  m.qscf        := 0.267366 ;     m.Boiler.ks      := 8.12786 ;
  m.qfcf        := 5.65107 ;      m.Boiler.L0      := 0.57;
  m.Sigma4      := 0.177821 ;     m.Boiler.xi0     := 0 ;
  m.Sigma5      := 13.099 ;       m.Boiler.b1      := 1 ;
  m.Boiler.md   := 0 ;            m.Boiler.b2      := 0 ;
  m.Boiler.mr   := 345208 ;       m.Boiler.dVwt0   := 0 ;
  m.Boiler.Ad   := 26.1435 ;      m.Boiler.P0      := 10.6089 ;
  m.Boiler.kf   := 0.01 ;         m.Boiler.xr0     := 0.110195 ;
  s.start;

  s.reset;
  m.Boiler.xr0                               := 0.10 ;
  s.start;

  s.reset;
  m.Boiler.xr0                               := 0.15 ;
  s.start;
END;
```

Listing 3.1: NonEquilibriumInit.ocl—Simulation script for Figure 3.3 using dataset E and the third-order model structure ($\mathcal{M}_3$); cf. Listing B.24 on pg. 77.

dependency of q_{dc} on x_r however prohibits a closed-form solution for x_r^0. An approximate *iterative* solution is derived in Section A.3.7 and encoded in Listing B.22; see pages 51 and 76 respectively.

As discussed in Section 2.5, an iterative sequence of discrete events cannot be translated to C-code by the MAPLE code generation tools [6]. Consequently we can not use the iterative solution in conjunction with IDKIT. Instead, we must account for any non-equilibrium state initialization. To do this we reintroduced the L_0 parameter into the drum level model. Our final revised variational measurement model is:

$$\delta l(t) = \frac{\Big(V_{wd}(t) - V_{wd}(0)\Big) + \Big(V_{sd}(t) - V_{sd}(0)\Big)}{A_d} + L_0. \tag{3.4}$$

Both Equations 2.2 and 3.4 appear in the OMOLA model definition as multiple realizations; see lines 151–152 in Listing B.12.

3.3 Structure Determination

To complete this chapter, we present an example showing how questions of model structure can be answered simply and definitively through simulation testing. The example also demonstrates the utility of good simulation tools.

3.3.1 An Example: Validity of Enthalpy Approximations in Energy Balances

The basic assumption is that internal energy u is well approximated by enthalpy h in the derivations of the compartmental energy balances. Since $h = u + P/\rho$ by definition, this is equivalent to assuming $u >> P/\rho$. For a given operating regime, it is easy to inspect this relationship through simulation. It is however desirable to verify such a question by actually having both realizations of the model structure available for testing. This is especially true for complex nonlinear systems. Recall we have defined the model in implicit form and this leads to extremly complex nonlinear equations when put in explicit form. Furthermore, we would ideally like to have some *quantitative* feel for how the approximation (or rather, that which we are neglecting) enters into the equations.

By running the derivations in Appendix A with both the exact and approximate substitutions, i.e.:

$$u = h - \frac{P}{\rho} \quad \text{and} \quad u \approx h,$$

we established that the approximation affects only the coefficients e_{22}, e_{32} and e_{42}. In each of these expressions, one or more "-1" components appear in the exact derivation. With a little thought, this makes sense: e_{22}, e_{32} and e_{42} are the coefficients of the time derivative of pressure P in each of the state equations. Note that energy and enthalpy do not enter into the derivation of the first state equation, hence e_{12} is not affected by the approximation. To summarize matters, we collect the OMOLA programming of e_{22}, e_{32} and e_{42}:

```
VectorVar ISA Std::VectorVar WITH
  EPS TYPE STATIC Real := 2^(-52); %% IEEE floating point
  abs    TYPE Column[n] := abs(value);
  logabs TYPE Column[n] := ln(abs(value+EPS*ones(n,1)))/ln(10);
  sum    TYPE Real;
  sum = ones(1,n)*value;
END;

e22 ISA DrumBoiler::VectorVar WITH
  n = 7;
  value = [Vst*[hs*drsdp; rs*dhsdp; -1*Ihu];
           Vwt*[hw*drwdp; rw*dhwdp; -1*Ihu]; (md+mr+mdc)*Cp*dTsdp];
END;

e32 ISA DrumBoiler::VectorVar WITH
  n = 8;
  value = [Vr*[    ar*[rs*dhsdp; (1-xr)*hc*drsdp; -1*Ihu];
              (1-ar)*[rw*dhwdp;    -xr*hc*drwdp; -1*Ihu];
              (rs + (rw-rs)*xr)*hc*dardp               ]; mr*Cp*dTsdp];
END;

e42 ISA DrumBoiler::VectorVar WITH
  n = 6;
  value = [       Vsd*[  1/rs*drsdp;    1/hc*dhsdp];
             1/rs/hc*[Vwd*rw*dhwdp; msd*Cp*dTsdp];
          -Ihu/rs/hc*[      Vwd+Vsd;    Vr*P*dardp]]; % [m3/MPa]
END;
```

See respectively Listings B.1 and B.12–B.14. The constant `Ihu` serves as a binary valued switch: when equal to one, the exact derivations are active; when zero, the approximation is active. Note the value semantics of the vector variables: the `sum` attribute is actually what enters the state equations (e. g. `e22.sum*dot(P)`).

To quantitatively assess the contribution of these "−1" terms, we devised a simple test. Notice how both the terms in question and the thermal capacitance effects and the enter linearly into the left-hand side of the state equations (look for `Mxdot` in the mentioned listings). By first neglecting thermal effects (letting $m = 0$) and then including it in a token sense (letting $m = 1$), we can compare quantitatively the magnitudes of the various components. A simulation script for this is shown in Listing 3.2.

Figure 3.4 shows the results of this simulation experiment using logarithmic scales. In each of the three plots, the token thermal capacitive effects are several orders of magnitude greater than the `Ihu`-switched components. These are in turn many orders of magnitude greater than IEEE floating point epsilon, `EPS = 2.2204e-16`. Nevertheless, since the unit of the metal mass is kilograms, realistic values ($m \approx 10^5$) are many orders of magnitude greater than the token value $m = 1$. In other words, the model is many orders of magnitude more sensitive to the thermal capacitive effects than the effects of the approximative enthalpy derivation. Based on this quantitative physical insight, we can safely proceed using the simplifications prescribed by Bell and Åström.

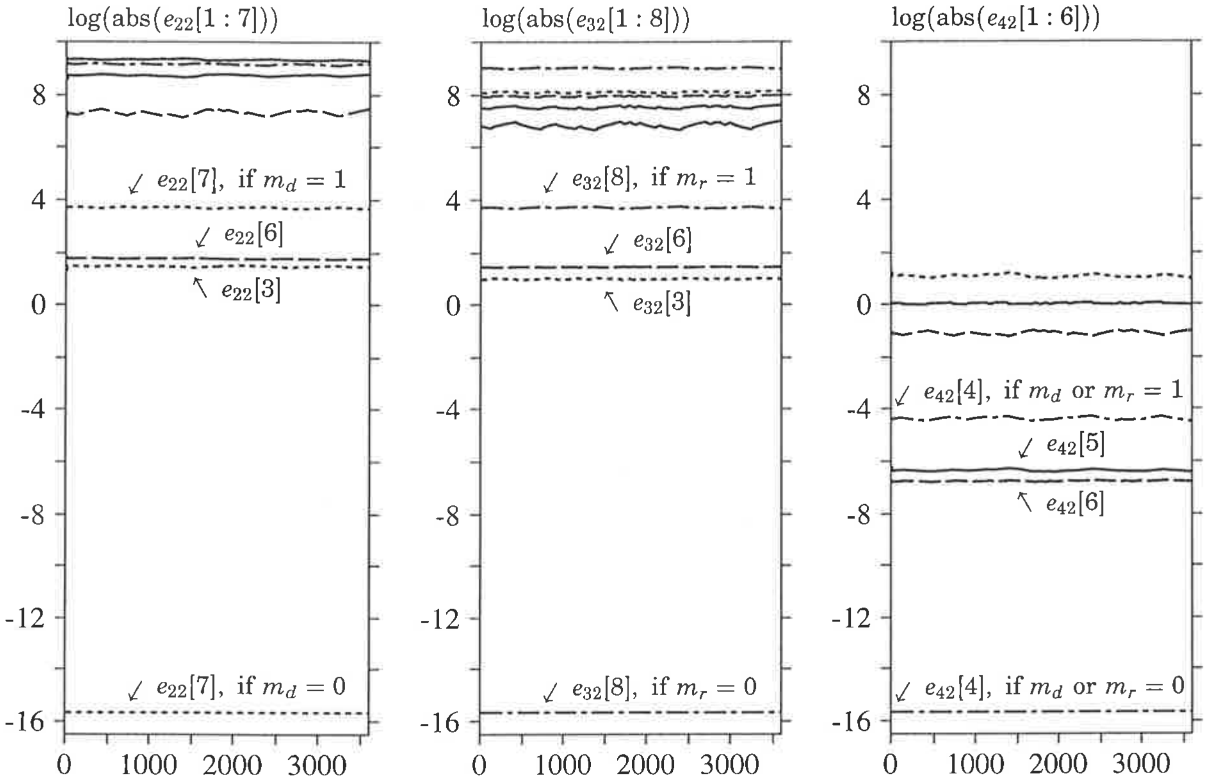


Figure 3.4: Simulation tests show the model is far more sensitive to the effects of thermal storage (i.e. metal masses) than to effects of approximating internal energy with enthalpy in the energy balance derivations.

```
BEGIN %% omsim  libs.om IhuMass.ocl
  Simulator s();              DrumBoiler::Oresund4 m;
  s.Model(m);                 s.StartTime  := 10.0;
  s.Display(250, 1000);       s.StopTime   := 3590.0;      s.OutputStep := 0.1; % (=3.58%)
  ReadFile Indata(m);         Indata.Display(750, 1000);   Indata.Name := "../data/ExpF.dat";
  Indata.Read(SteamFlow1, "SteamFlow1", SteamFlow2, "SteamFlow2", FeedWaterFlow,
    "FeedWaterFlow", FeedWaterTemp, "FeedWaterTemp", FuelFlow, "FuelFlow", DrumPressure,
    "DrumPressure", DrumLevel, "DrumLevel");
  Plotter Pe22(m);            Plotter Pe32(m);             Plotter Pe42(m);
  Pe22.Title :="logabs(e22)"; Pe32.Title :="logabs(e32)";  Pe42.Title :="logabs(e42)";
  Pe22.Display(250, 700);     Pe32.Display(500, 700);      Pe42.Display(750, 700);
  Pe22.Resize(250, 500);      Pe32.Resize(250, 500);       Pe42.Resize(250, 500);
  Pe22.HcopyFile := "e22.ps"; Pe32.HcopyFile := "e32.ps";  Pe42.HcopyFile := "e42.ps";
  Pe22.Xrange(0, 3600);       Pe32.Xrange(0, 3600);        Pe42.Xrange(0, 3600);
  Pe22.Yrange(-16.5, 10);     Pe32.Yrange(-16.5, 10);      Pe42.Yrange(-16.5, 10);
  Pe22.Y(Boiler.e22.logabs);  Pe32.Y(Boiler.e32.logabs);   Pe42.Y(Boiler.e42.logabs);

  m.qscf       := 0.252438 ;  m.Boiler.ks    := 4.02778 ;
  m.qfcf       := 6.08819 ;   m.Boiler.L0    := -0.0057723 ;
  m.Sigma4     := 0.405676 ;  m.Boiler.xi0   := 0 ;
  m.Sigma5     := 12.6251 ;   m.Boiler.xr0   := 0.0460863 ;
  m.Boiler.kf  := 0.005 ;     m.Boiler.Vsd0  := 8 ;
  m.Boiler.Ad  := 22.6071 ;   m.Boiler.dVwt0 := 0 ;
  m.Boiler.P0  := 8.6365 ;    m.Boiler.b1    := 0.7 ;

  m.Boiler.md := 0 ;          m.Boiler.mr    := 0 ;        s.reset;  s.start;
  m.Boiler.md := 1 ;          m.Boiler.mr    := 0 ;        s.reset;  s.start;
  m.Boiler.md := 0 ;          m.Boiler.mr    := 1 ;        s.reset;  s.start;
END;
```

Listing 3.2: IhuMass.ocl—Simulation testing script investigating model sensitivity to the approximative enthalpy derivation.

Chapter 4

Parameter Optimization

The provisional goal of this project was to see what improvements might be gained through parameter optimization. Our ambitions evolved into an investigation of structural fidelity due to the availability of multiple datasets. As discussed in Chapter 1, parameter reproducibility provides a quite stringent analysis tool.

The outline for this chapter is as follow: Section 4.1 discusses the design of the optimization trials and, in doing so, surveys the entire investigation. The remaining sections traverse through the results of the sequence of optimization trials.

4.1 Design of the Optimization Trials

A complete derivation of the modeling equations and their programming in OMOLA is given in Appendices A and B. Summarizing the model definition, we have third, fourth and fifth-order model structures $\mathcal{M}_3$, $\mathcal{M}_4$ and $\mathcal{M}_5$ with the parameterization shown in Table 2.2.

Figure 2.3 presents the OMOLA model of the system and the simulation interface definition. The latter includes the connection to the five measured inputs: two steam flows, feed-water flow, feed-water temperature and fuel flow. An interface with real data necessitates conversion factors, these are also indicated in Figure 2.3. Most uncertain is the calibration of the heat input Q. Because the chemical energy content of the fuel is known to vary, this gain was modeled probabilistically with a nominal value $q_{f_{cf}}$. More certain are the calibration factors of the steam mass flowrates $q_{s_{cf}}$ and feed-water mass flowrate $q_{fw_{cf}}$. For identifiability, one of these must be fixed. We took the later to be a known constant, assuming liquid flow measurements are more precise than vapor flow measurements.

Deterministic identification requires some form of an output error model. The simplest possible is additive discrete-time white noise. With this choice, the parameters σ_4 and σ_5 shown in Figure 2.3 represent the standard deviations of the drum pressure and level simulation errors. The magnitudes of σ_4 and σ_5 serve as gauges of the quality of the deterministic model.

4.2 Calibration Factors and Steam Valve Nonlinearity

Preliminary identification trials revealed three parameters to be essential in calibrating the model to the data. By this we mean reducing the simulation error sufficiently so that meaningful conclusions could be drawn from subsequent investigations. The three key parameters are $q_{s_{cf}}$, $q_{f_{cf}}$ and k_s. Figure 4.1 shows the optimization results for their calibration for each of the six datasets, three model structures and three fixed values of k_f (0.001, 0.005 and 0.01). The trials start with $k_s = 0$ and manually tuned values for $q_{s_{cf}}$ and $q_{f_{cf}}$.

The standard deviation of the drum pressure simulation error clearly indicates improvements in the tuning. Note the effect of the fixed non-zero k_s value in the fourth trial—the unified decrease in σ_4 clearly demonstrates the importance of steam valve non-linearities. Note also the mixed results in the fifth trial, where k_s was free for optimization, and the again unified decrease of σ_4 in the sixth trial—in the latter, thermal capacitance of the metal mass m_r was included.

Based on the functional dependence of $\mathcal{M}_3$ on k_f, we did not expect to see any affect of its variation. Interestingly, Figure 4.1 shows the three batches of data lying on top of each other, for all three model structures. This indicates for the entire family of models, the calibration to the data is independent of the value of k_f.

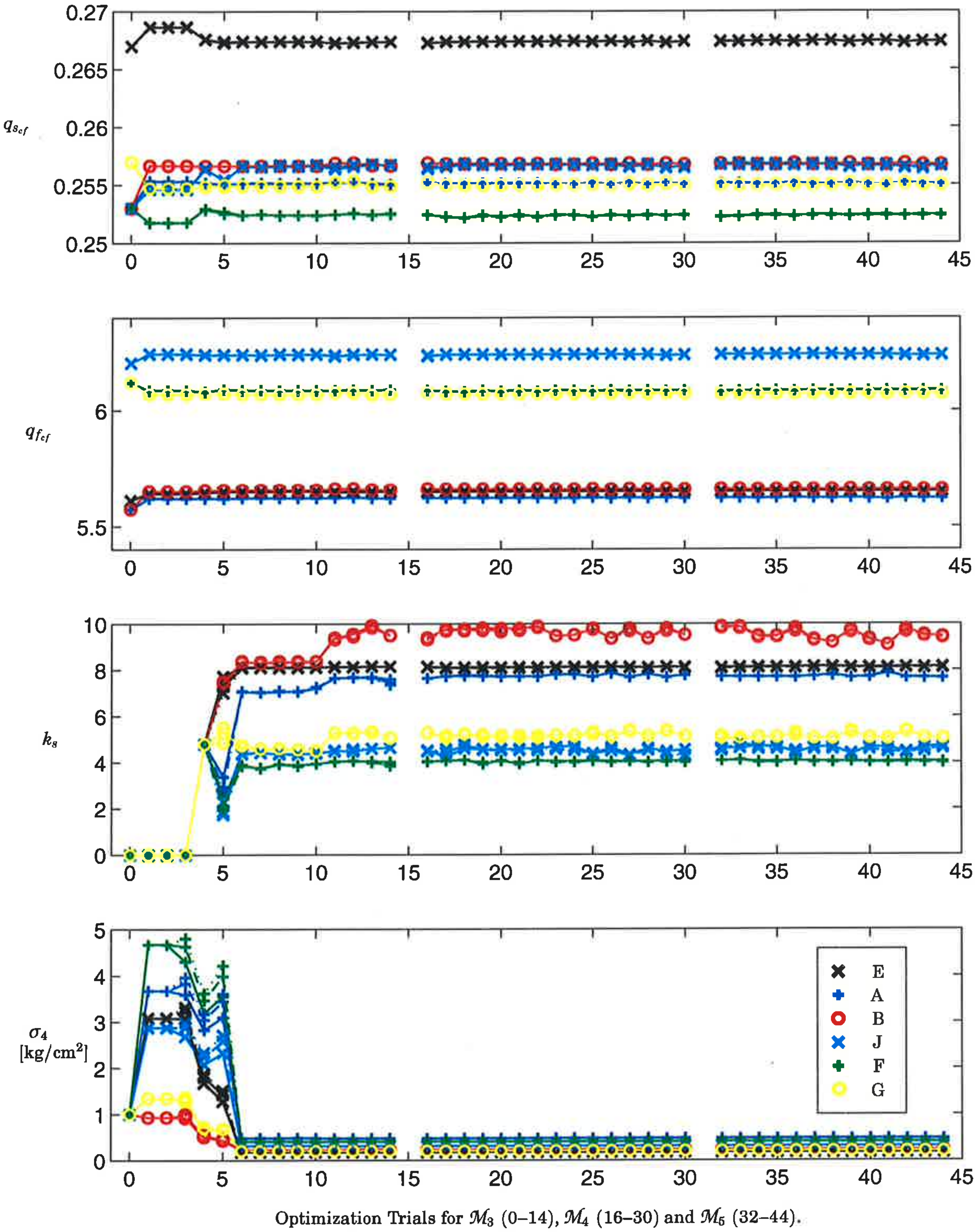


Figure 4.1: Optimization results for the calibration coefficients $q_{s_{cf}}$, $q_{f_{cf}}$ and k_s for each of the six datasets and three model structures.

4.3 Thermal Capacitance and Disposition of the Metal Mass

In the derivations of all energy balances, we included terms for thermal capacitance based on the metal mass of the drum, down-comers and risers: m_d, m_{dc} and m_r. For identifiability, one of these must be fixed. Based on physical considerations, we took m_{dc} to be zero. Figure 4.2 shows the optimization results for m_d and m_r. Trials 6–10 on $\mathcal{M}_3$ and 17–21 on $\mathcal{M}_4$ were designed as follows:

(*i*) m_r free for unbounded search from $m_r = 0$,
(*ii*) m_d free for unbounded search from $m_d = 0$,
(*iii*) both free for unbounded search from $m_r = m_d = 0$,
(*iv*) both free for constrained search $(m_r, m_d > 0)$ from $m_r = m_d = 1e5$,
(*v*) both free for unbounded search from preceding results.

The last variant was intended to check the global nature of the optimization result.

In Figure 4.2, the standard deviation σ_5 for trials 6 vs. 7 and 17 vs. 18 suggest the effects of m_r are more appropriate than those of m_d. Fortunately this agrees with engineering intuition. Trials 8, 10, 19 and 21 are interesting since they involve two-degrees of freedom. In $\mathcal{M}_3$ this led to negative values for m_d in all cases except datasets B and G (feed water flow perturbation). For these experiments, local minima are apparent since the m_r change sign from trial 8 to 10.

The results for $\mathcal{M}_4$ appear to be more plagued of local minima. Beyond a preference for m_d instead of m_r in datasets E and J (steam flow perturbation), little can be inferred from these results. This is especially unfortunate since it is in this model structure that the functional dependencies upon k_f become more pronounced (V_{sd} is dependent on q_{sd} which is a function of k_f). In $\mathcal{M}_4$ we would hope for some identifiability w.r.t. k_f, but nothing can be inferred from Figure 4.2.

The occurrence of negative values in Figure 4.2, although physically unrealistic, is interesting. A negative mass equates to a negative energy flux in the energy balances, i. e. an energy *loss*. In effect, optimization is telling us that the data would "prefer" inclusion of other phenomena, e. g. thermal radiation losses. This can be construed as data fitting, but the data is an important and viable source of information. Finally, these results agree with our preliminary investigations of stochastic input disturbance models (the Δ's in Figure 2.3).

4.4 $\mathcal{M}_3$ Shrink-and-Swell Heuristics vs. a Fourth State Variable

In $\mathcal{M}_3$, the volume of steam vapor in the drum below the liquid surface V_{sd} is heuristically modeled as $V_{sd} = b_1 \alpha_r V_r + b_2 q_{ct}/\rho_s$. In $\mathcal{M}_4$, this signal is the fourth state variable. When using grey-box heuristics, one should investigate the model's ***reproducibility*** [9]. Are we simply "data fitting" or have we truly captured the physics of the system? Trials 11–14 shown in Figure 4.3 were designed to test the reproducibility of the heuristics w.r.t. the six datasets. The trials were specified as follows:

(*i*) m_d, m_r or both free, plus A_d free and $b_1 = b_2 = 0$,
(*ii*) m_d, m_r or both free, plus A_d free and $b_1 = 1$, $b_2 = 0$,
(*iii*) m_d, m_r or both free, plus A_d and b_1 free, $b_2 = 0$,
(*iv*) m_d, m_r or both free, plus A_d, b_1 and b_2 free.

Comparing trials 11 and 12 ($b_1 = 0 \rightarrow 1$) in Figure 4.3, the standard deviation σ_5 shows improvements only for datasets E and J (steam flow perturbations). In all other cases, incorporating the b_1–heuristic actually degrades the model's performance. In trial 13, fitting b_1 decreases σ_5 uniformly w.r.t. the six datasets. The price for the improvement is the spread in the value of b_1. Additionally, negative values contradict the physics behind the heuristic. This is a good example of grey-box data fitting—the heuristic is of little use if we seek deterministic reproducibility.

Trial 14 tests the heuristic involving q_{ct}, a flow rate designated the "total condensation flow rate" in [3]. Simulation testing[1] showed that this signals dynamics transmit the excitation of both q_s and Q. It is perturbations of these inputs that gives rise to the shrink-and-swell phenomenon. Clearly, the spread in the optimization results indicates, again, data fitting.

The only conclusion we can really draw from these trials is the relative insensitivity of the metal mass results (see Figure 4.2) to these parameter variations. The difference between the time constants of thermal effects and the drum level dynamics would explain this. Finally we address the justification for adding the fourth state variable—it is with regard to reproducibility that we truly gain something. Virtually all standard deviations σ_5 results for $\mathcal{M}_4$ (trials 16–30 shown in Figure 4.2) lie near the best achieved results for $\mathcal{M}_3$ (shown in Figure 4.3).

[1]Actually, simulation testing showed a time delayed version of q_{ct} to be ripe for the basis of a heuristic model.

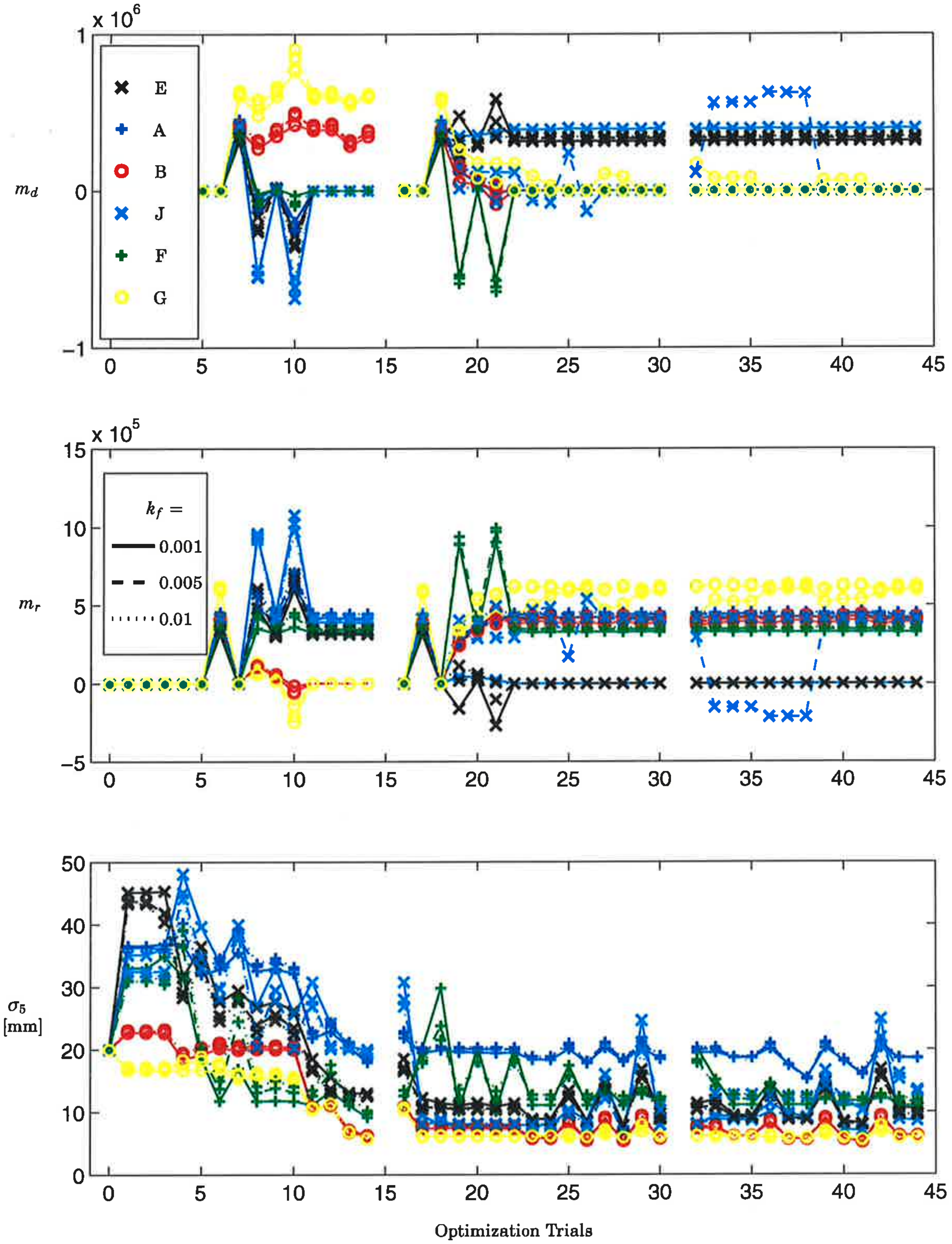


Figure 4.2: Optimization results for the drum and risers metal masses m_d and m_r for each of the six datasets, three model structures and three fixed values of k_f.

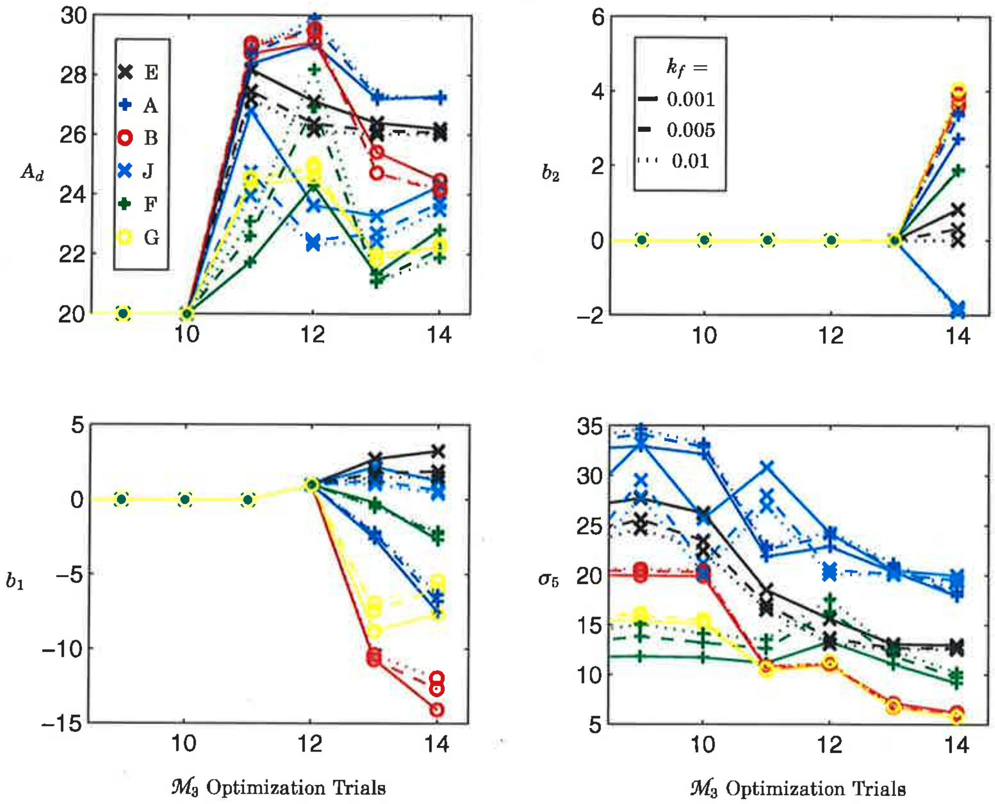


Figure 4.3: Optimization results for the surface area of liquid in the drum A_d and heuristic parameters b_1 and b_2 in $\mathcal{M}_3$ for each of the six datasets and three fixed values of k_f.

Dataset:	E	A	B	J	F	G
$q_{s_{cf}}$	0.267	0.255	0.257	0.257	0.252	0.255
$q_{f_{cf}}$	5.652	5.622	5.659	6.241	6.086	6.073
k_s	8.109	7.714	9.493	4.583	4.028	5.118
m_{tot} [tons]	337	442	409	408	346	614
A_d	28.31	25.02	29.07	26.80	25.02	24.87
C	0.3570	0.3879	0.3750	0.3559	0.3647	0.3778
D	0.5691	0.5545	0.5559	0.3293	0.3188	0.3248

Table 4.1: Mean values of some of the parameters for the six datasets. (Estimation "outliers" have been removed.) C and D are fitted parameters for the lines in Figure 4.5, $x_r^0 = Dk_f^C$.

4.5 Variable Time Delay of the Bubble Flow Rate

Both model structures $\mathcal{M}_4$ and $\mathcal{M}_5$ involve a heuristic model of the variable time delay constant τ_{sd}. In Section 2.1, four different hypotheses were established for this signal. In their programming, we re-used the grey-box parameter b_1 as a multiplicative constant. The fifth state in $\mathcal{M}_5$ comes from the Padé(0,1) approximation of the pure time delay.

A goal of the study was to assess which of the four heuristics works best. In trials 22, 25, 27, 29 ($\mathcal{M}_4$) and 33, 36, 39, 42 ($\mathcal{M}_5$), the grey-box parameter b_1 was held fixed ($b_1 = 0.7$ or 1.0 depending on the hypothesis). In each of the subsequent trials, b_1 was free for optimization. Additionally, in trials 35, 38, 41, 44 ($\mathcal{M}_5$), the initial condition V^0_{sd} was free for search. From the results for σ_5 shown in Figure 4.2, it would appear that something is to be gained especially for datasets A and F (fuel flow perturbation). Unfortunately, the spread in values of b_1 indicates we are once again data fitting. Furthermore, the effect of tuning is to reduce the nominal value of τ_{sd}. This aggravates the problem of numerical stiffness associated with the use of Padé approximations.

Note that optimization results which *reduce* τ_{sd} are essentially removing the time delay's effect. The detuning that we observed could be explained by the numerical stiffness. We used a fixed integration time step of 1 second—the data sample period is 10 seconds. Also, the number of degrees of freedom may also have been too great—between 8 and 10 parameters were being fit simultaneously. More investigation would be required to sort out this issue.

4.6 Friction Factor and Non-Equilibrium Initialization

Unfortunately, based on the optimization results shown in Figures 4.1, 4.2 & 4.3, little can be conclusively said about the uncertain friction factor k_f. The best guideline for its value remains the approximate knowledge of the flow rate q_{dc}. In Section 3.2 we established the coupling between k_f and the initial state condition x^0_r. Optimization results shown in Figure 4.5 verify the nature of this coupling.

4.7 Summary

The parameter optimization trials resulted in a vast amount of data, all of the optimization results are listed in Appendix C. It is not a trivial task to draw conclusions from this data. Preliminary results of this case-study were reported in [16]. The main difference to the results here is that the model in that article did not include the steam compressibility, k_s, in Equation 2.6 and that the results only covered the partial load data, datasets J, F and G. The inclusion of the compressibility factor, k_s, made the pressure dynamics in the model much better and the AIC values for comparable experiments in Appendix C are 20% lower than in [16].

However, the main conclusions remain; model structure $\mathcal{M}_4$ has better reproducibility compared to $\mathcal{M}_3$. For some hypotheses $\mathcal{M}_3$ can also give low AIC values, but this is seen as data-fitting since the spread of the grey-box parameters b_1 and b_2 is large over the different data-sets.

Additionally, in this study we also compared the model structure $\mathcal{M}_5$ to $\mathcal{M}_4$. The added complexity in $\mathcal{M}_5$ can be rejected although the AIC values for some cases are slightly lower than for the $\mathcal{M}_4$ structure. The difference in AIC is not consistent over the different datasets, and the spread in b_1 again indicates data-fitting. For the same reasons it is difficult to conclusively choose one of the τ_{sd}-hypotheses in $\mathcal{M}_4$, although the results in [16] as well as those for some of the datasets in this study indicate that hypothesis 2 in Equation 2.4 is to be preferred.

Mean values of some model parameters over all model structures are given in Table 4.1 on pg. 23. As in [16], we find that the metal mass is higher than the nominal value of 300 tons, but the values here are closer to the nominal due to the inclusion of steam compressibility. The extreme value, m_{tot}=614 tons, for data-set G is probably due to low excitation of the pressure dynamics. The compressibility factor, k_s, is larger at higher pressures, as can be expected.

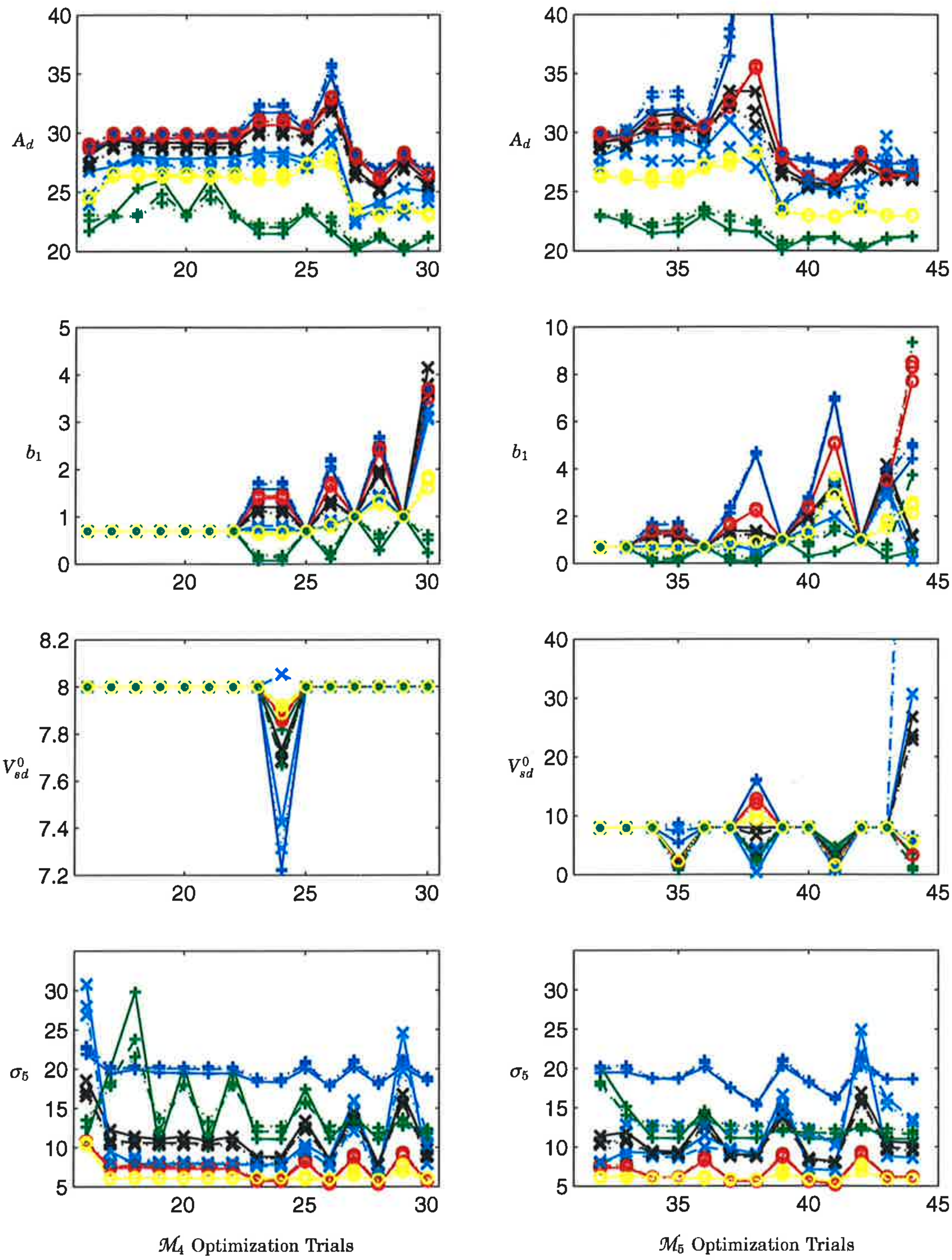


Figure 4.4: Optimization results for the surface area of liquid in the drum A_d, the heuristic parameter b_1 and V_{sd}^0 in $\mathcal{M}_4$ and $\mathcal{M}_5$, for each of the six datasets and three fixed values of k_f. The standard deviation of the drum level prediction error σ_5 indicates the quality of each trial's result.

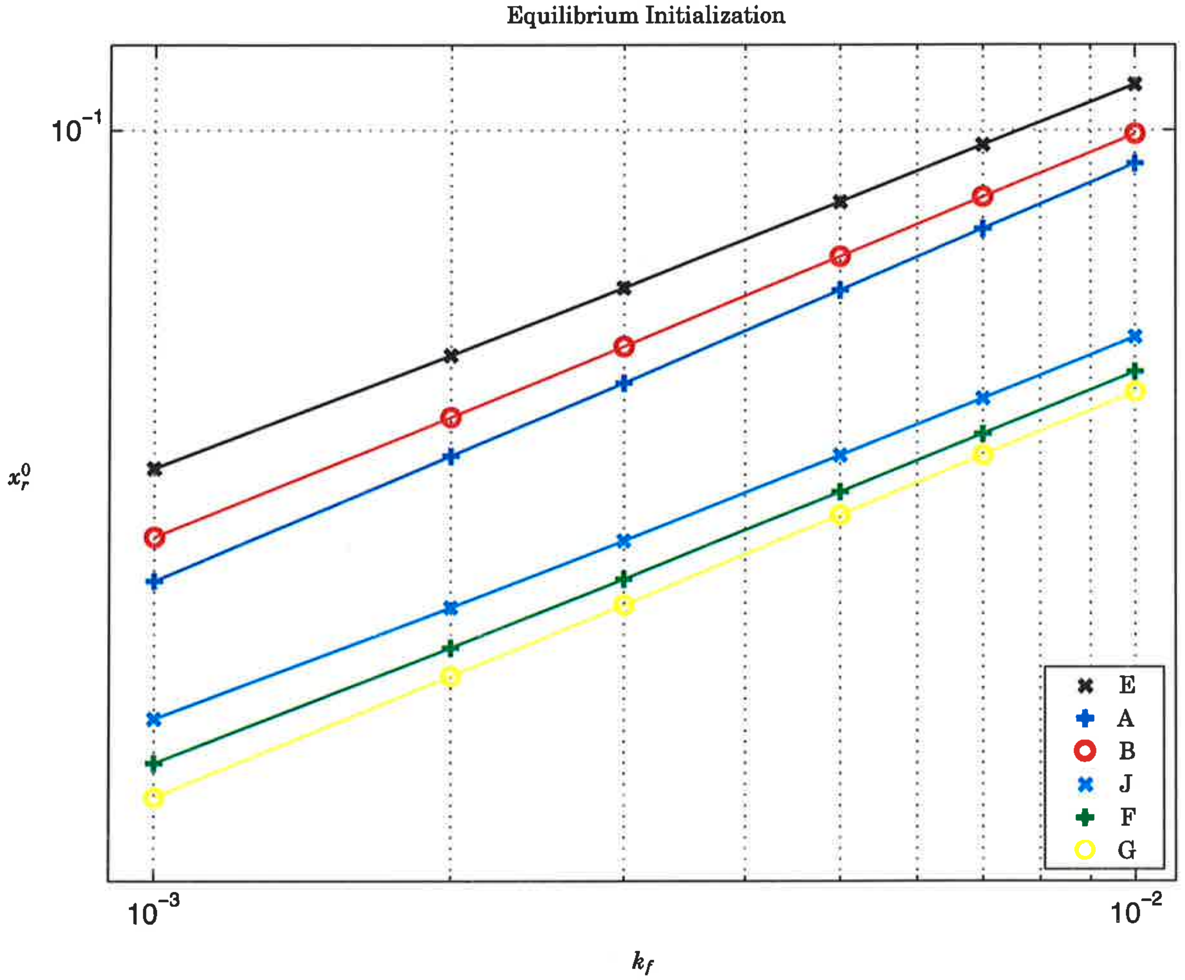


Figure 4.5: Optimization results from trial 2 with the initial state condition x_r^0 free, for each of the six datasets and six fixed values of k_f. Log-log plot axes reveal the nature of the coupling.

Chapter 5

Conclusion

Summary of Conclusions

Our experiences can be summarized as follows:

- Investigations of the third-order model structure $\mathcal{M}_3$ show that, in addition to the calibration factors $q_{f_{cf}}$ and $q_{s_{cf}}$, the compressibility coefficient k_s and metal mass m_r (or alternately m_d) are essential for calibrating the model to the data. Furthermore, the pressure dependency of k_s indicates that it should itself be parameterized as a function of the operating point P^0. The uncertainty in k_f proves to be not so consequential. The fidelity of the entire family of models appears to be quite insensitive to this parameter.
- Comparisons of the three main model structures, $\mathcal{M}_3, \mathcal{M}_4$ and $\mathcal{M}_5$, show that the extra steam volume state in $\mathcal{M}_4$ adds reproducibility. On the other hand, the delay state in $\mathcal{M}_5$ does not give any conclusively better results. Thus, it can be concluded that $\mathcal{M}_4$ is the most powerful unfalsified model.
- Simulation testing and deterministic identification suggest the shrink-and-swell effect will require more complex modeling than the simple time delay model. The simple model is best suited to datasets A and F (fuel flow perturbations). Reproducibility suffers in the other cases. Better heuristics for the time-varying time delay τ_{sd} based possibly on the signal q_{ct} would be worth investigating.
- In view of the problems in estimating time delays, more investigations should be made into developing identification methods suited for systems with time delays.
- Finally, our experience indicates that an identification investigation of stochastic models would be useful. By considering state disturbances, more information (about *where* to improve the model) may be extracted from the data.

Appendix A

Maple Derivations

A.1 Preliminaries

Begin by initializing the Maple computational engine to guarantee a fresh start, and loading a few Maple libraries. The first provides support for linear algebra, while the second contains several procedures useful in manipulating the derived expressions. For documentation, type `?linalg` or `?student` in Maple.

```
> restart:
> with(linalg):
> with(student):
```

Also define some utility procedures; type `?operators[functional]` for documentation. These will be used throughout.

```
> REVERSE := eqn -> rhs(eqn) = lhs(eqn):
> STRIP := eqn -> sort(subs(
>    map( f->f=op(0,f), indets(eqn,anyfunc(string)) ), eqn )):
```

To show their usage, we make a quick demonstration. The first simply reverses the order of a relation statement. The second is more for cosmetic purposes; it strips expressions of their time-dependency making them easier to look at when type-set.

```
> x(t) = y(t) + z(t);
```

$$x(t) = y(t) + z(t)$$

```
> REVERSE(");
```

$$y(t) + z(t) = x(t)$$

```
> STRIP("");
```

$$x = y + z$$

A.1.1 Approximation of Thermodynamic Property Data

To set the scene for the derivations, we recount the approximate relations given in [3] for the thermodynamic properties of saturated water:

```
>    h[s](t) = a01+(a11+a21*(P(t)-10))*(P(t)-10),
> rho[s](t) = a02+(a12+a22*(P(t)-10))*(P(t)-10),
>    h[w](t) = a03+(a13+a23*(P(t)-10))*(P(t)-10),
> rho[w](t) = a04+(a14+a24*(P(t)-10))*(P(t)-10),
> T[sat](t) = a05+(a15+a25*(P(t)-10))*(P(t)-10):
> eq[tdp] := ["]:
```

The last command stores the derived result in a Maple data object known as a table. The table name, eq, and mnemonic indices provide a convenient system for saving results for later recall. Returning to the property data, Figure A.1 attempts to motivate the use of

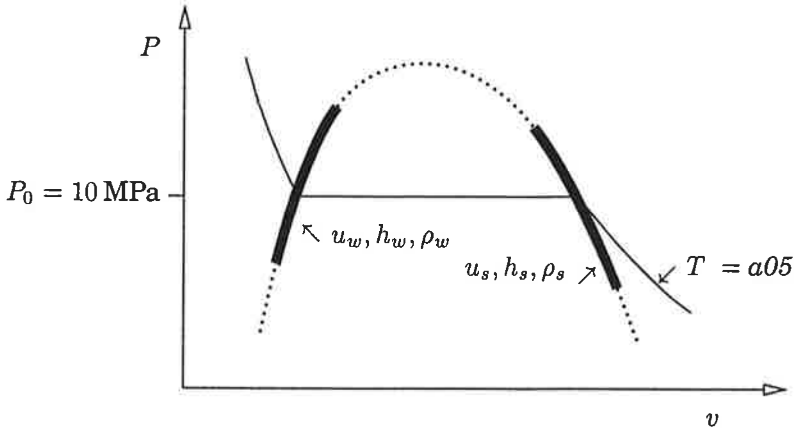


Figure A.1: Qualitative P–v diagram of the thermodynamic properties for saturated water. Shown in bold is the parabolic nature of the curve-fits used.

second-order polynomials by illustrating the region of validity of the above approximations. In the derivations, time-derivatives of the properties will be required.

```
> map(simplify@diff,",t):
> map(collect,",[diff(P(t),t),a21,a22,a23,a24,a25]);
```

$$\left[\frac{\partial}{\partial t} h_s(t) = ((2\,\mathrm{P}(t) - 20)\, a21 + a11)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right),\right.$$
$$\frac{\partial}{\partial t}\rho_s(t) = ((2\,\mathrm{P}(t) - 20)\, a22 + a12)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right),$$
$$\frac{\partial}{\partial t} h_w(t) = ((2\,\mathrm{P}(t) - 20)\, a23 + a13)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right),$$
$$\frac{\partial}{\partial t}\rho_w(t) = ((2\,\mathrm{P}(t) - 20)\, a24 + a14)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right),$$
$$\left.\frac{\partial}{\partial t} T_{sat}(t) = ((2\,\mathrm{P}(t) - 20)\, a25 + a15)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right)\right]$$

Using the chain-rule for differentiation, these derivatives can be expressed in terms of the following differentials:

```
> Diff(  h[s],P)  = a11+2*a21*(P(t)-10),
> Diff(rho[s],P)  = a12+2*a22*(P(t)-10),
> Diff(  h[w],P)  = a13+2*a23*(P(t)-10),
> Diff(rho[w],P)  = a14+2*a24*(P(t)-10),
> Diff(T[sat],P)  = a15+2*a25*(P(t)-10);
```

$$\frac{\partial}{\partial P} h_s = a11 + 2\, a21\,(\mathrm{P}(t) - 10), \frac{\partial}{\partial P}\rho_s = a12 + 2\, a22\,(\mathrm{P}(t) - 10),$$
$$\frac{\partial}{\partial P} h_w = a13 + 2\, a23\,(\mathrm{P}(t) - 10), \frac{\partial}{\partial P}\rho_w = a14 + 2\, a24\,(\mathrm{P}(t) - 10),$$
$$\frac{\partial}{\partial P} T_{sat} = a15 + 2\, a25\,(\mathrm{P}(t) - 10)$$

```
> eq[dtdp] := ["]:
```

Treating the feed water as an incompressible fluid, $\rho_{fw}(t) = \rho_w(t)$. Then by definition, the enthalpy of the feed water, $h_{fw}(t) = u_{fw}(t) + P(t)v(t)$ can be expressed:

```
> h[fw](t) = c[fw]*T[fw](t) + P(t)/rho[w](t);
```

$$h_{fw}(t) = c_{fw}\, T_{fw}(t) + \frac{\mathrm{P}(t)}{\rho_w(t)}$$

```
> eq[lhs(")] := ":
```

A.2 Second Order Structure

In this section, we shall derive the modeling equations with pressure, $P(t)$, and total volume of the liquid water phase, $V_{wt}(t)$, as the physical state variables. The key assumptions are:

A1: the water inside the system is everywhere in a saturated thermodynamic state;

A2: instantaneous uniform thermal equilibrium between metal and water;

A3: homogeneous mixing of liquid in the drum.

With the first assumption, all thermodynamic properties can be characterized by one independent variable. This makes it possible to use the approximations given in previous section. With the second assumption, capacitive thermal effects of the metal can be included. The third assumption is necessary since the feed water enters the system in a sub-cooled liquid state.

The section continues with the derivation of a single-state model, i. e. a model reduction of the two-state structure. By making the additional assumption:

A4: the drum level controller actions appear to be instantaneous when compared with the dynamics of the system,

the dynamics of the second state, $V_{wt}(t)$, can be neglected. Models with such approximations can be motivated for the purpose of control design.

A.2.1 Global Mass and Energy Balances

Consider conservation of mass applied to the global control volume shown in Figure 2.1 (c.v. I, page 3). At any time, the total mass of water in the system is equal to the mass of the two phases combined.

```
> M(t) = M[wt](t) + M[st](t);
```

$$\mathrm{M}(t) = M_{wt}(t) + M_{st}(t)$$

Assuming saturation conditions throughout the system, the mass of each phase is given by the density and total volume of the respective phase.

```
> M[wt](t) = rho[w](t)*V[wt](t),
> M[st](t) = rho[s](t)*V[st](t);
```

$$M_{wt}(t) = \rho_w(t)\,V_{wt}(t), M_{st}(t) = \rho_s(t)\,V_{st}(t)$$

The time rate of change of mass in the system is equal to the feed water mass flow rate in, minus the steam mass flow rate out of the system,

```
> Diff(M(t),t) = q[fw](t) - q[s](t);
```

$$\frac{\partial}{\partial t}\mathrm{M}(t) = q_{fw}(t) - q_s(t)$$

Substituting expressions, we arrive at the global mass balance:

```
> subs( """, "", " );
```

$$\frac{\partial}{\partial t}(\rho_w(t)\,V_{wt}(t) + \rho_s(t)\,V_{st}(t)) = q_{fw}(t) - q_s(t)$$

```
> eq[gmb] := ":
```

Note that the definition is made in terms of the "inert" form of the differential operator; see `?Diff` for documentation.

Now consider the energy stored in the system. At any time, the total energy is equal to the internal energy of the two phases, plus the thermal energy stored in the metal.

```
> U(t) = U[wt](t) + U[st](t) + U[T](t);
```

$$\mathrm{U}(t) = U_{wt}(t) + U_{st}(t) + U_T(t)$$

Again, assuming saturation conditions throughout, as well as an instantaneous thermal equilibrium between the metal and saturated water, we have:

```
> U[wt](t) = rho[w](t)*u[w](t)*V[wt](t),
> U[st](t) = rho[s](t)*u[s](t)*V[st](t),
> U[T](t) = M[T]*c[p]*T[sat](t);
```

$$U_{wt}(t) = \rho_w(t)\, u_w(t)\, V_{wt}(t), U_{st}(t) = \rho_s(t)\, u_s(t)\, V_{st}(t), U_T(t) = M_T\, c_p\, T_{sat}(t)$$

The time rate of change of energy in the system is equal to the flux in minus the flux out.

```
> Diff(U(t),t) = Q(t) + h[fw](t)*q[fw](t) - h[s](t)*q[s](t) + Delta[geb](t);
```

$$\frac{\partial}{\partial t}\mathrm{U}(t) = \mathrm{Q}(t) + h_{fw}(t)\, q_{fw}(t) - h_s(t)\, q_s(t) + \Delta_{geb}(t)$$

The thermal heat flow, $Q(t)$, comes from the combustion of fuel. The second and third terms represent the energy flux due to the feed water in and the steam flow out respectively; see Figure 2.1 on page 3. The last right-hand term, $\Delta_{geb}(t)$, represents all neglected energy interactions. Note that it has units of power and we shall take its nominal value to be zero. Conceptually, $\Delta_{geb}(t)$ is the under-modeling associated with our assumptions. Practically, it serves as a place-holder so that its effects, when filtered through subsequent derivations, will be clear. Substituting definitions into the left-hand side, we have:

```
> subs( """, "", " );
```

$$\frac{\partial}{\partial t}\left(\rho_w(t)\, u_w(t)\, V_{wt}(t) + \rho_s(t)\, u_s(t)\, V_{st}(t) + M_T\, c_p\, T_{sat}(t)\right) = \mathrm{Q}(t) + h_{fw}(t)\, q_{fw}(t) - h_s(t)\, q_s(t) + \Delta_{geb}(t)$$

Before ending the formal definition, we replace specific internal energy with the equivalent expression in terms of density, enthalpy and pressure.

```
> u[w](t)=h[w](t)-P(t)/rho[w](t),
> u[s](t)=h[s](t)-P(t)/rho[s](t);
```

$$u_w(t) = h_w(t) - \frac{\mathrm{P}(t)}{\rho_w(t)}, u_s(t) = h_s(t) - \frac{\mathrm{P}(t)}{\rho_s(t)}$$

This change of variables simplifies the programming in OMOLA as well as subsequent derivations where the mass and energy balances are combined (to eliminate flux terms on the right-hand side). Our final formulation of the global energy balance is:

```
> subs( ", "" );
```

$$\frac{\partial}{\partial t}\left(\rho_w(t)\left(h_w(t) - \frac{\mathrm{P}(t)}{\rho_w(t)}\right) V_{wt}(t) + \rho_s(t)\left(h_s(t) - \frac{\mathrm{P}(t)}{\rho_s(t)}\right) V_{st}(t) + M_T\, c_p\, T_{sat}(t)\right) = \mathrm{Q}(t) + h_{fw}(t)\, q_{fw}(t) - h_s(t)\, q_s(t) + \Delta_{geb}(t)$$

```
> eq[geb] := ":
> eq[u] := """:
```

A.2.2 Explicit Second-Order State Equations

To derive the explicit state space formulation, begin by eliminating the total volume of steam. Although this is a time-varying quantity, the system's total physical volume, V_T, is not.

```
> V[st](t) = V[T] - V[wt](t);
```

$$V_{st}(t) = V_T - V_{wt}(t)$$

```
> eq[Vst] := ":
> subs( ", eq[gmb] );
```

$$\frac{\partial}{\partial t}\left(\rho_w(t)\, V_{wt}(t) + \rho_s(t)\left(V_T - V_{wt}(t)\right)\right) = q_{fw}(t) - q_s(t)$$

Using the `student` library's `value` operator, we now evaluate the inert `Diff` operator. Distributing the differential operator yields:

```
> simplify(value(")):
> simplify(subs( V[T] = V[wt](t) + V[st](t), " )):
> collect( ", diff(V[wt](t),t) );
```

$$(\rho_w(t) - \rho_s(t)) \left(\frac{\partial}{\partial t} V_{wt}(t)\right) + \left(\frac{\partial}{\partial t} \rho_w(t)\right) V_{wt}(t) + \left(\frac{\partial}{\partial t} \rho_s(t)\right) V_{st}(t) = q_{fw}(t) - q_s(t)$$

By the first assumption, all thermodynamic property data can be expressed in terms of pressure. Using the chain-rule, we can express the time-derivatives of these quantities in terms of the state derivative.

```
> subs( diff(rho[s](t),t) = Diff(rho[s],P)*Diff(P,t),
>       diff(rho[w](t),t) = Diff(rho[w],P)*Diff(P,t),
>       diff(V[wt](t),t)  = Diff(V[wt],t), " ):
> collect( ", Diff(P,t) );
```

$$\left(\left(\frac{\partial}{\partial P} \rho_w\right) V_{wt}(t) + \left(\frac{\partial}{\partial P} \rho_s\right) V_{st}(t)\right) \left(\frac{\partial}{\partial t} P\right) + (\rho_w(t) - \rho_s(t)) \left(\frac{\partial}{\partial t} V_{wt}\right) = q_{fw}(t) - q_s(t)$$

Inspecting this result, we see the left-hand side of the balance equation is a linear combination of the state derivatives. The coefficients of the time-derivatives are:

```
> e11 = STRIP(coeff(lhs("), Diff(V[wt],t)));
```

$$e11 = \rho_w - \rho_s$$

```
> e12 = STRIP(coeff(lhs(""),Diff(P,t)));
```

$$e12 = \left(\frac{\partial}{\partial P} \rho_w\right) V_{wt} + \left(\frac{\partial}{\partial P} \rho_s\right) V_{st}$$

Here we have used our "cosmetic" utility to strip the time dependency from the expressions. Continuing, we use these coefficients to simplify the implicit form of the mass balance:

```
> subs( REVERSE("), REVERSE(""), STRIP(""") );
```

$$e12 \left(\frac{\partial}{\partial t} P\right) + e11 \left(\frac{\partial}{\partial t} V_{wt}\right) = q_{fw} - q_s$$

```
> eq[GMB] := [", """, ""]:
```

This implicit formulation is in fact what we shall program in OMOLA. To derive the explicit formulation, we need to first repeat the above steps, operating on the energy balance. As before, begin by eliminating the total volume of steam and then evaluating the inert differential operator.

```
> subs( eq[Vst], eq[geb] ):
> simplify(value(")):
> simplify(subs( V[T] = V[wt](t) + V[st](t), " )):
> collect( ", [diff(V[wt](t),t), diff(P(t),t)] );
```

$$\begin{aligned}&(h_w(t)\,\rho_w(t) - h_s(t)\,\rho_s(t)) \left(\frac{\partial}{\partial t} V_{wt}(t)\right) + (-V_{wt}(t) - V_{st}(t)) \left(\frac{\partial}{\partial t} \mathrm{P}(t)\right)\\ &+ \left(\frac{\partial}{\partial t} \rho_w(t)\right) V_{wt}(t)\, h_w(t) + V_{wt}(t) \left(\frac{\partial}{\partial t} h_w(t)\right) \rho_w(t) + M_T\, c_p \left(\frac{\partial}{\partial t} T_{sat}(t)\right)\\ &+ \left(\frac{\partial}{\partial t} \rho_s(t)\right) h_s(t)\, V_{st}(t) + \left(\frac{\partial}{\partial t} h_s(t)\right) \rho_s(t)\, V_{st}(t) =\\ &\mathrm{Q}(t) + h_{fw}(t)\, q_{fw}(t) - h_s(t)\, q_s(t) + \Delta_{geb}(t)\end{aligned}$$

Again, our first assumption allows complete characterization of the thermodynamic properties in terms of pressure. Applying the chain-rule yields:

```
> subs( diff(  h[s](t),t)  = Diff(  h[s],P)*Diff(P,t),
>       diff(  h[w](t),t)  = Diff(  h[w],P)*Diff(P,t),
>       diff(rho[s](t),t)  = Diff(rho[s],P)*Diff(P,t),
>       diff(rho[w](t),t)  = Diff(rho[w],P)*Diff(P,t),
>       diff(T[sat](t),t)  = Diff(T[sat],P)*Diff(P,t),
>       diff(P(t),t)       = Diff(P,t),
>       diff(V[wt](t),t)   = Diff(V[wt],t), " ):
> collect( ", [ Diff(V[wt],t), Diff(P,t), V[wt](t), V[st](t)] ):
```

As with the mass balance, the left-hand side is a linear combination of the time-derivatives. The state dependent coefficients are:

```
> e21 = STRIP( coeff(lhs("), Diff(V[wt],t)) );
```

$$e21 = -h_s\,\rho_s + h_w\,\rho_w$$

```
> e22 = STRIP( coeff(lhs(""),Diff(P,t)) );
```

$$e22 = M_T\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right) + \left(h_w\left(\frac{\partial}{\partial P}\rho_w\right) + \rho_w\left(\frac{\partial}{\partial P}h_w\right) - 1\right)V_{wt} + \left(h_s\left(\frac{\partial}{\partial P}\rho_s\right) + \rho_s\left(\frac{\partial}{\partial P}h_s\right) - 1\right)V_{st}$$

Using these definitions, the global energy balance reduces to:

```
> subs( REVERSE("), REVERSE(""), STRIP(""") );
```

$$e22\left(\frac{\partial}{\partial t}P\right) + e21\left(\frac{\partial}{\partial t}V_{wt}\right) = -h_s\,q_s + h_{fw}\,q_{fw} + \Delta_{geb} + Q$$

```
> eq[GEB] := [", """, ""]:
> eq[coef2] := table( [eq[GMB][2..3], eq[GEB][2..3]] ):
```

Again, it is this implicit formulation of the state equations that we shall program in OMOLA. To better understand the nature of the couplings present in the model, we need to examine the explicit formulation. To do this we first collect the implicit equations using matrix notation:

```
> &*( matrix(2,2,[e11,e12,e21,e22]),
>     matrix(2,1,[Diff(V[wt],t), Diff(P,t)]) )
>   = matrix(2,1,[rhs(eq[GMB][1]),rhs(eq[GEB][1])]);
```

$$\begin{bmatrix} e11 & e12 \\ e21 & e22 \end{bmatrix} \&* \begin{bmatrix} \frac{\partial}{\partial t}V_{wt} \\ \frac{\partial}{\partial t}P \end{bmatrix} = \begin{bmatrix} q_{fw} - q_s \\ -h_s\,q_s + h_{fw}\,q_{fw} + \Delta_{geb} + Q \end{bmatrix}$$

```
> eq[sys2] := ":
```

Thanks to the linear structure of the left-hand side, we can solve explicitly for the state derivatives. Inverting the coefficient matrix reveals the, in this case, full coupling present in the equations:

```
> inverse(op(1,lhs(eq[sys2])));
```

$$\begin{bmatrix} \frac{e22}{e11\ e22 - e12\ e21} & -\frac{e12}{e11\ e22 - e12\ e21} \\ -\frac{e21}{e11\ e22 - e12\ e21} & \frac{e11}{e11\ e22 - e12\ e21} \end{bmatrix}$$

Solving algebraically for the state derivatives, we obtain the explicit formulation:

```
> op(2,lhs(eq[sys2])) =
> map(collect, evalm( " &* rhs(eq[sys2]) ), [e11,e12,e21,e22]);
```

$$\begin{bmatrix} \frac{\partial}{\partial t}V_{wt} \\ \frac{\partial}{\partial t}P \end{bmatrix} = \begin{bmatrix} \frac{e22\ (q_{fw} - q_s) + e12\ (h_s\,q_s - h_{fw}\,q_{fw} - \Delta_{geb} - Q)}{e11\ e22 - e12\ e21} \\ -\frac{e11\ (h_s\,q_s - h_{fw}\,q_{fw} - \Delta_{geb} - Q) + e21\ (q_{fw} - q_s)}{e11\ e22 - e12\ e21} \end{bmatrix}$$

```
> eq[sys2e] := ":
```

This clearly shows the mixing of the two balance equations. Also, note the presence of the under-modeling place-holder $\Delta_{geb}(t)$ in *both* state equations.

A practical advantage of first-principle mechanistic models is the physical interpretation of the parameters and signals involved. This significance can be exploited in guiding attempts at model reduction. This is what we shall do next.

A.2.3 A Simplified Single-State Model

The simplification is based on the following postulate. Assume the controller which regulates the drum water level is well tuned. Additionally, assume the control actions are "fast" compared with the dynamics of the rest of the system. If the variation in the water level in the drum is small, then variation in $V_{wt}(t)$ will also be small. This equates to the following approximation in the mathematical model:

```
> diff(V[wt](t),t)=0;
```

$$\frac{\partial}{\partial t} V_{wt}(t) = 0$$

Given that $V_{wt}(t) + V_{st}(t) = V_T$, the assumption also requires:

```
> diff(V[st](t),t)=0;
```

$$\frac{\partial}{\partial t} V_{st}(t) = 0$$

Note that this relation does not imply a constant *spatial* distribution of steam vapor.

Now, we have two balance equations involving the time-derivative of the remaining state variable, $P(t)$. By combining them, we will hopefully cancel some of the complexity in the coefficient matrix, e. Inspecting the expressions for $e12$ and $e22$, we see that either $h_s(t)$ or $h_w(t)$ will lead to cancellations when multiplied by the mass balance and subtracted from the energy balance. Note that using $h_s(t)$ has the undesirable side effect of canceling one of the plants controlled inputs, namely the steam mass flow rate, $q_s(t)$. For this reason, we choose to use $h_w(t)$ and combining the balance equations yields:

```
> simplify(subs( ", "", value(eq[geb] - h[w](t)*eq[gmb]) )):
> collect( ", [V[st](t), V[wt](t), q[fw](t), q[s](t)] );
```

$$\left(\left(\frac{\partial}{\partial t}\rho_s(t)\right) h_s(t) + \left(\frac{\partial}{\partial t}h_s(t)\right)\rho_s(t) - \left(\frac{\partial}{\partial t}\mathrm{P}(t)\right) - h_w(t)\left(\frac{\partial}{\partial t}\rho_s(t)\right)\right) V_{st}(t)$$
$$+ \left(\left(\frac{\partial}{\partial t}h_w(t)\right)\rho_w(t) - \left(\frac{\partial}{\partial t}\mathrm{P}(t)\right)\right) V_{wt}(t) + M_T\, c_p \left(\frac{\partial}{\partial t}T_{sat}(t)\right) =$$
$$(-h_w(t) + h_{fw}(t))\, q_{fw}(t) + (h_w(t) - h_s(t))\, q_s(t) + \mathrm{Q}(t) + \Delta_{geb}(t)$$

Note that choosing $h_w(t)$ as the multiplier eliminates the time-derivative of $\rho_w(t)$; investigating this terms qualitative behavior and contribution to the second-order equations is one way to assess the validity of the simplification. As before, we need to express everything in terms of the state variable. This begins with the chain-rule expansion of the time-derivatives:

```
> subs(diff(  h[s](t),t) = Diff(  h[s],P)*Diff(P,t),
>      diff(  h[w](t),t) = Diff(  h[w],P)*Diff(P,t),
>      diff(rho[s](t),t) = Diff(rho[s],P)*Diff(P,t),
>      diff(T[sat](t),t) = Diff(T[sat],P)*Diff(P,t),
>      diff(P(t),t)      = Diff(P,t), " ):
> collect( ", [Diff(P,t), V[st](t), V[wt](t), Diff(rho[s],P)] ):
```

Next we recognize the enthalpy of vaporization, $h_c(t) = h_s(t) - h_w(t)$, and make a simplifying change of variables before collecting the coefficient of the time-derivative:

```
> changevar(h[s](t)-h[w](t)=h[c](t), "):
> e1 = STRIP( coeff( lhs("), Diff(P,t)));
```

$$e1 = M_T\, c_p \left(\frac{\partial}{\partial P}T_{sat}\right) + \left(\rho_w \left(\frac{\partial}{\partial P}h_w\right) - 1\right) V_{wt} + \left(\rho_s \left(\frac{\partial}{\partial P}h_s\right) + \left(\frac{\partial}{\partial P}\rho_s\right) h_c - 1\right) V_{st}$$

The reduced first-order model is:

```
> subs( REVERSE("), STRIP(""));
```

$$el\left(\frac{\partial}{\partial t}P\right) = -q_s\,h_c + \Delta_{geb} + (-h_w + h_{fw})\,q_{fw} + Q$$

```
> eq[sys1r] := ":
> eq[coef1r] := """:
```

With only the one state, it is trivial to derive the explicit formulation:

```
> Diff(P,t) = collect( solve(eq[sys1r], Diff(P,t)), [e1, q[fw]] );
```

$$\frac{\partial}{\partial t}P = \frac{-q_s\,h_c + \Delta_{geb} + (-h_w + h_{fw})\,q_{fw} + Q}{el}$$

Comparing the second and first-order equations (and units), we note that the approximation made is to neglect the steam terms, i. e. implicitly assume:

```
> eq[coef2][e11] = rho[w];
```

$$\rho_w - \rho_s = \rho_w$$

```
> eq[coef2][e21] = rho[w]*h[w];
```

$$-h_s\,\rho_s + h_w\,\rho_w = h_w\,\rho_w$$

The validity of these approximations can be checked through simulation. If these approximations are valid, then the denominators agree exactly. Stated another way, we can derive the reduced result from the original state equations directly:

```
> e1 = simplify( eq[coef2][e22] - h[w]*eq[coef2][e12] ):
> collect(", [V[wt],V[st],Diff(rho[s],P)]);
```

$$el = \left(\rho_w\left(\frac{\partial}{\partial P}h_w\right) - 1\right)V_{wt} + \left((-h_w + h_s)\left(\frac{\partial}{\partial P}\rho_s\right) - 1 + \rho_s\left(\frac{\partial}{\partial P}h_s\right)\right)V_{st} + M_T\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right)$$

With first and second-order state equations derived, we can now proceed with model refinement, i. e. adding complexity.

```
> save eq, 'Second.Order.mpl':
```

A.3 Third Order Structure

```
> restart:
> with(linalg):
> with(student):
> REVERSE := eqn -> rhs(eqn) = lhs(eqn):
> STRIP := eqn->subs(map(f->f=op(0,f),indets(eqn,anyfunc(string))),eqn):
> read 'Second.Order.mpl':
```

The focus of this section is refinement of the state equations. We begin by deriving a simple model of the how the liquid level inside the drum varies. This is of interest because of a non-minimum phase behavior known as the “shrink and swell” effect: When subject to a control action, the drum level momentarily responds in the counter-intuitive direction, either rising or falling. Physically, the phenomenon is a function of the steam vapor that exits the risers and bubbles up through the liquid in the drum. Variations in drum pressure lead to surges in the rate the bubble rise to the surface, as well as to a kind of inverse cavitation effect—the bubbles collapse, condensing to saturated liquid. Capturing this behavior in the model is one of our chief objectives. The heuristics of this measurement model motivate the refinement of the state equations, i. e. the augmentation of an additional state.

In the second subsection, the variable that will be augmented is the mass fraction of saturated vapor at the outlet of the risers, $x_r(t)$. The idea is to better characterize the quantity of thc vapor bubbling up through the liquid in the drum. A linear combination of the mass and energy balances for the risers gives us the augmented third state equation.

A key quantity in both the definition of the measurement model and the derivation of the mass and energy balances turns out to be the *total* volume fraction of steam in the risers, $\alpha_r(t)$. This is defined intuitively as follows:

```
> alpha[r](t) = V[sr](t)/V[r];
```

$$\alpha_r(t) = \frac{V_{sr}(t)}{V_r}$$

By assuming an approximate spatial distribution of the two phases in the risers is known, it is possible to approximate this quantity analytically as a function of the state variables, specifically:

```
> alpha[r](t) = fcn( P(t), x[r](t) );
```

$$\alpha_r(t) = \mathrm{fcn}(\mathrm{P}(t), x_r(t))$$

The approximation is derived in the third subsection.

In the fourth subsection, we consider another key variable in the augmented state equation: the mass flow rate entering the risers from the down-comers, $q_{dc}(t)$. This value will be established by considering the steady-state fluid momentum balances for the down-comers and risers.

This section concludes by presenting an alternate choice of state variables and revisiting model reduction. This provides two additional model structures with distinctly different structural couplings.

A.3.1 A Drum Level Measurement Model

A simple model relating the variations in drum level to fluid volume is obtained by ignoring the drum's geometric design. Consider approximating it with a constant "equivalent" area, A_d. Then the relation between the level and volume of water in the drum is:

```
> A[d]*(l[0] + delta[l](t)) = V[wd](t);
```

$$A_d\ (l_0 + \delta_l(t)) = V_{wd}(t)$$

We have expressed the drum level as a set-point l_0 plus the variation $\delta_l(t)$ about the set-point.

In various formulations, Åström and Bell [3–5] have postulated the "shrink and swell" effect to be a function of the volume of steam vapor below the surface, $V_{sd}(t)$. The vapor comes from the risers and bubbles to the surface. Incorporating the volume of this vapor in the drum level model, we have:

```
> V[wd](t) + V[sd](t) = A[d]*(l[0] + delta[l](t));
```

$$V_{wd}(t) + V_{sd}(t) = A_d\ (l_0 + \delta_l(t))$$

Solving explicitly for the variation in the drum level gives:

```
> delta[l](t) = collect(solve( ", delta[l](t) ), A[d]);
```

$$\delta_l(t) = -l_0 + \frac{V_{wd}(t) + V_{sd}(t)}{A_d}$$

```
> eq[dl] := ":
```

In terms of the state variable, $V_{wt}(t)$, the volume of water in the drum is given by:

```
> V[wd](t) = V[wt](t) - V[dc] - V[wr](t);
```

$$V_{wd}(t) = V_{wt}(t) - V_{dc} - V_{wr}(t)$$

```
> eq[Vwd] := ":
```

Note the volume of water in the down-comers is constant since we assume they contain only the liquid phase. The last term in preceding equation corresponds to the volume of saturated liquid in the risers. Note that $V_r = V_{sr}(t) + V_{wr}(t)$. The partitioning between phases of the total volume can be expressed by introducing the time-varying total volume fraction of steam in the risers, $\alpha_r(t)$.

```
> alpha[r](t) = V[sr](t)/V[r];
```

$$\alpha_r(t) = \frac{V_{sr}(t)}{V_r}$$

An approximate expression for this quantity is derived in Section A.3.3. For now it suffices to work with this exact analytic definition. Observe that:

```
> V[sr](t) = alpha[r](t)*V[r];
```

$$V_{sr}(t) = \alpha_r(t)\,V_r$$

```
> V[wr](t) = (1 - alpha[r](t))*V[r];
```

$$V_{wr}(t) = (1 - \alpha_r(t))\,V_r$$

```
> eq[Vsr] := "":
> eq[Vwr] := "":
```

It remains to define $V_{sd}(t)$, the volume of bubbles below the surface. In [3, 4], Åström and Bell reason that:

```
> V[sd](t) = alpha[r](t)*V[r];
```

$$V_{sd}(t) = \alpha_r(t)\,V_r$$

This states the volume of steam vapor bubbling to the surface is instantaneously equal to the volume of steam vapor in the risers, $V_{sr}(t)$. This relationship is believed to be a heuristic based on the observation that the steam flow rate exiting the risers is roughly equal to the flow vented from the drum. Because this is a heuristic, and because it is likely that some steam condenses due to mixing with feed water in a sub-cooled state, we chose to add an additional degree of freedom to the model by introducing the constant, b_1. The relationship is then:

```
> V[sd](t) = subs( eq[Vsr], b[1]*V[sr](t) );
```

$$V_{sd}(t) = b_1\,\alpha_r(t)\,V_r$$

```
> eq[Vsd] := ":
```

A larger heuristic step would be to let $V_{sd}(t)$ to be a function of the controlled inputs which evoke the shrink/swell effect. For now the simplicity of a constant suffices. Substituting the definitions above yields the following model for the drum level variation:

```
> simplify(subs( eq[Vwd], eq[Vsd], eq[Vwr], eq[dl])):
> collect( ", [A[d],V[r],alpha[r](t)]);
```

$$\delta_l(t) = -l_0 + \frac{((1+b_1)\,\alpha_r(t) - 1)\,V_r + V_{wt}(t) - V_{dc}}{A_d}$$

This is the measurement model we shall use in conjunction with the first, second and third-order state equations. In [5], the volume of steam below the surface, $V_{sd}(t)$, is augmented as a state variable. The measurement model is then simply:

```
> simplify(subs( eq[Vwd], eq[Vwr], eq[dl])):
> collect( ", [A[d],V[r]]);
```

$$\delta_l(t) = -l_0 + \frac{(-1+\alpha_r(t))\,V_r + V_{wt}(t) - V_{dc} + V_{sd}(t)}{A_d}$$

Augmentation of a fourth state variable is the focus of Section A.4. We now proceed with the derivation of the third state equation.

A.3.2 Vapor Mass Fraction at Risers Outlet as an Augmented Third State

The extra state equation is derived in much the same way the first-order state equation was derived in Section A.2. We begin by defining the mass and energy balances. Then, by taking a linear combination of the two equations, we eliminate one of the key unknowns in the model, $q_r(t)$, the mass flow rate exiting the risers. Note that once the augmented state equations are solved, this flow rate effectively becomes a known value—it is a function of the state variables and their derivatives. With regard to the "shrink and swell" effect, this is important because together $q_r(t)$ and $x_r(t)$ characterize the rate the steam vapor bubbles enter the drum from the risers.

Consider the thermodynamic control volume for the risers, c.v. II, shown in Figure 2.1. At any time, the total mass is equal to the mass of the two phases combined.

```
> M[r](t) = M[wr](t) + M[sr](t);
```

$$M_r(t) = M_{wr}(t) + M_{sr}(t)$$

As before, the mass of each phase is given by the saturation density and total volume of the respective phase:

```
> M[wr](t) = rho[w](t)*V[wr](t),
> M[sr](t) = rho[s](t)*V[sr](t);
```

$$M_{wr}(t) = \rho_w(t)\,V_{wr}(t), M_{sr}(t) = \rho_s(t)\,V_{sr}(t)$$

The time rate of change of mass is equal to the mass flow rate entering from the down-comers, minus the mass flow rate of the wet mixture exiting at the top:

```
> Diff(M[r](t),t) = q[dc](t) - q[r](t);
```

$$\frac{\partial}{\partial t} M_r(t) = q_{dc}(t) - q_r(t)$$

Substituting expressions yields the risers mass balance:

```
> subs( """, "", eq[Vwr], eq[Vsr], " );
```

$$\frac{\partial}{\partial t} (\rho_w(t)\,(1-\alpha_r(t))\,V_r + \rho_s(t)\,\alpha_r(t)\,V_r) = q_{dc}(t) - q_r(t)$$

```
> eq[rmb] := ":
```

Now consider the energy balance for the control volume. As before, the energy stored at any time is:

```
> U[r](t) = U[wr](t) + U[sr](t) + U[T](t);
```

$$U_r(t) = U_{wr}(t) + U_{sr}(t) + U_T(t)$$

Assuming saturation conditions and instantaneous thermal equilibrium between metal and water, the components are:

```
> U[wr](t) = subs( eq[Vwr], rho[w](t)*u[w](t)*V[wr](t) ),
> U[sr](t) = subs( eq[Vsr], rho[s](t)*u[s](t)*V[sr](t) ),
> U[T](t)  = M[r]*c[p]*T[sat](t);
```

$$U_{wr}(t) = \rho_w(t)\,u_w(t)\,(1-\alpha_r(t))\,V_r, U_{sr}(t) = \rho_s(t)\,u_s(t)\,\alpha_r(t)\,V_r, U_T(t) = M_r\,c_p\,T_{sat}(t)$$

Note that we can investigate the effects of the thermal storage term included here by setting the metal mass, M_r, to zero. The time rate of change of energy storage equals the flux in minus the flux out.

```
> Diff(U[r](t),t) = Q(t) + h[w](t)*q[dc](t) - h[r](t)*q[r](t) + Delta[reb](t);
```

$$\frac{\partial}{\partial t} U_r(t) = Q(t) + h_w(t)\,q_{dc}(t) - h_r(t)\,q_r(t) + \Delta_{reb}(t)$$

Here, $Q(t)$ is the thermal heat flow coming from the combustion process. We have assumed the fluid state entering from the down-comers is a saturated liquid, i. e. in precisely the same state the fluid entered the down-comers. The third flux component involves the enthalpy of the saturated mixture at the outlet of the risers, $h_r(t)$; this is defined below. The last term on the right represents under-modeling. As with the global energy balance, this term serves as a place-holder in subsequent derivations; again its nominal value will be zero. Substitution yields the risers' energy balance:

```
> subs( """, "", eq[u], " );
```

$$\frac{\partial}{\partial t}\left(\rho_w(t)\left(h_w(t)-\frac{P(t)}{\rho_w(t)}\right)(1-\alpha_r(t))\,V_r+\rho_s(t)\left(h_s(t)-\frac{P(t)}{\rho_s(t)}\right)\alpha_r(t)\,V_r+M_r\,c_p\,T_{sat}(t)\right)=Q(t)+h_w(t)\,q_{dc}(t)-h_r(t)\,q_r(t)+\Delta_{reb}(t)$$

```
> eq[reb] := ":
```

As mentioned already, the augmented state equation is derived by taking a linear combination of the two balance equations. A key step is choosing the multiplier. For model reduction in Section A.2, we chose to eliminate complexity in coefficient of the time-derivative. Here we choose to eliminate an unknown; $q_r(t)$, the mass flow rate exiting the risers. A quick look at the right-hand sides of the balance equations tells us that the multiplier is the enthalpy at the risers' exit:

```
> h[r](t) = h[w](t) + h[c](t)*x[r](t);
```

$$h_r(t)=h_w(t)+h_c(t)\,x_r(t)$$

This is a function of the augmented state, $x_r(t)$, and the thermodynamic properties of saturated water. To facilitate simplification, the definition is made in terms of the enthalpy of vaporization:

```
> h[c](t) = h[s](t) - h[w](t);
```

$$h_c(t)=h_s(t)-h_w(t)$$

Taking the linear combination yields:

```
> eq[reb] - h[r](t)*eq[rmb];
```

$$\left(\frac{\partial}{\partial t}\left(\rho_w(t)\left(h_w(t)-\frac{P(t)}{\rho_w(t)}\right)(1-\alpha_r(t))\,V_r+\rho_s(t)\left(h_s(t)-\frac{P(t)}{\rho_s(t)}\right)\alpha_r(t)\,V_r+M_r\,c_p\,T_{sat}(t)\right)\right)-h_r(t)\left(\frac{\partial}{\partial t}\left(\rho_w(t)\,(1-\alpha_r(t))\,V_r+\rho_s(t)\,\alpha_r(t)\,V_r\right)\right)=Q(t)+h_w(t)\,q_{dc}(t)-h_r(t)\,q_r(t)+\Delta_{reb}(t)-h_r(t)\,(q_{dc}(t)-q_r(t))$$

The right-hand side can be further simplified by substituting in the definition for $h_r(t)$.

```
> subs( """, REVERSE(""), " ):
> collect( ", q[dc](t) );
```

$$\left(\frac{\partial}{\partial t}\left(\rho_w(t)\left(h_w(t)-\frac{P(t)}{\rho_w(t)}\right)(1-\alpha_r(t))\,V_r+\rho_s(t)\left(h_s(t)-\frac{P(t)}{\rho_s(t)}\right)\alpha_r(t)\,V_r+M_r\,c_p\,T_{sat}(t)\right)\right)-(h_w(t)+h_c(t)\,x_r(t))\left(\frac{\partial}{\partial t}\left(\rho_w(t)\,(1-\alpha_r(t))\,V_r+\rho_s(t)\,\alpha_r(t)\,V_r\right)\right)=-h_c(t)\,x_r(t)\,q_{dc}(t)+Q(t)+\Delta_{reb}(t)$$

Before proceeding, we make a change of variables that will aid in collecting the subsequent results. Technically, this new variable corresponds to the total volume fraction of liquid in the risers.

```
> changevar( 1 - alpha[r](t) = beta[r](t), " ):
```

Distributing the differential operator and applying the chain-rule to the differentials of the thermodynamic properties yields:

```
> simplify(value(")):
> subs(diff(  h[s](t),t)   = Diff(  h[s],P)*Diff(P,t),
```

```
>       diff( h[w](t),t)      = Diff( h[w],P)*Diff(P,t),
>       diff(rho[s](t),t)     = Diff(rho[s],P)*Diff(P,t),
>       diff(rho[w](t),t)     = Diff(rho[w],P)*Diff(P,t),
>       diff(T[sat](t),t)     = Diff(T[sat],P)*Diff(P,t),
>       diff(beta[r](t),t)    = -diff(alpha[r](t),t),
>       diff(alpha[r](t),t)   = Diff(alpha[r],P)*Diff(P,t)
>                             + Diff(alpha[r],x[r])*Diff(x[r],t),
>       diff(P(t),t)          = Diff(P,t), " ):
```

Note the expansion of the derivative of $\alpha_r(t)$ involves partial derivatives with respect to both state variables $P(t)$ and $x_r(t)$. Along with the approximation for $\alpha_r(t)$ itself, these partial derivatives will be derived in the following subsection. Now, proceeding with the job of simplifying and collecting the result:

```
> collect( ", [Diff(P,t), V[r], Diff(x[r],t), alpha[r](t), beta[r](t),
>   Diff(alpha[r],P), Diff(rho[s],P), Diff(alpha[r],x[r]), rho[s](t) ] ):
> powsubs( -x[r](t)*h[c](t) - h[w](t) + h[s](t) = h[c](t)*(1-x[r](t)),"):
> collect( ", [Diff(P,t), V[r], Diff(x[r],t), alpha[r](t), beta[r](t),
>   Diff(alpha[r],P), Diff(rho[s],P), Diff(alpha[r],x[r]), h[c](t), x[r](t)]):
```

Finally we can revert back to the total volume fraction of vapor. The preceding simplifications and this substitution yield:

```
> changevar( beta[r](t) = 1 - alpha[r](t), " );
```

$$\begin{aligned}&\Bigg(\Bigg(\left(h_c(t)\,(1-x_r(t))\left(\frac{\partial}{\partial P}\rho_s\right)-1+\left(\frac{\partial}{\partial P}h_s\right)\rho_s(t)\right)\alpha_r(t)\\&\quad+\left(-1+\left(\frac{\partial}{\partial P}h_w\right)\rho_w(t)-h_c(t)\,x_r(t)\left(\frac{\partial}{\partial P}\rho_w\right)\right)(1-\alpha_r(t))\\&\quad+((-\rho_s(t)+\rho_w(t))\,x_r(t)+\rho_s(t))\,h_c(t)\left(\frac{\partial}{\partial P}\alpha_r\right)\Bigg)V_r+M_r\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right)\Bigg)\left(\frac{\partial}{\partial t}P\right)\\&\quad+((-\rho_s(t)+\rho_w(t))\,x_r(t)+\rho_s(t))\,h_c(t)\,\mathrm{Diff}(\alpha_r,x_r)\left(\frac{\partial}{\partial t}x_r\right)V_r=\\&\quad-h_c(t)\,x_r(t)\,q_{dc}(t)+\mathrm{Q}(t)+\Delta_{reb}(t)\end{aligned}$$

```
> eq[rcb] := ":
```

As with the global balances, the left-hand side is a linear combination of the time-derivatives. Extracting the state dependent coefficients yields:

```
> e32 = STRIP( coeff(lhs("), Diff(P,t)) );
```

$$\begin{aligned}e32=&\left(\left(h_c\,(1-x_r)\left(\frac{\partial}{\partial P}\rho_s\right)-1+\rho_s\left(\frac{\partial}{\partial P}h_s\right)\right)\alpha_r\right.\\&\left.+\left(-1+\rho_w\left(\frac{\partial}{\partial P}h_w\right)-h_c\,x_r\left(\frac{\partial}{\partial P}\rho_w\right)\right)(1-\alpha_r)+((\rho_w-\rho_s)\,x_r+\rho_s)\,h_c\left(\frac{\partial}{\partial P}\alpha_r\right)\right)V_r\\&+M_r\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right)\end{aligned}$$

```
> e33 = STRIP( coeff(lhs(""),Diff(x[r],t)) );
```

$$e33=((\rho_w-\rho_s)\,x_r+\rho_s)\,h_c\,\mathrm{Diff}(\alpha_r,x_r)\,V_r$$

```
> ["","]:
```

Using these definitions, the risers' combined mass-energy balance reduces to:

```
> powsubs( REVERSE( "[1]), STRIP(eq[rcb]) ):
> powsubs( REVERSE(""[2]), " );
```

$$e32\left(\frac{\partial}{\partial t}P\right)+\left(\frac{\partial}{\partial t}x_r\right)e33=-h_c\,x_r\,q_{dc}+Q+\Delta_{reb}$$

```
> eq[RCB] := [", op(""")]:
```

Now, collecting the augmented state equations in matrix form, we can derive the explicit formulation of the state derivatives. The implicit system of equations has form:

```
> &*( matrix(3,3,[e11,e12,0, e21,e22,0, 0,e32,e33]),
>     matrix(3,1,[Diff(V[wt],t), Diff(P,t), Diff(x[r],t)]) )
>   = matrix(3,1,[rhs(eq[GMB][1]),rhs(eq[GEB][1]),rhs(eq[RCB][1])]);
```

$$\begin{bmatrix} e11 & e12 & 0 \\ e21 & e22 & 0 \\ 0 & e32 & e33 \end{bmatrix} \&* \begin{bmatrix} \frac{\partial}{\partial t} V_{wt} \\ \frac{\partial}{\partial t} P \\ \frac{\partial}{\partial t} x_r \end{bmatrix} = \begin{bmatrix} q_{fw} - q_s \\ -h_s\, q_s + h_{fw}\, q_{fw} + \Delta_{geb} + Q \\ -h_c\, x_r\, q_{dc} + Q + \Delta_{reb} \end{bmatrix}$$

```
> eq[sys3] := ":
```

Summarizing, the elements of the coefficient matrix are:

```
> eq[coef3] := table( [eq[GMB][2..3], eq[GEB][2..3], eq[RCB][2..3]] );
```

eq_{coef3} := table([

$$e32 = \left(\left(h_c\,(1-x_r)\left(\frac{\partial}{\partial P}\rho_s\right) - 1 + \rho_s\left(\frac{\partial}{\partial P}h_s\right)\right)\alpha_r + \left(-1+\rho_w\left(\frac{\partial}{\partial P}h_w\right) - h_c\,x_r\left(\frac{\partial}{\partial P}\rho_w\right)\right)(1-\alpha_r) + ((\rho_w-\rho_s)\,x_r+\rho_s)\,h_c\left(\frac{\partial}{\partial P}\alpha_r\right)\right)V_r + M_r\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right)$$

$$e12 = \left(\frac{\partial}{\partial P}\rho_w\right)V_{wt} + \left(\frac{\partial}{\partial P}\rho_s\right)V_{st}$$

$$e11 = \rho_w - \rho_s$$

$$e21 = -h_s\,\rho_s + h_w\,\rho_w$$

$$e33 = ((\rho_w-\rho_s)\,x_r+\rho_s)\,h_c\,\mathrm{Diff}(\alpha_r, x_r)\,V_r$$

$$e22 = M_T\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right) + \left(h_w\left(\frac{\partial}{\partial P}\rho_w\right) + \rho_w\left(\frac{\partial}{\partial P}h_w\right) - 1\right)V_{wt} + \left(h_s\left(\frac{\partial}{\partial P}\rho_s\right) + \rho_s\left(\frac{\partial}{\partial P}h_s\right) - 1\right)V_{st}$$

])

Inverting the coefficient matrix yields:

```
> inverse(op(1,lhs(eq[sys3])));
```

$$\begin{bmatrix} \frac{e22}{e11\,e22 - e12\,e21} & -\frac{e12}{e11\,e22 - e12\,e21} & 0 \\ -\frac{e21}{e11\,e22 - e12\,e21} & \frac{e11}{e11\,e22 - e12\,e21} & 0 \\ \frac{e21\,e32}{e33\,(e11\,e22 - e12\,e21)} & -\frac{e11\,e32}{e33\,(e11\,e22 - e12\,e21)} & \frac{1}{e33} \end{bmatrix}$$

Thanks to the linear structure on the left-hand side, we can solve explicitly for the state derivatives. The explicit state space formulation is:

```
> linsolve( op(1,lhs(eq[sys3])), rhs(eq[sys3]) ):
> op(2,lhs(eq[sys3])) = map(collect, ", [e11,e12,e21,e22,e32]);
```

$$\begin{bmatrix} \frac{\partial}{\partial t} V_{wt} \\ \frac{\partial}{\partial t} P \\ \frac{\partial}{\partial t} x_r \end{bmatrix} =$$

$$\left[-\frac{\%1\,e12 + (-q_{fw}+q_s)\,e22}{e11\,e22 - e12\,e21}\right]$$

$$\left[\frac{\%1\,e11 + (-q_{fw}+q_s)\,e21}{e11\,e22 - e12\,e21}\right]$$

$$\left[-\left(((-Q-\Delta_{reb}+h_c\,x_r\,q_{dc})\,e22 + \%1\,e32)\,e11 + (-h_c\,x_r\,q_{dc}+Q+\Delta_{reb})\,e21\,e12 + (-q_{fw}+q_s)\,e32\,e21\right)/(e33\,(e11\,e22 - e12\,e21))\right]$$

$$\%1 := -h_s\,q_s + h_{fw}\,q_{fw} + \Delta_{geb} + Q$$

Note the functional dependency on the under-modeling place-holders: $\Delta_{geb}(t)$ and $\Delta_{reb}(t)$. The former appears in all three state equations, while the latter appears only in the augmented state equation. Rearranging this equation makes matters more clear:

```
> lhs(")[3,1] = collect( combine(""[3,1]),
>   [Delta[geb], Delta[reb], Q, q[s], q[fw], q[dc], x[r], h[c]]):
> lhs(") = map(collect,
>             map(simplify, rhs(")), [e32, e11, e21]);
```

$$\frac{\partial}{\partial t} x_r = -\frac{e11\ e32\ \Delta_{geb}}{e33\,(\,e11\ e22 - e12\ e21\,)} + \frac{\Delta_{reb}}{e33} - \frac{e11\ Q\ e32}{e33\,(\,e11\ e22 - e12\ e21\,)} - \frac{(\,-e11\ e22 + e12\ e21\,)\,Q}{e33\,(\,e11\ e22 - e12\ e21\,)} + \frac{e32\ (e11\ h_s - e21)\ q_s}{e33\,(\,e11\ e22 - e12\ e21\,)} - \frac{e32\ (e11\ h_{fw} - e21)\ q_{fw}}{e33\,(\,e11\ e22 - e12\ e21\,)} - \frac{h_c\ x_r\ q_{dc}}{e33}$$

This structure is important if we attempt to represent the under-modeling using stochastic processes. The linear structure will lead to an identifiability problem if we attempt to simultaneously estimate the statistics of $\Delta_{geb}(t)$ and $\Delta_{reb}(t)$.

Before proceeding with the derivations of $\alpha_r(t)$ and its partial derivatives, we mention that explicit formulation of the state equations is *not* the wisest formulation for numerical implementation. The coefficient matrix of the time-derivatives clearly shows the original state equations are decoupled i.e. independent of the augmented equation. Utilizing this decoupling, a better formulation for numerical implementation is:

```
> lhs(""") = extend(submatrix(rhs("""),1..2,1..1), 1, 0,
>               (rhs(eq[sys3])[3,1] - e32*Diff(P,t))/e33 );
```

$$\begin{bmatrix} \frac{\partial}{\partial t} V_{wt} \\ \frac{\partial}{\partial t} P \\ \frac{\partial}{\partial t} x_r \end{bmatrix} = \begin{bmatrix} -\frac{(-h_s\, q_s + h_{fw}\, q_{fw} + \Delta_{geb} + Q)\ e12 + (-q_{fw} + q_s)\ e22}{e11\ e22 - e12\ e21} \\ \frac{(-h_s\, q_s + h_{fw}\, q_{fw} + \Delta_{geb} + Q)\ e11 + (-q_{fw} + q_s)\ e21}{e11\ e22 - e12\ e21} \\ \frac{-h_c\, x_r\, q_{dc} + Q + \Delta_{reb} - e32\ (\frac{\partial}{\partial t} P)}{e33} \end{bmatrix}$$

In implementing this, the third computation is a function of the result of the second. Thus, the ordering of the computations is crucial.

We mention that this is automatically the formulation that is derived by the compilers of today's modern acausal model definition languages, *e.g.* OMOLA, DYMOLA and MODELICA. We now proceed with derivations of signals used above which we have not yet defined:

(*i*) $\alpha_r(t)$, the total volume fraction of steam vapor in the risers and its partial derivatives w.r.t. the state variables;

(*ii*) $q_{dc}(t)$, the mass flow rate passing through the down-comers.

A.3.3 Approximation of the Total Vapor Volume Fraction in the Risers

In Section A.2, the gross nature of the analysis allowed us to ignore the spatial distribution of the two phases. Our aim here is to encapsulate in a function of the augmented state variable, $x_r(t)$, the effects of the spatial distribution in the risers. The function which does this is the total volume fraction of steam vapor in the risers. Its definition is intuitively:

```
> alpha[r](t) = V[sr](t)/V[r];
```

$$\alpha_r(t) = \frac{V_{sr}(t)}{V_r}$$

In [3, 4], Åström and Bell developed an approximate expression for this quantity in terms of the state variables, i. e.:

```
> lhs(") = f(P(t),x[r](t));
```

$$\alpha_r(t) = \mathrm{f}(\mathrm{P}(t), x_r(t))$$

The basis of the approximation is the following assumption: assume the distribution of the liquid and vapor phases spatially from the top to bottom of the risers is known. The mass fraction of steam vapor at any point is defined:

```
> x(t,xi) = m[s](t,xi)/(m[s](t,xi) + m[w](t,xi));
```

$$x(t,\xi) = \frac{m_s(t,\xi)}{m_s(t,\xi) + m_w(t,\xi)}$$

Here ξ is the normalized spatial coordinate ranging from 0 at the bottom to 1 at the top of the risers. Based on results of finite-element modeling, Åström and Bell found the mass fraction of vapor varies linearly from the bottom to the top of the risers. Expressed in terms of the outlet conditions at the top, a *model* of the spatial distribution is:

```
> x(t,xi) = x[r](t)*xi;
```

$$x(t,\xi) = x_r(t)\,\xi$$

```
> eq[lhs(")] := ":
```

By definition, the *specific* volume fraction of steam vapor is the specific volume of the vapor component divided by the specific volume of the saturated mixture:

```
> alpha(t,xi) = v[s](t)*x(t,xi)/(v[w](t) + v[c](t)*x(t,xi));
```

$$\alpha(t,\xi) = \frac{v_s(t)\,x(t,\xi)}{v_w(t) + v_c(t)\,x(t,\xi)}$$

Expressed in terms of density, the definition becomes:

```
> v[c](t) = v[s](t)-v[w](t), v[w](t) = 1/rho[w](t), v[s](t) = 1/rho[s](t):
> subs( ", "" ):
> collect(simplify("), x(t,xi)):
> subs( rho[s](t)-rho[w](t)=-rho[ws](t),
>       -rho[s](t)+rho[w](t)= rho[ws](t), " );
```

$$\alpha(t,\xi) = \frac{x(t,\xi)\,\rho_w(t)}{\rho_{ws}(t)\,x(t,\xi) + \rho_s(t)}$$

```
> eq[lhs(")] := ":
```

In the definition, we have made a change of variables: $\rho_{ws}(t) = \rho_w(t) - \rho_s(t)$; this greatly facilitates simplification of the approximation which will be based on this expression.

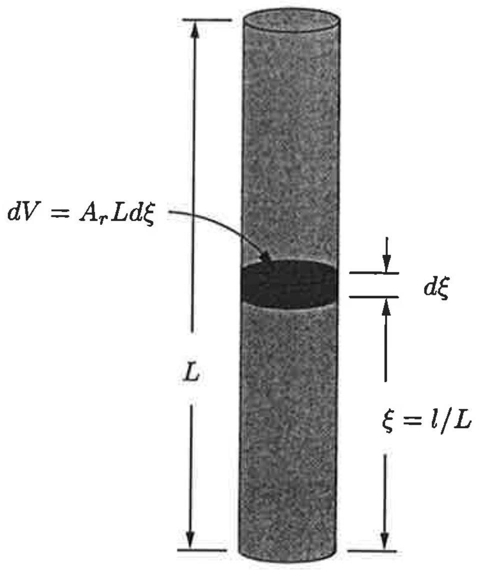


Figure A.2: A simplified geometric representation of the risers.

The relationship between the total and specific volume fractions of steam vapor is derived by integrating over the spatial variable ξ. Consider a differential volume slice and the geometry shown in Figure A.2. The specific volume fraction has the following interpretation:

```
> dV[sr](t,xi) = alpha(t,xi)*dV(xi);
```

$$dV_{sr}(t,\xi) = \alpha(t,\xi)\,dV(\xi)$$

This corresponds to the volume of the vapor component in the differential slice shown in Figure A.2. Assuming the area A_r is constant, geometrical relations lead to:

```
> dV(xi) = A[r]*dl, dl = L[r]* d.xi, A[r]*L[r] = V[r]:
> powsubs( ", "" );
```

$$dV_{sr}(t,\xi) = \alpha(t,\xi)\, dxi\, V_r$$

Integrating this over the range of the spatial variable yields the total volume of steam vapor in the risers:

```
> V[sr](t) = Int( rhs(")/d.xi, xi=0..1 );
```

$$V_{sr}(t) = \int_0^1 \alpha(t,\xi)\, V_r\, d\xi$$

Hence, the total volume fraction of steam in the risers is:

```
> alpha[r](t) = simplify( rhs(")/V[r] );
```

$$\alpha_r(t) = \int_0^1 \alpha(t,\xi)\, d\xi$$

Combining the approximate expression for the spatial distribution with the definition of the specific volume fraction gives:

```
> subs( eq[alpha(t,xi)], eq[x(t,xi)],  " );
```

$$\alpha_r(t) = \int_0^1 \frac{x_r(t)\,\xi\,\rho_w(t)}{\rho_{ws}(t)\,x_r(t)\,\xi + \rho_s(t)}\, d\xi$$

Evaluating the integral yields:

```
> normal(value(")):
> collect( ", rho[s](t)):
> combine( ", ln );
```

$$\alpha_r(t) = \frac{\rho_w(t)\ln\left(\frac{\rho_s(t)}{\rho_s(t)+\rho_{ws}(t)\,x_r(t)}\right)\rho_s(t)}{x_r(t)\,\rho_{ws}(t)^2} + \frac{\rho_w(t)}{\rho_{ws}(t)}$$

```
> eq[lhs(")] := ":
```

This expression is the approximation for the total steam volume fraction in the risers. Because of our assumption of saturation conditions, the densities are functions of pressure. Thus we have $\alpha_r(t) = f(P(t), x_r(t))$. In [12] a change of variables is made:

```
> eta(t) = rho[ws](t)*x[r](t)/rho[s](t);
```

$$\eta(t) = \frac{\rho_{ws}(t)\,x_r(t)}{\rho_s(t)}$$

```
> eq[lhs(")] := ":
```

Applying this change, we arrive at their expression for $\alpha_r(t)$:

```
> powsubs( rho[s](t)*REVERSE(eq[eta(t)]), eq[alpha[r](t)] ):
> simplify(");
```

$$\alpha_r(t) = \frac{\rho_w(t)\,(-\ln(1+\eta(t))+\eta(t))}{\rho_{ws}(t)\,\eta(t)}$$

The augmented state equation requires partial derivatives of this expression with respect to the state variables. Below we verify the expressions given in [12].

```
> diff(rhs(eq[alpha[r](t)]),t):
> subs(diff(rho[ws](t),t)   = diff(rho[w](t)-rho[s](t),t),
>        diff(rho[s](t),t)  = Diff(rho[s],P)*Diff(P,t),
>        diff(rho[w](t),t)  = Diff(rho[w],P)*Diff(P,t),
>        diff(x[r](t),t)    = Diff(x[r],t),
>        diff(P(t),t)       = Diff(P,t), " ):
> collect( ", [Diff(x[r],t), Diff(P,t),
>    Diff(rho[w],P), Diff(rho[s],P), rho[s](t), rho[w](t) ] ):
> powsubs( rho[s](t)*REVERSE(eq[eta(t)]), " ):
```

The partial with respect to the outlet mass fraction is:

```
> Diff(alpha[r],x[r]) = collect(coeff(",Diff(x[r],t)),ln(1/(1+eta(t))));
```

$$\mathrm{Diff}\left(\alpha_r, x_r\right) = -\frac{\rho_w(t)\ln\left(\frac{1}{1+\eta(t)}\right)}{\rho_s(t)\,\eta(t)^2} - \frac{\rho_w(t)}{\rho_s(t)\,\eta(t)\,(1+\eta(t))}$$

The partial with respect to pressure is more complicated. To verify the known expression, we proceed by eliminating terms from the right-hand side.

```
> Diff(alpha[r],P) = coeff( "", Diff(P,t) ):
> rho[ws](t)^2/(rho[w](t)*Diff(rho[s],P) - rho[s](t)*Diff(rho[w],P));
```

$$\frac{\rho_{ws}(t)^2}{\rho_w(t)\,\left(\frac{\partial}{\partial P}\rho_s\right) - \rho_s(t)\,\left(\frac{\partial}{\partial P}\rho_w\right)}$$

```
> simplify( " * "" ):
> lhs(") = subs( rho[ws](t)=rho[w](t)-rho[s](t), rhs(") ):
> normal("):
> collect( ", [ln(1+eta(t)), rho[s](t), rho[w](t), eta(t)] ):
> lhs(") = map(simplify, rhs("));
```

$$\frac{\rho_{ws}(t)^2\,\left(\frac{\partial}{\partial P}\alpha_r\right)}{\rho_w(t)\,\left(\frac{\partial}{\partial P}\rho_s\right) - \rho_s(t)\,\left(\frac{\partial}{\partial P}\rho_w\right)} = -\frac{(\rho_s(t)+\rho_w(t))\ln(1+\eta(t))}{\rho_s(t)\,\eta(t)} + 1 + \frac{\rho_w(t)}{(1+\eta(t))\,\rho_s(t)}$$

Finally, we put the terms that we moved to the left-hand side back on the right. This yields the desired expression:

```
> Diff(alpha[r],P) = solve( ", Diff(alpha[r],P) );
```

$$\frac{\partial}{\partial P}\alpha_r = -\left(\frac{\ln(1+\eta(t))}{\eta(t)} + \frac{\ln(1+\eta(t))\,\rho_w(t)}{\rho_s(t)\,\eta(t)} - 1 - \frac{\rho_w(t)}{(1+\eta(t))\,\rho_s(t)}\right)$$
$$\left(\rho_w(t)\left(\frac{\partial}{\partial P}\rho_s\right) - \rho_s(t)\left(\frac{\partial}{\partial P}\rho_w\right)\right)\Big/\rho_{ws}(t)^2$$

A.3.4 Mass Flow Rate through the Down-comers

The one-dimensional momentum balance for a pipe of length L can be written:

```
> L*Diff(q,t) = A[i]*P[i] - A[o]*P[o] - F +V*rho[t]*g[c];
```

$$L\left(\frac{\partial}{\partial t}q\right) = A_i\,P_i - A_o\,P_o - F + V\,\rho_t\,g_c$$

```
> eq[mombal] := ":
```

Apply the momentum balance to the down-comer tubes as well as the riser tubes:

```
> subs( L=L[dc], q=q[dc](t), A[i]=A[dc], A[o]=A[dc], P[i]=P(t),
>    P[o]=P(t)+rho[r](t)*g[c]*L[r], rho[t]=rho[w](t), V=V[dc],  eq[mombal] );
```

$$L_{dc}\left(\frac{\partial}{\partial t}q_{dc}(t)\right) = A_{dc}\,\mathrm{P}(t) - A_{dc}\,(\mathrm{P}(t) + \rho_r(t)\,g_c\,L_r) - F + V_{dc}\,\rho_w(t)\,g_c$$

```
> eq[dcbal] := ":
> subs( L=L[r], q=q[dc](t), A[i]=A[r], A[o]=A[r], P[o]=P(t),
>   P[i]=P(t)+rho[w](t)*g[c]*L[dc], rho[t]=rho[r](t), V=-V[r], eq[mombal]);
```

$$L_r \left(\frac{\partial}{\partial t} q_{dc}(t)\right) = A_r\,(\mathrm{P}(t) + \rho_w(t)\,g_c\,L_{dc}) - A_r\,\mathrm{P}(t) - F - V_r\,\rho_r(t)\,g_c$$

```
> eq[risbal] := ":
```

Here $\rho_r(t)$ is the average density in the risers. This can be expressed in terms of the total vapor volume fraction $\alpha_r(t)$ as follows:

```
> rho[r](t) = (1-alpha[r](t))*rho[w](t)+alpha[r](t)*rho[s](t);
```

$$\rho_r(t) = (1 - \alpha_r(t))\,\rho_w(t) + \alpha_r(t)\,\rho_s(t)$$

By combining the two momentum balance equations and then assuming $L_{dc} = L_r = L$, we obtain a differential equation for the mass flow in the down-comer riser loop:

```
> simplify(value( eq[dcbal] + eq[risbal] )):
> simplify(subs( "", L[dc]=L, L[r]=L, " )):
> simplify(powsubs( L*A[dc]=V[dc], L*A[r]=V[r], " )):
> collect( ", [alpha[r](t), g[c], V[dc], V[r]] ):
> collect( subs( -rho[s](t)+rho[w](t)=rho[ws](t),"), rho[ws](t) );
```

$$2\,L \left(\frac{\partial}{\partial t} q_{dc}(t)\right) = (V_{dc} + V_r)\;g_c\,\alpha_r(t)\,\rho_{ws}(t) - 2\,F$$

We observe that the volumes on the right hand side can be combined to form the total volume in the down-comer rise loop:

```
> subs( V[r] + V[dc] = V[tot], " );
```

$$2\,L \left(\frac{\partial}{\partial t} q_{dc}(t)\right) = V_{tot}\,g_c\,\alpha_r(t)\,\rho_{ws}(t) - 2\,F$$

To find the static solution to this equation we substitute an expression for the frictional losses and solve for the constant mass flow:

```
> F = xi/2*q[dc]^2/rho[w]/A[dc];
```

$$F = \frac{1}{2}\,\frac{\xi\,{q_{dc}}^2}{\rho_w\,A_{dc}}$$

```
> solve( value(subs( q[dc](t)=q[dc], ", "" )), {q[dc]^2} ):
```

This is not exactly the same solution that is derived in [12], but it differs only in that the friction factor in our derivation will take on the value:

```
> xi=k/2*V[tot]/V[r];
```

$$\xi = \frac{1}{2}\,\frac{k\,V_{tot}}{V_r}$$

Inserting this gives us hypothesis 2 (line 166 in Listing B.12) for the down-comer flow:

```
> subs( ", "" );
```

$$\left\{ {q_{dc}}^2 = 2\,\frac{g_c\,\alpha_r(t)\,\rho_{ws}(t)\,V_r\,\rho_w\,A_{dc}}{k} \right\}$$

The primary hypothesis (line 165 in Listing B.12) is taken from the previous Bell-Åström articles where they used a "lumped" friction factor k instead of the dimensionless factor used in this derivation.

```
> k=k[f]*g[c]*rho[w]*A[dc];
```

$$k = k_f\,g_c\,\rho_w\,A_{dc}$$

```
> subs(",""):
> q[dc](t) = sqrt( rhs(op(1,")));
```

$$q_{dc}(t) = \sqrt{2}\sqrt{\frac{\alpha_r(t)\,\rho_{ws}(t)\,V_r}{k_f}}$$

```
> eq[q[dc](t)] := ":
```

This removes the dependence on A_{dc}, so as to have one less physical parameter in the model. In the implementation of these hypotheses for this study A_{dc} was calculated to make k equal to k_f since we wanted to have the same friction factor in both hypotheses. This gives $A_{dc} \approx 10^{-4}$ which is physically unrealistic.

A.3.5 Third-Order Equations with an Alternate Choice of State Variable

In [3–5] the volume of liquid water in the drum, $V_{wd}(t)$, was chosen to be a state variable instead of the total volume of water, $V_{wt}(t)$. Effectively, this is a linear coordinate transformation so little appears to be gained with the switch. For the third-order state equations, the transformation actually destroys the decoupling present in the original formulation (page 42). Because we are dealing with nonlinear equations, we include it in the study for thoroughness. The change of variables is based on the following relation:

```
> V[wt](t) = solve( subs(eq[Vwr],eq[Vwd]), V[wt](t) );
```

$$V_{wt}(t) = V_{wd}(t) + V_{dc} + V_r - \alpha_r(t)\,V_r$$

To transform the state equations, we need the corresponding expression relating the time derivatives. Straight-forward differentiation yields:

```
> diff(",t):
> subs(diff(V[wt](t),t)       = Diff(V[wt],t),
>        diff(V[wd](t),t)     = Diff(V[wd],t),
>        diff(alpha[r](t),t)  = Diff(alpha[r],P)*Diff(P,t)
>                             + Diff(alpha[r],x[r])*Diff(x[r],t), " );
```

$$\frac{\partial}{\partial t} V_{wt} = \left(\frac{\partial}{\partial t} V_{wd}\right) - \left(\left(\frac{\partial}{\partial P}\alpha_r\right)\left(\frac{\partial}{\partial t} P\right) + \mathrm{Diff}(\alpha_r, x_r)\left(\frac{\partial}{\partial t} x_r\right)\right) V_r$$

```
> eq[dVwt] := ":
```

Now recall the definition of the global mass balance:

```
> eq[GMB][1];
```

$$e12\left(\frac{\partial}{\partial t} P\right) + e11\left(\frac{\partial}{\partial t} V_{wt}\right) = q_{fw} - q_s$$

Making the change of variables yields:

```
> subs( eq[dVwt], eq[GMB][1] ):
> collect( ", [Diff(V[wd],t),    Diff(P,t),      Diff(x[r],t),
>              Diff(alpha[r],P), Diff(alpha[r],x[r])] );
```

$$e11\left(\frac{\partial}{\partial t} V_{wd}\right) + \left(e12 - e11\left(\frac{\partial}{\partial P}\alpha_r\right) V_r\right)\left(\frac{\partial}{\partial t} P\right) - e11\,\mathrm{Diff}(\alpha_r, x_r)\left(\frac{\partial}{\partial t} x_r\right) V_r = q_{fw} - q_s$$

As usual, we collect the coefficients for the matrix formulation:

```
> e11a = coeff( lhs("), Diff(V[wd],t) ),
> e12a = coeff( lhs("), Diff(P,t) ),
> e13a = coeff( lhs("), Diff(x[r],t) );
```

$$e11a = e11, e12a = e12 - e11\left(\frac{\partial}{\partial P}\alpha_r\right) V_r, e13a = -e11\,\mathrm{Diff}(\alpha_r, x_r)\,V_r$$

The alternate formulation of the global mass balance is then:

```
> powsubs( REVERSE("[3]), "" ):
> subs( map(REVERSE,[""[2],""[1]]), " );
```

$$e11a\left(\frac{\partial}{\partial t}V_{wd}\right)+e12a\left(\frac{\partial}{\partial t}P\right)+\left(\frac{\partial}{\partial t}x_r\right)e13a=q_{fw}-q_s$$

```
> eq[GMBa] := [",""""]:
```

Next we repeat these steps, applying them to the global energy balance:

```
> eq[GEB][1];
```

$$e22\left(\frac{\partial}{\partial t}P\right)+e21\left(\frac{\partial}{\partial t}V_{wt}\right)=-h_s\,q_s+h_{fw}\,q_{fw}+\Delta_{geb}+Q$$

Substituting and collecting yields the coefficients:

```
> subs( eq[dVwt], eq[GEB][1] ):
> collect( ", [Diff(V[wd],t),     Diff(P,t),      Diff(x[r],t),
>              Diff(alpha[r],P), Diff(alpha[r],x[r])] ):
> e21a = coeff( lhs("), Diff(V[wd],t) ),
> e22a = coeff( lhs("), Diff(P,t) ),
> e23a = coeff( lhs("), Diff(x[r],t) );
```

$$e21a=e21,e22a=e22-e21\left(\frac{\partial}{\partial P}\alpha_r\right)V_r,e23a=-e21\,\mathrm{Diff}(\alpha_r,x_r)\,V_r$$

The alternate formulation of the global energy balance is then:

```
> powsubs( REVERSE("[3]), "" ):
> subs( map(REVERSE,[""[2],""[1]]), " );
```

$$e21a\left(\frac{\partial}{\partial t}V_{wd}\right)+e22a\left(\frac{\partial}{\partial t}P\right)+\left(\frac{\partial}{\partial t}x_r\right)e23a=-h_s\,q_s+h_{fw}\,q_{fw}+\Delta_{geb}+Q$$

```
> eq[GEBa] := [",""""]:
```

Collecting these results in matrix form, we have:

```
> &*( matrix(3,3,[e11a,e12a,e13a, e21a,e22a,e23a, 0,e32,e33]),
>     matrix(3,1,[Diff(V[wd],t), Diff(P,t), Diff(x[r],t)]) )
>   = matrix(3,1,[rhs(eq[GMBa][1]),rhs(eq[GEBa][1]),rhs(eq[RCB][1])]);
```

$$\begin{bmatrix} e11a & e12a & e13a \\ e21a & e22a & e23a \\ 0 & e32 & e33 \end{bmatrix} \&* \begin{bmatrix} \frac{\partial}{\partial t}V_{wd} \\ \frac{\partial}{\partial t}P \\ \frac{\partial}{\partial t}x_r \end{bmatrix} = \begin{bmatrix} q_{fw}-q_s \\ -h_s\,q_s+h_{fw}\,q_{fw}+\Delta_{geb}+Q \\ -h_c\,x_r\,q_{dc}+Q+\Delta_{reb} \end{bmatrix}$$

```
> eq[sys3a] := ":
```

where the elements of the coefficient matrix are:

```
> eq[coef3a] := table( [eq[GMBa][2..4], eq[GEBa][2..4], eq[RCB][2..3]] );
```

$$eq_{coef3a}:=\mathrm{table}([$$

$$e32=\left(\left(h_c\,(1-x_r)\left(\frac{\partial}{\partial P}\rho_s\right)-1+\rho_s\left(\frac{\partial}{\partial P}h_s\right)\right)\alpha_r+\left(-1+\rho_w\left(\frac{\partial}{\partial P}h_w\right)-h_c\,x_r\left(\frac{\partial}{\partial P}\rho_w\right)\right)(1-\alpha_r)+((\rho_w-\rho_s)\,x_r+\rho_s)\,h_c\left(\frac{\partial}{\partial P}\alpha_r\right)\right)V_r+M_r\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right)$$

$$e21a=e21$$

$$e22a=e22-e21\left(\frac{\partial}{\partial P}\alpha_r\right)V_r$$

$$e33=((\rho_w-\rho_s)\,x_r+\rho_s)\,h_c\,\mathrm{Diff}(\alpha_r,x_r)\,V_r$$

$$e11a=e11$$

$$e13a=-e11\,\mathrm{Diff}(\alpha_r,x_r)\,V_r$$

$$e12a=e12-e11\left(\frac{\partial}{\partial P}\alpha_r\right)V_r$$

$$e23a=-e21\,\mathrm{Diff}(\alpha_r,x_r)\,V_r$$

$$])$$

and the coefficients $e11, e12, e21$ and $e22$ are the same as before (page 33). Now with the non-zero elements $e13$ and $e23$, all three state equations are coupled. This is most evident in the coefficient matrix inverse:

```
> inverse(op(1,lhs(eq[sys3a])));
```

$$\begin{bmatrix} \frac{-e22a\, e33 + e23a\, e32}{\%1} & \frac{e12a\, e33 - e13a\, e32}{\%1} & -\frac{e12a\, e23a - e13a\, e22a}{\%1} \\ \frac{e21a\, e33}{\%1} & -\frac{e11a\, e33}{\%1} & \frac{e11a\, e23a - e13a\, e21a}{\%1} \\ -\frac{e21a\, e32}{\%1} & \frac{e11a\, e32}{\%1} & -\frac{e11a\, e22a - e12a\, e21a}{\%1} \end{bmatrix}$$

$$\%1 := -e11a\, e22a\, e33 + e11a\, e23a\, e32 + e21a\, e12a\, e33 - e21a\, e13a\, e32$$

Thus, we can still solve explicitly for the time-derivatives, but the result is very complex. The explicit state space formulation for this alternate choice of basis is:

```
> linsolve( op(1,lhs(eq[sys3a])), rhs(eq[sys3a]) ):
> op(2,lhs(eq[sys3a])) =
>    map(collect, ", [e11a,e12a,e13a,e21a,e22a,e23a,e32,e33]);
```

$$\begin{bmatrix} \frac{\partial}{\partial t} V_{wd} \\ \frac{\partial}{\partial t} P \\ \frac{\partial}{\partial t} x_r \end{bmatrix} =$$

$$\Big[\Big(((-\Delta_{reb} - Q + \%2)\ e23a + \%3\ e33)\ e12a$$
$$+ ((-\%2 + Q + \Delta_{reb})\ e22a + (h_s\, q_s - h_{fw}\, q_{fw} - \Delta_{geb} - Q)\ e32)\ e13a$$
$$+ (q_s - q_{fw})\ e33\ e22a + (q_{fw} - q_s)\ e32\ e23a\Big) / (\%1)\Big]$$
$$\Big[-\Big(((-\Delta_{reb} - Q + \%2)\ e23a + \%3\ e33)\ e11a + (-\%2 + Q + \Delta_{reb})\ e21a\ e13a$$
$$+ (q_s - q_{fw})\ e33\ e21a\Big) / (\%1)\Big]$$
$$\Big[\Big(((-\Delta_{reb} - Q + \%2)\ e22a + \%3\ e32)\ e11a + (-\%2 + Q + \Delta_{reb})\ e21a\ e12a$$
$$+ (q_s - q_{fw})\ e32\ e21a\Big) / (\%1)\Big]$$
$$\%1 := (-e22a\, e33 + e23a\, e32)\, e11a + e21a\, e12a\, e33 - e21a\, e13a\, e32$$
$$\%2 := h_c\, x_r\, q_{dc}$$
$$\%3 := -h_s\, q_s + h_{fw}\, q_{fw} + \Delta_{geb} + Q$$

Note the functional dependency on the under-modeling place-holders: $\Delta_{geb}(t)$ and $\Delta_{reb}(t)$ now appear simultaneously in all three state equations. This essentially makes differentiating their effects in an error analysis impossible.

A.3.6 An Augmented Reduced Two-State Model

We close out this section by revisiting model reduction. Recall the basis for the single-state model was the following assumption:

```
> Diff(V[wt],t) = 0;
```

$$\frac{\partial}{\partial t} V_{wt} = 0$$

It is immediately clear that we can augment the risers combined mass-energy balance to the one-state model. In matrix form, this yields:

```
> &*( matrix(2,2,[e1,0, e32,e33]),
>      matrix(2,1,[Diff(P,t), Diff(x[r],t)]) )
>   = matrix(2,1,[rhs(eq[sys1r]), rhs(eq[RCB][1])]);
```

$$\begin{bmatrix} e1 & 0 \\ e32 & e33 \end{bmatrix} \&* \begin{bmatrix} \frac{\partial}{\partial t} P \\ \frac{\partial}{\partial t} x_r \end{bmatrix} = \begin{bmatrix} -q_s\, h_c + \Delta_{geb} + (-h_w + h_{fw})\, q_{fw} + Q \\ -h_c\, x_r\, q_{dc} + Q + \Delta_{reb} \end{bmatrix}$$

```
> eq[sys2r] := ":
> eq[coef2r] := table( [eq[coef1r], eq[RCB][2..3]] );
```

$$eq_{coef2r} := \text{table}([$$

$$e32 = \left(\left(h_c\,(1-x_r)\left(\frac{\partial}{\partial P}\rho_s\right) - 1 + \rho_s\left(\frac{\partial}{\partial P}h_s\right)\right)\alpha_r + \left(-1+\rho_w\left(\frac{\partial}{\partial P}h_w\right) - h_c\,x_r\left(\frac{\partial}{\partial P}\rho_w\right)\right)(1-\alpha_r) + ((\rho_w-\rho_s)\,x_r+\rho_s)\,h_c\left(\frac{\partial}{\partial P}\alpha_r\right)\right)V_r + M_r\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right)$$

$$e1 = M_T\,c_p\left(\frac{\partial}{\partial P}T_{sat}\right) + \left(\rho_w\left(\frac{\partial}{\partial P}h_w\right) - 1\right)V_{wt} + \left(\rho_s\left(\frac{\partial}{\partial P}h_s\right) + \left(\frac{\partial}{\partial P}\rho_s\right)h_c - 1\right)V_{st}$$

$$e33 = ((\rho_w-\rho_s)\,x_r+\rho_s)\,h_c\,\text{Diff}(\alpha_r, x_r)\,V_r$$

$$])$$

Inverting the coefficient matrix yields:

```
> inverse(op(1,lhs(eq[sys2r])));
```

$$\begin{bmatrix} \frac{1}{e1} & 0 \\ -\frac{e32}{e1\,e33} & \frac{1}{e33} \end{bmatrix}$$

Solving for the explicit state space formulation yields:

```
> linsolve( op(1,lhs(eq[sys2r])), rhs(eq[sys2r]) ):
> op(2,lhs(eq[sys2r])) = map(collect, ", [e1,e32,e33]);
```

$$\begin{bmatrix} \frac{\partial}{\partial t}P \\ \frac{\partial}{\partial t}x_r \end{bmatrix} = \begin{bmatrix} \frac{-q_s\,h_c + \Delta_{geb} - q_{fw}\,h_w + h_{fw}\,q_{fw} + Q}{e1} \\ \frac{-h_c\,x_r\,q_{dc} + Q + \Delta_{reb}}{e33} + \frac{(q_s\,h_c - \Delta_{geb} + q_{fw}\,h_w - h_{fw}\,q_{fw} - Q)\,e32}{e33\,e1} \end{bmatrix}$$

Again thanks to the decoupled structure we have a more compact formulation suited for simulation.

```
> lhs(") = matrix(2,1, [rhs(")[1,1],
>                     (rhs(eq[sys2r])[2,1] - e32*Diff(P,t))/e33] );
```

$$\begin{bmatrix} \frac{\partial}{\partial t}P \\ \frac{\partial}{\partial t}x_r \end{bmatrix} = \begin{bmatrix} \frac{-q_s\,h_c + \Delta_{geb} - q_{fw}\,h_w + h_{fw}\,q_{fw} + Q}{e1} \\ \frac{-h_c\,x_r\,q_{dc} + Q + \Delta_{reb} - e32\,(\frac{\partial}{\partial t}P)}{e33} \end{bmatrix}$$

Finally, we verify that the preceding sections change in state variables has no effect on the derivation of the reduced one-state model. This is intuitively obvious, but easy to check. Begin by assessing the effect of the assumption behind the model reduction on the state variable transformation:

```
> Diff(V[wt],t)=0:
> Diff(V[wd],t) = solve(subs(",eq[dVwt]), Diff(V[wd],t) );
```

$$\frac{\partial}{\partial t}V_{wd} = V_r\left(\frac{\partial}{\partial P}\alpha_r\right)\left(\frac{\partial}{\partial t}P\right) + V_r\,\text{Diff}(\alpha_r, x_r)\left(\frac{\partial}{\partial t}x_r\right)$$

Recall the expressions for the alternate coefficients:

```
> eq[GMBa][2..4];
```

$$e11a = e11, e12a = e12 - e11\left(\frac{\partial}{\partial P}\alpha_r\right)V_r, e13a = -e11\,\text{Diff}(\alpha_r, x_r)\,V_r$$

Substituting and simplifying, we see the alternate first and augmented third states cancel each other out.

```
> subs( ", eq[GMBa][1] ):
> simplify(subs( """, " ));
```

$$e12\left(\frac{\partial}{\partial t}P\right) = q_{fw} - q_s$$

The same result holds for the global energy balance:

```
> Diff(V[wd],t) = solve(subs(Diff(V[wt],t)=0, eq[dVwt]), Diff(V[wd],t) ):
> eq[GEBa][2..4];
```

$$e21a = e21,\, e22a = e22 - e21\left(\frac{\partial}{\partial P}\alpha_r\right)V_r,\, e23a = -e21\,\mathrm{Diff}(\alpha_r, x_r)\,V_r$$

```
> subs( ", eq[GEBa][1] );
```

$$e21\left(\frac{\partial}{\partial t}V_{wd}\right) + \left(e22 - e21\left(\frac{\partial}{\partial P}\alpha_r\right)V_r\right)\left(\frac{\partial}{\partial t}P\right) - e21\,\mathrm{Diff}(\alpha_r, x_r)\left(\frac{\partial}{\partial t}x_r\right)V_r = -h_s\,q_s + h_{fw}\,q_{fw} + \Delta_{geb} + Q$$

```
> simplify(subs( """, " ));
```

$$e22\left(\frac{\partial}{\partial t}P\right) = -h_s\,q_s + h_{fw}\,q_{fw} + \Delta_{geb} + Q$$

Hence, the combination of the two balance will lead to the same result, regardless of the choice for the first state variable.

A.3.7 Iterative Initialization of the Third State

Load procedure definitions for computing multivariate Taylor series expansions.

```
> readlib(mtaylor):
```

Begin by deriving a linear approximation of the non-linear down-comer flow rate relation derived in Section A.3.4. The approximation is obtained by taking a Taylor series expansion in α_r and keeping only the first two terms of the series. The expansion is made about the nominal value $ar0$ which, for simulation purposes, we shall take as the initial value of α_r.

```
> STRIP( eq[q[dc](t)] );
```

$$q_{dc} = \sqrt{2}\sqrt{\frac{\alpha_r\,\rho_{ws}\,V_r}{k_f}}$$

```
> lhs(") = mtaylor(rhs("),alpha[r]=ar0,2);
```

$$q_{dc} = \sqrt{2}\sqrt{\frac{ar0\,\rho_{ws}\,V_r}{k_f}} + \frac{1}{2}\,\frac{\sqrt{2}\sqrt{\frac{ar0\,\rho_{ws}\,V_r}{k_f}}\,(\alpha_r - ar0)}{ar0}$$

For notational purposes, and to facilitate symbolic manipulation, we introduce the following parameterization:

```
> qdc0 = subs(alpha[r]=ar0,rhs(""));
>
```

$$qdc0 = \sqrt{2}\sqrt{\frac{ar0\,\rho_{ws}\,V_r}{k_f}}$$

The linear approximation is thus:

```
> powsubs(REVERSE("),"");
```

$$q_{dc} = qdc0 + \frac{1}{2}\,\frac{(\alpha_r - ar0)\,qdc0}{ar0}$$

The augmented third state equation gives us the following condition for equilibrium:

```
> rhs(eq[sys3])[3,1]:
> subs( Delta[reb]=0, " ) = 0;
```

$$-h_c\, x_r\, q_{dc} + Q = 0$$

In terms of the above approximation we have:

```
> subs(""",");
```

$$-h_c\, x_r \left(qdc0 + \frac{1}{2}\frac{(\alpha_r - ar0)\, qdc0}{ar0} \right) + Q = 0$$

We save this relation for use later. Next, we repeat the above steps in deriving a linear approximation for the nonlinear relationship between α_r and x_r.

```
> tmp := ":
> STRIP(eq[alpha[r](t)]);
```

$$\alpha_r = \frac{\rho_w \ln\left(\frac{\rho_s}{\rho_s + \rho_{ws}\, x_r}\right) \rho_s}{x_r\, {\rho_{ws}}^2} + \frac{\rho_w}{\rho_{ws}}$$

```
> lhs(") = mtaylor(rhs("),x[r]=xr0,2);
```

$$\alpha_r = \frac{\rho_w \ln\left(\frac{\rho_s}{\rho_s + \rho_{ws}\, xr0}\right) \rho_s}{xr0\, {\rho_{ws}}^2} + \frac{\rho_w}{\rho_{ws}} + \frac{\left(-\frac{\rho_w\, \rho_{ws}}{xr0\, (\rho_s + \rho_{ws}\, xr0)} - \frac{\rho_w \ln\left(\frac{\rho_s}{\rho_s + \rho_{ws}\, xr0}\right)}{xr0^2} \right) \rho_s\, (x_r - xr0)}{{\rho_{ws}}^2}$$

```
> ar0 = subs(x[r]=xr0,rhs(""));
```

$$ar0 = \frac{\rho_w \ln\left(\frac{\rho_s}{\rho_s + \rho_{ws}\, xr0}\right) \rho_s}{xr0\, {\rho_{ws}}^2} + \frac{\rho_w}{\rho_{ws}}$$

```
> powsubs(REVERSE("),"");
```

$$\alpha_r = \frac{\rho_w \ln\left(\frac{\rho_s}{\rho_s + \rho_{ws}\, xr0}\right) \rho_s}{xr0\, {\rho_{ws}}^2} + \frac{\rho_w}{\rho_{ws}} + \frac{\left(-\frac{\rho_w\, \rho_{ws}}{xr0\, (\rho_s + \rho_{ws}\, xr0)} - \frac{\rho_w \ln\left(\frac{\rho_s}{\rho_s + \rho_{ws}\, xr0}\right)}{xr0^2} \right) \rho_s\, (x_r - xr0)}{{\rho_{ws}}^2}$$

Note that the substitution in the preceding command failed. Rather than expending time tinkering with Maple, we simply type manually the obvious simplifications:

```
> alpha[r] = ar0 + dardx*(x[r]-xr0);
```

$$\alpha_r = ar0 + dardx\, (x_r - xr0)$$

Combining the two linear approximations in the state equilibrium relationship gives:

```
> subs(",tmp);
```

$$-h_c\, x_r \left(qdc0 + \frac{1}{2}\frac{dardx\, (x_r - xr0)\, qdc0}{ar0} \right) + Q = 0$$

The result of the Taylor series approximations is a quadratic expression in terms of the state

x_r. This we can solve analytically, yielding an expression for the initial state condition x_r^0.

```
> { solve(", x[r]) }:
> xr0 = map(collect,",[qdc0,ar0,xr0]);
```

$$xr0 = \left\{ -\frac{ar0}{dardx} + \frac{1}{2}\,xr0 + \frac{1}{2}\Big(h_c\,qdc0\,(4\,h_c\,qdc0\,ar0^2 - 4\,h_c\,qdc0\,ar0\,dardx\,xr0 + h_c\,qdc0\,dardx^2\,xr0^2 + 8\,dardx\,Q\,ar0)\Big)^{1/2} \Big/ (h_c\,dardx\,qdc0),\; -\frac{ar0}{dardx} + \frac{1}{2}\,xr0 - \frac{1}{2}\Big(h_c\,qdc0\,(4\,h_c\,qdc0\,ar0^2 - 4\,h_c\,qdc0\,ar0\,dardx\,xr0 + h_c\,qdc0\,dardx^2\,xr0^2 + 8\,dardx\,Q\,ar0)\Big)^{1/2} \Big/ (h_c\,dardx\,qdc0) \right\}$$

Using OMSIM, we determined that the first of the two solutions is the correct form to base an iterative initialization upon. Iteration is necessary because the right hand side of the quadratic solution depends upon x_r^0. To facilitate programming the iteration in OMOLA, we make the following variable changes and then print out the equation in a textual format that we "clip and paste" into the OMOLA model definition; see Listing B.22 on page 76.

```
> subs(ar0=ar,h[c]=hc,qdc0=qdc,rhs(")[1]);
```

$$-\frac{ar}{dardx} + \frac{1}{2}\,xr0 + \frac{1}{2}(hc\,qdc\,(4\,hc\,qdc\,ar^2 - 4\,hc\,qdc\,ar\,dardx\,xr0 + hc\,qdc\,dardx^2\,xr0^2 + 8\,dardx\,Q\,ar))^{1/2}/(hc\,dardx\,qdc)$$

```
> lprint(");
-1/dardx*ar+1/2*xr0+1/2/hc/dardx*(hc*qdc*(4*hc*qdc*ar^2
-4*hc*qdc*ar*dardx*xr0+hc*qdc*dardx^2*xr0^2+8*dardx*Q*ar))^(1/2)/qdc
> save eq, 'Third.Order.mpl':
```

A.4 Fourth Order Structure

```
> restart:
> with(linalg):
> with(student):
> REVERSE := eqn -> rhs(eqn) = lhs(eqn):
> STRIP := eqn->subs(map(f->f=op(0,f),indets(eqn,anyfunc(string))),eqn):
> read 'Third.Order.mpl':
> Diff(rho[s](t)*V[sd](t) + rho[w](t)*V[wd](t),t) =
> q[r](t) - q[sd](t) + q[fw](t) - q[dc](t);
```

$$\frac{\partial}{\partial t}\left(\rho_s(t)\,V_{sd}(t) + \rho_w(t)\,V_{wd}(t)\right) = q_r(t) - q_{sd}(t) + q_{fw}(t) - q_{dc}(t)$$

```
> Diff( rho[s](t)*u[s](t)*V[sd](t) +
>       rho[w](t)*u[w](t)*V[wd](t) + m[sd]*C[p]*T[sat](t), t) =
> h[r](t)*q[r](t) - h[s](t)*q[sd](t) + h[fw](t)*q[fw](t) - h[w](t)*q[dc](t) +
> Delta[IV];
```

$$\frac{\partial}{\partial t}\left(\rho_s(t)\,u_s(t)\,V_{sd}(t) + \rho_w(t)\,u_w(t)\,V_{wd}(t) + m_{sd}\,C_p\,T_{sat}(t)\right) = h_r(t)\,q_r(t) - h_s(t)\,q_{sd}(t) + h_{fw}(t)\,q_{fw}(t) - h_w(t)\,q_{dc}(t) + \Delta_{IV}$$

```
> simplify( " - h[w](t)*"" );
```

$$\left(\frac{\partial}{\partial t}\left(\rho_s(t)\,u_s(t)\,V_{sd}(t) + \rho_w(t)\,u_w(t)\,V_{wd}(t) + m_{sd}\,C_p\,T_{sat}(t)\right)\right) - h_w(t)\left(\frac{\partial}{\partial t}\left(\rho_s(t)\,V_{sd}(t) + \rho_w(t)\,V_{wd}(t)\right)\right) = h_r(t)\,q_r(t) - h_s(t)\,q_{sd}(t) + h_{fw}(t)\,q_{fw}(t) + \Delta_{IV} - h_w(t)\,q_r(t) + h_w(t)\,q_{sd}(t) - h_w(t)\,q_{fw}(t)$$

```
> subs( eq[u], " ):
> h[r](t) = h[w](t) + h[c](t)*x[r](t);
```

$$h_r(t) = h_w(t) + h_c(t)\,x_r(t)$$

```
> simplify( subs( ", "" )):
> collect(", [q[sd](t),q[fw](t)]):
> changevar(-h[s](t)+h[w](t)=-h[c](t),"):
> collect(", [h[c](t),q[fw](t)]):
> changevar(-q[sd](t)+q[r](t)*x[r](t)=-rho[s](t)*dV[sd](t)/tau[sd],");
```

$$\left(\frac{\partial}{\partial t}\left(V_{sd}(t)\,h_s(t)\,\rho_s(t) - V_{sd}(t)\,\mathrm{P}(t) + V_{wd}(t)\,h_w(t)\,\rho_w(t) - V_{wd}(t)\,\mathrm{P}(t) + m_{sd}\,C_p\,T_{sat}(t)\right)\right) - h_w(t)\left(\frac{\partial}{\partial t}\left(\rho_s(t)\,V_{sd}(t) + \rho_w(t)\,V_{wd}(t)\right)\right) = -\frac{\rho_s(t)\,dV_{sd}(t)\,h_c(t)}{\tau_{sd}} + (-h_w(t) + h_{fw}(t))\,q_{fw}(t) + \Delta_{IV}$$

```
> simplify(value("));
```

$$\left(\frac{\partial}{\partial t}V_{sd}(t)\right)h_s(t)\,\rho_s(t) + V_{sd}(t)\left(\frac{\partial}{\partial t}h_s(t)\right)\rho_s(t) + V_{sd}(t)\,h_s(t)\left(\frac{\partial}{\partial t}\rho_s(t)\right) - \left(\frac{\partial}{\partial t}V_{sd}(t)\right)\mathrm{P}(t) - V_{sd}(t)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right) + V_{wd}(t)\left(\frac{\partial}{\partial t}h_w(t)\right)\rho_w(t) - \left(\frac{\partial}{\partial t}V_{wd}(t)\right)\mathrm{P}(t) - V_{wd}(t)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right) + m_{sd}\,C_p\left(\frac{\partial}{\partial t}T_{sat}(t)\right) - h_w(t)\left(\frac{\partial}{\partial t}\rho_s(t)\right)V_{sd}(t) - h_w(t)\,\rho_s(t)\left(\frac{\partial}{\partial t}V_{sd}(t)\right) = -\frac{\rho_s(t)\,dV_{sd}(t)\,h_c(t) + q_{fw}(t)\,\tau_{sd}\,h_w(t) - q_{fw}(t)\,\tau_{sd}\,h_{fw}(t) - \Delta_{IV}\,\tau_{sd}}{\tau_{sd}}$$

```
> subs(eq[Vwr],eq[Vwd]);
```

$$V_{wd}(t) = V_{wt}(t) - V_{dc} - (1 - \alpha_r(t))\,V_r$$

```
> diff(",t);
```

$$\frac{\partial}{\partial t}V_{wd}(t) = \left(\frac{\partial}{\partial t}V_{wt}(t)\right) + \left(\frac{\partial}{\partial t}\alpha_r(t)\right)V_r$$

```
> subs(",""");
```

$$\left(\frac{\partial}{\partial t}V_{sd}(t)\right)h_s(t)\,\rho_s(t) + V_{sd}(t)\left(\frac{\partial}{\partial t}h_s(t)\right)\rho_s(t) + V_{sd}(t)\,h_s(t)\left(\frac{\partial}{\partial t}\rho_s(t)\right) - \left(\frac{\partial}{\partial t}V_{sd}(t)\right)\mathrm{P}(t) - V_{sd}(t)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right) + V_{wd}(t)\left(\frac{\partial}{\partial t}h_w(t)\right)\rho_w(t) - \left(\left(\frac{\partial}{\partial t}V_{wt}(t)\right) + \left(\frac{\partial}{\partial t}\alpha_r(t)\right)V_r\right)\mathrm{P}(t) - V_{wd}(t)\left(\frac{\partial}{\partial t}\mathrm{P}(t)\right) + m_{sd}\,C_p\left(\frac{\partial}{\partial t}T_{sat}(t)\right) - h_w(t)\left(\frac{\partial}{\partial t}\rho_s(t)\right)V_{sd}(t) - h_w(t)\,\rho_s(t)\left(\frac{\partial}{\partial t}V_{sd}(t)\right) = -\frac{\rho_s(t)\,dV_{sd}(t)\,h_c(t) + q_{fw}(t)\,\tau_{sd}\,h_w(t) - q_{fw}(t)\,\tau_{sd}\,h_{fw}(t) - \Delta_{IV}\,\tau_{sd}}{\tau_{sd}}$$

```
> subs(diff( h[s](t),t)       = Diff( h[s],P)*Diff(P,t),
>       diff( h[w](t),t)      = Diff( h[w],P)*Diff(P,t),
>       diff(rho[s](t),t)     = Diff(rho[s],P)*Diff(P,t),
>       diff(T[sat](t),t)     = Diff(T[sat],P)*Diff(P,t),
>       diff(alpha[r](t),t)   = Diff(alpha[r],P)*Diff(P,t)
>                             + Diff(alpha[r],x[r])*Diff(x[r],t),
>
>       diff(V[sd](t),t)      = Diff(V[sd],t),
>       diff(V[wt](t),t)      = Diff(V[wt],t),
>       diff(P(t),t)          = Diff(P,t), " );
```

$$\left(\frac{\partial}{\partial t}V_{sd}\right) h_s(t)\,\rho_s(t) + V_{sd}(t)\left(\frac{\partial}{\partial P}h_s\right)\left(\frac{\partial}{\partial t}P\right)\rho_s(t) + V_{sd}(t)\,h_s(t)\left(\frac{\partial}{\partial P}\rho_s\right)\left(\frac{\partial}{\partial t}P\right)$$
$$-\left(\frac{\partial}{\partial t}V_{sd}\right)\mathrm{P}(t) - V_{sd}(t)\left(\frac{\partial}{\partial t}P\right) + V_{wd}(t)\left(\frac{\partial}{\partial P}h_w\right)\left(\frac{\partial}{\partial t}P\right)\rho_w(t)$$
$$-\left(\left(\frac{\partial}{\partial t}V_{wt}\right) + \left(\left(\frac{\partial}{\partial P}\alpha_r\right)\left(\frac{\partial}{\partial t}P\right) + \mathrm{Diff}\,(\alpha_r, x_r)\left(\frac{\partial}{\partial t}x_r\right)\right)V_r\right)\mathrm{P}(t) - V_{wd}(t)\left(\frac{\partial}{\partial t}P\right)$$
$$+ m_{sd}\,C_p\left(\frac{\partial}{\partial P}T_{sat}\right)\left(\frac{\partial}{\partial t}P\right) - h_w(t)\left(\frac{\partial}{\partial P}\rho_s\right)\left(\frac{\partial}{\partial t}P\right)V_{sd}(t) - h_w(t)\,\rho_s(t)\left(\frac{\partial}{\partial t}V_{sd}\right) =$$
$$-\frac{\rho_s(t)\,dV_{sd}(t)\,h_c(t) + q_{fw}(t)\,\tau_{sd}\,h_w(t) - q_{fw}(t)\,\tau_{sd}\,h_{fw}(t) - \Delta_{IV}\,\tau_{sd}}{\tau_{sd}}$$

```
> collect( ", [Diff(V[wt],t), Diff(P,t), Diff(x[r],t), Diff(V[sd],t),
>              V[sd](t), Diff(rho[s],P), rho[s](t), V[wd](t),
>              tau[sd], q[fw](t)]):
> changevar( h[s](t)-h[w](t)=h[c](t), " ):
> simplify( "/rho[s](t)/h[c](t) ):
> collect( ", [Diff(V[wt],t), Diff(P,t), Diff(x[r],t), Diff(V[sd],t),
>              V[sd](t), Diff(rho[s],P), rho[s](t), V[wd](t),
>              tau[sd], q[fw](t)]):
> eq[cvIV] := ":
> e42 = STRIP( coeff(lhs(eq[cvIV]), Diff(P,t) ) );
```

$$e42 = \left(\frac{\frac{\partial}{\partial P}\rho_s}{\rho_s} + \frac{\frac{\partial}{\partial P}h_s}{h_c} - \frac{1}{\rho_s\,h_c}\right)V_{sd} + \frac{\frac{\left(\rho_w\left(\frac{\partial}{\partial P}h_w\right) - 1\right)V_{wd}}{h_c} + \frac{m_{sd}\,C_p\left(\frac{\partial}{\partial P}T_{sat}\right) - \left(\frac{\partial}{\partial P}\alpha_r\right)V_r\,P}{h_c}}{\rho_s}$$

```
> powsubs( REVERSE("), STRIP( eq[cvIV] ) ):
> e43 = STRIP( coeff(lhs(eq[cvIV]), Diff(x[r],t) ) );
```

$$e43 = -\frac{\mathrm{Diff}\,(\alpha_r, x_r)\,V_r\,P}{h_c\,\rho_s}$$

```
> powsubs( REVERSE("), "" ):
> e44 = STRIP( coeff(lhs(eq[cvIV]), Diff(V[sd],t) ) );
```

$$e44 = 1 - \frac{P}{h_c\,\rho_s}$$

```
> powsubs( REVERSE("), "" ):
> e41 = STRIP( coeff(lhs(eq[cvIV]), Diff(V[wt],t) ) );
```

$$e41 = -\frac{P}{h_c\,\rho_s}$$

```
> powsubs( REVERSE("), "" );
```

$$\left(\frac{\partial}{\partial t} V_{wt}\right) e41 + e42 \left(\frac{\partial}{\partial t} P\right) + \left(\frac{\partial}{\partial t} x_r\right) e43 + e44 \left(\frac{\partial}{\partial t} V_{sd}\right) =$$

$$-\frac{dV_{sd}}{\tau_{sd}} + \frac{-\frac{(h_w - h_{fw})\, q_{fw}}{h_c} + \frac{\Delta_{IV}}{h_c}}{\rho_s}$$

Appendix B

Omola Definitions

B.1 Library Definitions

```
LIBRARY DrumBoiler;
USES k2db, K2TerminalLib;
USES Std, StdComp;
%% $Id: library.ol,v 1.18 1997/10/06 19:39:59 sorliej Exp $

MatrixVar ISA Std::MatrixVar WITH
  EPS TYPE STATIC Real := 2^(-52); %% IEEE floating point
  abs    TYPE Matrix [m,n] := abs(value);
  logabs TYPE Matrix [m,n] := ln(abs(value+EPS*ones(m,n)))/ln(10);
  rowsum TYPE Column [m];
  colsum TYPE Row    [n];
  rowsum = value*ones(n,1);
  colsum = ones(1,m)*value;
END;

VectorVar ISA Std::VectorVar WITH
  EPS TYPE STATIC Real := 2^(-52); %% IEEE floating point
  abs    TYPE Column[n] := abs(value);
  logabs TYPE Column[n] := ln(abs(value+EPS*ones(n,1)))/ln(10);
  sum    TYPE Real;
  sum = ones(1,n)*value;
END;

TimeDelay ISA Variable WITH
  u, T ISA Variable;
  x ISA Std::VectorVar;
END;

PureDelay ISA TimeDelay WITH
  %% Utilize OmSim's built-in function.  Note the continuous-discrete
  %% equations that result CANNOT be loaded into Maple for code generation.
  value := delay(u,T,u);
  x.n := 0;
END;

Pade01 ISA TimeDelay WITH
  %% Implements the Pade(0,1) approximation of a pure time delay:
  %%
  %%    Y(s)                      Y(s)      1
  %%    ---- = exp(-s*T)   ==>    ---- = -------
  %%    U(s)                      U(s)   1 + s*T
  %%
  x.n := 1;
equations:
  x + T*x' = u;
  value := x;
initialization:
  Init, ReInit ISAN Event;
  OnEvent Init DO
    new(x) := u;          % Initialize state assuming an equilibrium state.
    schedule(ReInit,0.0); % Fire immediately after OmSim's init-solver.
  END;
```

Listing B.1: library.ol—Base definitions used in much of the model library.

```
    OnEvent ReInit DO
      new(x) := u;          % Re-initialize with a non-zero input.
    END;
  END;
  Pade11 ISA TimeDelay WITH
    %% Implement the Pade(1,1) approximation of a pure time delay:
    %%
    %%    Y(s)                   Y(s)   1 - s*T/2      2
    %%    ---- = exp(-s*T)  ==>  ---- = --------- = --------- - 1
    %%    U(s)                   U(s)   1 + s*T/2   1 + s*T/2
    x.n := 1;
  equations:
    x + T/2*x' = 2*u;
    value := x - u;
  initialization:
    Init, ReInit ISAN Event;
    OnEvent Init DO
      new(x) := 2*u;        % Initialize state assuming an equilibrium state.
      schedule(ReInit,0.0); % Fire immediately after OmSim's init-solver.
    END;
    OnEvent ReInit DO
      new(x) := 2*u;        % Re-initialize with a non-zero input.
    END;
  END;
  Pade12 ISA TimeDelay WITH
    %% Implement the Pade(1,2) approximation of a pure time delay:
    %%
    %%    Y(s)                   Y(s)         3 - s*T             Z(s) X(s)
    %%    ---- = exp(-s*T)  ==>  ---- = --------------------- = ----*----
    %%    U(s)                   U(s)   3 + 2*s*T + (s*T)^2/2     X(s) U(s)
    %%
    %%          Z(s)                   X(s)            1
    %% where    ---- = 3 - s*T   and   ---- = ---------------------
    %%          X(s)                   U(s)   3 + 2*s*T + (s*T)^2/2
    x.n := 2;
  equations:
          x[1]' = x[2];
    T^2/2*x[2]' = u - 3*x[1] - 2*T*x[2];
    value := 3*x[1] - T*x[2];
  initialization:
    Init, ReInit ISAN Event;
    OnEvent Init DO
  %   new(x) := [u/3;0];    % Initialize state assuming an equilibrium state.
      schedule(ReInit,0.0); % Fire immediately after OmSim's init-solver.
    END;
    OnEvent ReInit DO
      new(x) := [u/3;0];    % Re-initialize with a non-zero input.
    END;
  END;
  Pade22 ISA TimeDelay WITH
    %% Implement the Pade(2,2) approximation of a pure time delay:
    %%
    %%    Y(s)                   Y(s)   1 - s*T/2 + (s*T)^2/12       Z(s) X(s)
    %%    ---- = exp(-s*T)  ==>  ---- = ---------------------- = 1 - ----*----
    %%    U(s)                   U(s)   1 + s*T/2 + (s*T)^2/12       X(s) U(s)
    %%
    %%          Z(s)               X(s)            1
    %% where    ---- = s*T   and   ---- = ----------------------
    %%          X(s)               U(s)   1 + s*T/2 + (s*T)^2/12
    x.n := 2;
  equations:
           x[1]' = x[2];
    T^2/12*x[2]' = u - x[1] - T/2*x[2];
    value := u - T*x[2];
  initialization:
    Init, ReInit ISAN Event;
    OnEvent Init DO
      new(x) := [u;0];      % Initialize state assuming an equilibrium state.
      schedule(ReInit,0.0); % Fire immediately after OmSim's init-solver.
    END;
    OnEvent ReInit DO
      new(x) := [u;0];      % Re-initialize with a non-zero input.
    END;
  END;
```

Listing B.1: library.ol (*continued*).

```
BoilerIC ISA Model WITH
%% $Id: BoilerIC.om,v 1.7 1997/06/27 08:29:36 sorliej Exp $

  Graphic ISA Super::Graphic WITH
    bitmap TYPE String := "BoilerIC"; x_pos := 200; y_pos := 175;
  END;

  Q ISA SimpleTerminal WITH
    Graphic ISA Super::Graphic WITH
      x_pos := 0.0;
      y_pos := 150.0;
    END;
  END;

  Water ISA K2TerminalLib::FlowInTC WITH
    Graphic ISA Super::Graphic WITH
      x_pos := 200.0;
      y_pos := 300.0;
    END;
    p.unit := "MPa";
    M ISA K2TerminalLib::SteamMediumTC WITH Q := 'Water; END;
  END;

  Steam ISA K2TerminalLib::FlowOutTC WITH
    Graphic ISA Super::Graphic WITH
      x_pos := 400.0;
      y_pos := 225.0;
    END;
    p.unit := "MPa";
    M ISA K2TerminalLib::SteamMediumTC WITH
      Q := 'Steam;
      z ISA K2TerminalLib::HeightTC;
    END;
  END;

  Disturbance ISA RecordTerminal WITH
    Graphic ISA Super::Graphic WITH
      x_pos := 200.0;
      y_pos := 0.0;
    END;
    V1, V2, V3 ISA SimpleInput;
  END;
END;
```

Listing B.2: BoilerIC.om—Interface class definition for the drum boiler flow model.

```
BoundedVariableGain ISA Base::Model WITH
%% $Id: BoundedVariableGain.om,v 1.2 1997/06/27 08:53:58 sorliej Exp $

  % The output equals the nominal "value" and,
  % depending on the input, may vary upto plus
  % or minus 1/2 the specified "range".
  Graphic ISA Super::Graphic WITH
    bitmap TYPE String := "BoundedVariableGain";
  END;
terminals:
  T1 ISA Base::SimpleInput WITH
    Graphic ISA Super::Graphic WITH x_pos:=  0; y_pos:=150; invisible:=1; END;
  END;
  T2 ISA Base::SimpleOutput WITH
    Graphic ISA Super::Graphic WITH x_pos:=400; y_pos:=150; invisible:=1; END;
  END;
variables:
  nominal, range ISA Base::Parameter;
  Pi TYPE STATIC Real := atan2(0,-1);
equations:
  T2 = nominal + range*atan(T1)/Pi;
END;
```

Listing B.3: BoundedVariableGain.om—Definition of a bounded smooth nonlinear gain block.

```
LowPassFilter ISA Base::Model WITH
%% $Id: LowPassFilter.om,v 1.2 1997/06/27 08:54:29 sorliej Exp $
  Graphic ISA super::Graphic WITH bitmap TYPE String := "LowPassFilter"; END;
terminals:
  T1 ISA Base::SimpleInput WITH
    Graphic ISA super::Graphic WITH invisible:=1; x_pos:=0; y_pos:=150; END;
  END;
  T2 ISA Base::SimpleOutput WITH
    Graphic ISA super::Graphic WITH invisible:=1; x_pos:=400; y_pos:=150; END;
  END;
parameter:
  omega ISA Base::Parameter WITH
    default := 1.0; % Bandwidth equals the inverse of the filter time constant
  END;
variables:
  x   ISA Base::Variable;
  dW  TYPE Real;
connections:
  T1 = dW;
  T2 = x;
equations:
  x' + omega*x = sqrt(2*omega)*dW;  % scaled for unit variance
END;
```

Listing B.4: LowPassFilter.om—A first-order low pass filter block.

```
ProductJunction ISA Base::Model WITH
%% $Id: ProductJunction.om,v 1.2 1997/06/27 08:55:05 sorliej Exp $
  Graphic ISA super::Graphic WITH
    bitmap TYPE String := "ProductJunction";
  END;
terminals:
  T1 ISA Base::SimpleInput WITH
    Graphic ISA super::Graphic WITH
      x_pos :=   0; y_pos := 150; invisible := 1;
    END;
  END;
  T2 ISA Base::SimpleInput WITH
    Graphic ISA super::Graphic WITH
      x_pos := 200; y_pos :=   0; invisible := 1;
    END;
  END;
  T3 ISA Base::SimpleOutput WITH
    Graphic ISA super::Graphic WITH
      x_pos := 400; y_pos := 150; invisible := 1;
    END;
  END;
equation:
  T3 = T1*T2;
END;
```

Listing B.5: ProductJunction.om—A scalar signal multiplier block.

```
StaticGain ISA StdComp::StaticGain WITH
%% $Id: StaticGain.om,v 1.2 1997/06/27 09:02:58 sorliej Exp $
  Graphic ISA Super::Graphic WITH
    bitmap TYPE String := "StaticGain";
  END;
  T1 ISA Super::T1 WITH
    Graphic ISA Super::Graphic WITH invisible := 1; END;
  END;
  T2 ISA Super::T2 WITH
    Graphic ISA Super::Graphic WITH invisible := 1; END;
  END;
END;
```

Listing B.6: StaticGain.om—A constant linear gain block.

```
SumJunction ISA Base::Model WITH
%% $Id: SumJunction.om,v 1.2 1997/06/27 09:07:46 sorliej Exp $
  Graphic ISA super::Graphic WITH
    bitmap TYPE String := "SumJunction";
  END;
 terminals:
  u1 ISA Base::SimpleInput WITH
    Graphic ISA super::Graphic WITH
      x_pos :=   0.0; y_pos := 200.0; invisible := 1;
    END;
  END;
  u2 ISA Base::SimpleInput WITH
    Graphic ISA super::Graphic WITH
      x_pos :=   0.0; y_pos := 100.0; invisible := 1;
    END;
  END;
  y ISA Base::SimpleOutput WITH
    Graphic ISA super::Graphic WITH
      x_pos := 400.0; y_pos := 150.0; invisible := 1;
    END;
  END;
 equation:
  y := u1 + u2;
END;
```

Listing B.7: SumJunction.om—A scalar signal summer block.

```
WienerProcess ISA Base::Model WITH
%% $Id: WienerProcess.om,v 1.2 1997/06/27 09:03:29 sorliej Exp $
  Graphic ISA super::Graphic WITH bitmap TYPE String := "WienerProcess"; END;
terminals:
  T1 ISA Base::SimpleInput WITH
    Graphic ISA super::Graphic WITH invisible:=1; x_pos:=0; y_pos:=150; END;
  END;
  T2 ISA Base::SimpleOutput WITH
    Graphic ISA super::Graphic WITH invisible:=1; x_pos:=400; y_pos:=150; END;
  END;
variables:
  W, dW ISA Base::Variable;
connections:
  T1 = dW;
  T2 = W;
equations:
  W' = dW;
END;
```

Listing B.8: WienerProcess.om—A pure integration which, mathematically, yields a Wiener process if driven by continuous-time white Gaussian noise.

```
SignalModelMapping ISA Base::Model WITH
%% $Id: SignalModelMapping.om,v 1.6 1997/06/27 09:01:46 sorliej Exp $
  Graphic ISA super::Graphic WITH
    bitmap TYPE String := "SignalModelMapping"; x_pos := 250; y_pos := 300;
  END;

input_signals:
  U, U0, Wv, Wy ISA Std::VectorVar;

state_signals:
  X ISA Std::VectorVar;

output_signals:
  Y ISA Std::VectorVar;

data_store:
  PM ISA Std::MatrixVar; % parameter map
  NaN ISA Parameter;     % dummy name for indicating unused elements in PM
END;
```

Listing B.9: SignalModelMapping.om—The parameterized signal model names used in equation export to Maple.

```
SaturationMM ISA Base::Model WITH
%% A medium model describing the thermodynamic
%%   properties of saturated water/steam.
%% Author      : Jonas Eborn
%% Assumptions : medium state is pressure.
%% States      : static
%% Model use   : inside boiler models
%% Model type  : medium model. (Saturated Water/Steam)
%% Units       : pressure    [MPa]    (10 bar = 1 MPa, 1 Pa = 1 N/m2)
%%             : density     [kg/m3]  (1 kg/m3 = 1e3 g/cm3)
%%             : enthalpy    [MJ/kg]
%%             : temperature [degC]
%%  $Id: SaturationMM.om,v 1.10 1997/06/27 08:56:49 sorliej Exp $
icon:
  Graphic ISA super::Graphic WITH
    bitmap TYPE String := "SaturationMM";
    x_pos := 300;
    y_pos := 150;
  END;
terminals:
  Min ISA Base::RecordTerminal WITH
    Graphic ISA super::Graphic WITH x_pos :=   0.0; y_pos := 150.0; END;
    p      ISA K2TerminalLib::PressureTC;
  END;
  Mout ISA Base::RecordTerminal WITH
    Graphic ISA super::Graphic WITH x_pos := 400.0; y_pos := 150.0; END;
    hs, hw ISA K2TerminalLib::EnthalpyTC;
    rs, rw ISA Base::SimpleTerminal;
    Ts     ISA K2TerminalLib::TemperatureTC;
    dhsdp, dhwdp, drsdp, drwdp, dTsdp ISA Base::SimpleTerminal;
  END;
parameters:
  a01 TYPE STATIC Real := 2.7254E6;
  a11 TYPE STATIC Real := -1.8992E4;
  a21 TYPE STATIC Real := -1160.0;

  a02 TYPE STATIC Real := 53.1402;
  a12 TYPE STATIC Real := 7.673;
  a22 TYPE STATIC Real := 0.36;

  a03 TYPE STATIC Real := 1.4035E6;
  a13 TYPE STATIC Real := 4.9339E4;
  a23 TYPE STATIC Real := -880.0;

  a04 TYPE STATIC Real := 691.35;
  a14 TYPE STATIC Real := -18.672;
  a24 TYPE STATIC Real := -0.0603;

  a05 TYPE STATIC Real := 310.6;
  a15 TYPE STATIC Real := 8.523;
  a25 TYPE STATIC Real := -0.33;
equations:
  Mout.hs = a01+(a11+a21*(Min.p-10))*(Min.p-10);
  Mout.dhsdp = a11+2*a21*(Min.p-10);

  Mout.rs = a02+(a12+a22*(Min.p-10))*(Min.p-10);
  Mout.drsdp = a12+2*a22*(Min.p-10);

  Mout.hw = a03+(a13+a23*(Min.p-10))*(Min.p-10);
  Mout.dhwdp = a13+2*a23*(Min.p-10);

  Mout.rw = a04+(a14+a24*(Min.p-10))*(Min.p-10);
  Mout.drwdp = a14+2*a24*(Min.p-10);

  Mout.ts = a05+(a15+a25*(Min.p-10))*(Min.p-10);
  Mout.dtsdp = a15+2*a25*(Min.p-10);
END;
```

Listing B.10: SaturationMM.om—Medium model containing the thermodynamic properties of saturated water at a given pressure.

```
OresundSimIC ISA Model WITH
%%  $Id: OresundSimIC.om,v 1.13 1997/06/27 08:36:52 sorliej Exp $
  Graphic ISA Super::Graphic WITH y_size := 305; END;
boiler_model:
  Boiler ISA DrumBoiler::BoilerIC WITH
    Graphic ISA Super::Graphic WITH x_pos := 200; y_pos := 175; END;
  END;
read_file_inputs:
  FeedWaterFlow,
  FuelFlow,
  SteamFlow1,
  SteamFlow2,
  FeedWaterTemp ISA ContinuousInput; % measured inputs
  ContinuousWhiteNoise1,
  ContinuousWhiteNoise2,
  ContinuousWhiteNoise3,
  ContinuousWhiteNoise4 ISA ContinuousInput; % exogenous inputs (dynamics)
  DiscreteWhiteNoise1,
  DiscreteWhiteNoise2   ISA ContinuousInput; % exogenous inputs (measurments)
read_file_outputs:
  DrumPressure,
  DrumLevel      ISA ContinuousInput; % for output-error calculations
parameters:
  qscf, qfwcf, qfcf, qfrng, pcf, dlcf         ISA Parameter;
  Tcf, sigma1, sigma2, sigma3, sigma4, sigma5 ISA Parameter;
  qs10, qs20, qfw0, tfw0, qf0                 ISA Parameter;
parameterization:
  qscf.default   := 0.253;    % Experiment J, F, G:  0.253,    0.2528,  0.253
                              %             E, A, B:  0.2549,   0.2548,  0.2688
  qfwcf          := 1e3/3600; % [t/hr]->[kg/s], except Exp. A = 0.2764
  qfcf.default   := 6.205; % [t/hr]->[MW] Exp's J, F, G:  6.205, 6.11,  6.035
  qfrng.default  := 0.5;   %                     E, A, B:  5.61,  5.612, 5.648
  pcf            := 0.08;  % [kg/cm2] -> [MPa]
  dlcf           := 1e-3;
  Tcf.default    := 100;
  sigma1.default := 0;
  sigma2.default := 0;
  sigma3.default := 0;
  sigma4.default := 0;
  qs10.default   := 125;
  qs20.default   := 125;
  qfw0.default   := 250; % initial equilibrium state requires q_fw == q_s
  tfw0.default   := 240;
  qf0.default    := 17.2;
variables:
  OutputError ISA Std::VectorVar WITH
    n := 2;
    value := [dp - DrumPressure; dl - DrumLevel];
  END;
initialization:
  Init ISAN Event;
  OnEvent Init DO
    new(LPF1.x)  := 0;
    new(Wp1.W)   := 0;
    new(Wp2.W)   := 0;
    new(Wp3.W)   := 0;
  END;
measured_input_terminals:
  qs1 ISA SimpleInput WITH
    Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos := 276; END;
    value := SteamFlow1;
    default := qs10;
  END;
  qs2 ISA SimpleInput WITH
    Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos := 251; END;
    value := SteamFlow2;
    default := qs20;
  END;
  qfw ISA SimpleInput WITH
    Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos := 226; END;
    value := FeedWaterFlow;
    default := qfw0;
  END;
```

Listing B.11: OresundSimIC.om—The simulation interface to the experimental data, including stochastic input and output error modeling.

```
      Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos := 201; END;
      value := FeedWaterTemp;
      quantity := "thermodynamic.temperature";
      unit := "K";
      default := tfw0;
    END;
    qf ISA SimpleInput WITH
      Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos := 176; END;
      value := FuelFlow;
      default := qf0;
    END;
  continuous_Gaussian_noise_input_terminals:
    CN1 ISA SimpleInput WITH
      Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos := 150; END;
      value := ContinuousWhiteNoise1;
    END;
    CN2 ISA SimpleInput WITH
      Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos := 125; END;
      value := ContinuousWhiteNoise2;
    END;
    CN3 ISA SimpleInput WITH
      Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos := 100; END;
      value := ContinuousWhiteNoise3;
    END;
    CN4 ISA SimpleInput WITH
      Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos :=  75; END;
      value := ContinuousWhiteNoise3;
    END;
  discrete_Gaussian_noise_input_terminals:
    DN1 ISA SimpleInput WITH
      Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos :=  50; END;
      value := DiscreteWhiteNoise1;
    END;
    DN2 ISA SimpleInput WITH
      Graphic ISA Super::Graphic WITH x_pos :=   0; y_pos :=  25; END;
      value := DiscreteWhiteNoise2;
    END;
  measured_output_terminals:
    dp ISA SimpleOutput WITH
      Graphic ISA Super::Graphic WITH x_pos := 400; y_pos := 176; END;
    END;
    dl ISA SimpleOutput WITH
      Graphic ISA Super::Graphic WITH x_pos := 400; y_pos := 150; END;
    END;
  junctions:
    Sum1 ISA DrumBoiler::SumJunction WITH
      Graphic ISA Super::Graphic WITH x_pos :=  50; y_pos := 254; END;
    END;
    Sum2 ISA DrumBoiler::SumJunction WITH
      Graphic ISA Super::Graphic WITH x_pos := 350; y_pos := 175; END;
    END;
    Sum3 ISA DrumBoiler::SumJunction WITH
      Graphic ISA Super::Graphic WITH x_pos := 350; y_pos := 150; END;
    END;
    Prod1 ISA DrumBoiler::ProductJunction WITH
      Graphic ISA Super::Graphic WITH x_pos := 125; y_pos := 175; END;
    END;
  input_conversion_factors:
    SG1 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH x_pos :=  75; y_pos := 254; END;
      T2 ISA K2TerminalLib::MassFlowTC WITH
         Graphic ISA Super::Graphic WITH
          invisible := 1; x_pos := 400; y_pos := 150;
        END;
      END;
      K := qscf; % Steam FlowRate Conversion Factor
    END;
    SG2 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH x_pos :=  75; y_pos := 225; END;
      T2 ISA K2TerminalLib::MassFlowOutTC WITH
         Graphic ISA Super::Graphic WITH
          invisible := 1; x_pos := 400; y_pos := 150;
```

Listing B.11: OresundSimIC.om (*continued*).

```
        END;
      END;
      K := qfwcf; % FeedWater Flowrate Conversion Factor (t/hr -> kg/s)
    END;
    BVG1 ISA DrumBoiler::BoundedVariableGain WITH
      Graphic ISA Super::Graphic WITH x_pos := 100; y_pos := 150; END;
      nominal := qfcf*1e6; % Fuel FlowRate Conversion Factor (t/hr -> MW)
      range := qfrng*1e6; % Range of Variation (peak-to-peak)
    END;
  output_conversion_factors:
    SG3 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH x_pos := 290; y_pos := 179; END;
      T1 ISA K2TerminalLib::PressureTC WITH
        Graphic ISA Super::Graphic WITH
          invisible := 1; x_pos :=   0; y_pos := 150;
        END;
      END;
      K := 1/pcf; % Inverse Drum Pressure Conversion Factor (MPa -> kg/cm2)
    END;
    SG4 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH x_pos := 290; y_pos := 154; END;
      T1 ISA K2TerminalLib::HeightTC WITH
         Graphic ISA Super::Graphic WITH
          invisible := 1; x_pos :=   0; y_pos := 150;
        END;
      END;
      K := 1/dlcf; % Inverse Drum Level Conversion Factor
    END;
    LPF1 ISA DrumBoiler::LowPassFilter WITH
      Graphic ISA Super::Graphic WITH x_pos :=  50; y_pos := 150; END;
      omega := 1/Tcf; % Time Constant of variation (inverse of filter bandwidth)
    END;
    Wp1 ISA DrumBoiler::WienerProcess WITH
      Graphic ISA Super::Graphic WITH x_pos :=  50; y_pos := 125; END;
    END;
    Wp2 ISA DrumBoiler::WienerProcess WITH
      Graphic ISA Super::Graphic WITH x_pos :=  50; y_pos := 100; END;
    END;
    Wp3 ISA DrumBoiler::WienerProcess WITH
      Graphic ISA Super::Graphic WITH x_pos :=  50; y_pos :=  75; END;
    END;
    SG5 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH
        bitmap TYPE String := "StaticGain.sigma"; x_pos := 100; y_pos := 125;
      END;
      K := sigma1; % Std. Deviation of State Disturbance 1
    END;
    SG6 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH
        bitmap TYPE String := "StaticGain.sigma"; x_pos := 100; y_pos := 100;
      END;
      K := sigma2; % Std. Deviation of State Disturbance 2
    END;
    SG7 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH
        bitmap TYPE String := "StaticGain.sigma"; x_pos := 100; y_pos :=  75;
      END;
      K := sigma3; % Std. Deviation of State Disturbance 2
    END;
    SG8 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH
        bitmap TYPE String := "StaticGain.sigma"; x_pos := 250; y_pos :=  50;
      END;
      K := sigma4; % Std. Deviation of Pressure Meas. Error
    END;
    SG9 ISA DrumBoiler::StaticGain WITH
      Graphic ISA Super::Graphic WITH
```

Listing B.11: OresundSimIC.om (*continued*).

```
        bitmap TYPE String := "StaticGain.sigma"; x_pos := 250; y_pos :=  25;
      END;
      K := sigma5; % Std. Deviation of Drum Level Meas. Error
    END;
  connections:
    % Steam Flow Rate
    qs1 AT Sum1.u1;
    qs2 AT Sum1.u2;
    Sum1.y AT SG1.T1;
    C1 ISA Connection WITH
      SG1.T2 AT Boiler.Steam.w;
      bpoints TYPE STATIC Matrix[4,2] := [100,254; 250,254; 250,200; 225,190];
    END;
    % Feed Water Flow Rate
    qfw AT SG2.T1;
    C2 ISA Connection WITH
      SG2.T2 AT Boiler.Water.w;
      bpoints TYPE STATIC Matrix[3,2] := [75,225; 200,225; 200,200];
    END;
    % Feed Water Temperature
    C3 ISA Connection WITH
      tfw AT Boiler.Water.M.T;
      bpoints TYPE STATIC Matrix[5,2] := [0,201;75,201;100,216;190,216;200,200];
    END;
    % Fuel Flow Rate
    qf AT Prod1.T1;
    C4 ISA Connection WITH
      BVG1.T2 AT Prod1.T2;
      bpoints TYPE STATIC Matrix[3,2] := [100,150; 125,150; 125,175];
    END;
    Prod1.T3 AT Boiler.q;
    % Drum Pressure
    Boiler.Steam.p AT SG3.T1;
    SG3.T2 AT Sum2.u1;
    Sum2.y AT dp;
    % Drum Level
    Boiler.Steam.M.z AT SG4.T1;
    SG4.T2 AT Sum3.u1;
    Sum3.y AT dl;
    % Low Pass Filtered Input
    CN1 AT LPF1.T1;
    LPF1.T2 AT BVG1.T1;
    % Wiener Process Disturbances
    CN2 AT Wp1.T1;
    Wp1.T2 AT SG5.T1;
    C5 ISA Connection WITH
      SG5.T2 AT Boiler.Disturbance.V1;
      bpoints TYPE STATIC Matrix[3,2] := [110,125; 175,125; 200,150];
    END;
    CN3 AT Wp2.T1;
    Wp2.T2 AT SG6.T1;
    C6 ISA Connection WITH
      SG6.T2 AT Boiler.Disturbance.V2;
      bpoints TYPE STATIC Matrix[3,2] := [110,100; 175,100; 200,150];
    END;
    CN4 AT Wp3.T1;
    Wp3.T2 AT SG7.T1;
    C7 ISA Connection WITH
      SG7.T2 AT Boiler.Disturbance.V3;
      bpoints TYPE STATIC Matrix[3,2] := [110,075; 200,075; 200,150];
    END;
    % Measurement Errors
    DN1 AT SG8.T1;
    SG8.T2 AT Sum2.u2;
    DN2 AT SG9.T1;
    SG9.T2 AT Sum3.u2;
  END;
```

Listing B.11: OresundSimIC.om (*continued*).

B.2 Model Structures

See the inheritance hierarchy in Figure 2.2 on page 6.

```
Boiler2FM ISA DrumBoiler::BoilerIC WITH
%% $Id: Boiler2FM.om,v 1.46 1997/06/27 10:57:50 sorliej Exp sorliej $
submodel:
  Media ISA DrumBoiler::SaturationMM WITH
    Min.P  := Outer::P;
  END;
variables:
  % state variables
  Vwt, P ISA Variable; % [m3], [MPa] respectively

  % feedwater properties
  qfw   TYPE         Real := Water.w;                   % [kg/s]
  tfw   TYPE         Real := Water.M.T;                 % [degC]
  Cfw   TYPE STATIC Real := 4.18;                       % [kJ/kg/degC]
  hfw   TYPE         Real := 1e3*(Cfw*tfw + p*1e3/rw); % [MJ/kg]

  % metal properties
  Cp    TYPE STATIC Real := 550;

  % saturated water properties
  hs    TYPE         Real := Media.Mout.hs;     % [MJ/kg]
  hw    TYPE         Real := Media.Mout.hw;     % [MJ/kg]
  hc    TYPE         Real := hs - hw;           % [MJ/kg]
  rs    TYPE         Real := Media.Mout.rs;     % [kg/m3]
  rw    TYPE         Real := Media.Mout.rw;     % [kg/m3]
  Ts    TYPE         Real := Media.Mout.Ts;     % [degC]
  dhsdp TYPE         Real := Media.Mout.dhsdp; % [J/kg/Pa]
  dhwdp TYPE         Real := Media.Mout.dhwdp; % [J/kg/Pa]
  drsdp TYPE         Real := Media.Mout.drsdp; % [kg/m3/MPa]
  drwdp TYPE         Real := Media.Mout.drwdp; % [kg/m3/MPa]
  dTsdp TYPE         Real := Media.Mout.dTsdp; % [degC/MPa]

  % total vapor volume fraction in the risers, and its partial derivatives
  eta   TYPE         Real := (rw-rs)*xr/rs; % common sub-expression
  ar    TYPE         Real := (1-xi0)*rw*(1 - ln(1+eta)/eta)/(rw-rs);
  dardx TYPE         Real := (1-xi0)*rw*(ln(1+eta)/eta - 1/(1+eta))/eta/rs;
  dardp TYPE         Real := (1-xi0)*(rw*drsdp - rs*drwdp)
              *(1 + rw/rs/(1+eta) - (1+rw/rs)*ln(1+eta)/eta)/((rw-rs)^2);

  % mass balance for the risers
  dMrdp TYPE         Real := Vr*((drsdp-drwdp)*ar + (rs-rw)*dardp + drwdp);
  dMrdx TYPE         Real := Vr*(rs-rw)*dardx;
  qr    TYPE         Real := qdc - dMrdp*p'; % mass flow rate out (xr'=0),[kg/s]

  % model of the steam valve nonlinearity
  qs    TYPE         Real := Steam.w + ks*(p-P0); % mass flow rate steam, [kg/s]

  % compliance relationships
  Vsr   TYPE         Real := ar*Vr;             % volume vapor in risers,  [m3]
  Vwr   TYPE         Real := Vr - Vsr;          % volume liquid in risers, [m3]
  Vwd   TYPE         Real := Vwt - Vdc - Vwr;   % volume liquid in drum,   [m3]
  Vst   TYPE         Real := Vd - Vwd + Vsr;    % total volume of vapor,   [m3]
  M     TYPE         Real := rw*Vwt + rs*Vst;   % total mass of water,     [kg]

  % condensation flow, total and in risers (Åström and Bell, 1988)
  qct   TYPE         Real := 1/hc*(Vst*(rs*dhsdp-Ihu) + Vwt*(rw*dhwdp-Ihu)
                             + (md+mr+mdc)*Cp*dTsdp)*p';   % [kg/s]
  qcr   TYPE         Real := (rs*ar + rw*(1-ar))*Vr*dhsdp*p'/hc; % [kg/s]

  % Indicator function, equals 0/1 for enthalpy/internal energy derivations.
  Ihu   TYPE         Real := if Sw0 < 1 then 0.0 else 1.0;

  % under-modelling representation
  Delta_geb TYPE    Real := Disturbance.V1;
  Delta_xr  TYPE    Real := Disturbance.V2;
  Delta_qdc TYPE    Real := Disturbance.V3;

  % functions of initial conditions
  Vwd0, ar0, qfw0, qr0, qs0, qct0 TYPE DISCRETE Real;
  rs0, rw0  ISA     DiscreteVariable WITH initial := 1; END;
```

Listing B.12: Boiler2FM.om—Definition of the second-order *root* model structure.

```
ordinary_parameters:
  % initial conditions
  dVwt0 ISA Parameter WITH default := 0.0;    END; % [m3]
  P0    ISA Parameter WITH default := 8.72;   END; % [MPa]
  % constants
  Ad    ISA Parameter WITH default := 20;     END; % [m2]
  Vd    ISA Parameter WITH default := 40;     END; % [m3]
  Vr    ISA Parameter WITH default := 38;     END; % [m3]
  Vdc   ISA Parameter WITH default := 11;     END; % [m3]
  md    ISA Parameter WITH default := 2.5E5;  END; % [kg]
  mr    ISA Parameter WITH default := 2.0E5;  END; % [kg]
  mdc   ISA Parameter WITH default := 0.0;    END; % [kg]
  kf    ISA Parameter WITH default := 0.005;  END; % [s2/kg, s2/kg, --]
  ks    ISA Parameter WITH default := 0.0;    END; % [kg/s/MPa]
  xi0   ISA Parameter WITH default := 0.0;    END; % [--]
  xr0   ISA Parameter WITH default := 0.05;   END; % [--]
  b1    ISA Parameter WITH default := 1.0;    END; % [m3, --, s]
  b2    ISA Parameter WITH default := 0.0;    END; % [m3*sec/kg]
  L0    ISA Parameter WITH default := 0.0;    END; % [m]

class_parameters:
  %% To elimintate the complexity due to switches in the exported equations
  %% fix the switch parameters as constants, thereby allowing the compiler
  %% to eliminate them from the equation set (i.e. simplify them).
  %  Sw0, Sw1, Sw2, Sw3  ISA Parameter WITH default := 1; END;
  Sw0, Sw1, Sw2, Sw3  TYPE STATIC Real;
  Sw0 := 1; Sw1 := 1; Sw2 := 2; Sw3 := 4;

state_equations:
  % 1. Global mass balance
  % 2. Global energy balance
  Mxdot ISA DrumBoiler::MatrixVar WITH
    m = n;  n = 2;
    value = [e[1,1]*Vwt', e[1,2]*p';
             e[2,1]*Vwt', e[2,2]*p'];
    rowsum[1] = qfw - qs;
    rowsum[2] = Q + qfw*hfw - qs*hs + Delta_geb;
  END;
  e TYPE Matrix[2,2] := [rw-rs, e12.sum; rw*hw - rs*hs, e22.sum];
  e12 ISA DrumBoiler::VectorVar WITH
    n = 2;
    value = [Vst*drsdp; Vwt*drwdp];
  END;
  e22 ISA DrumBoiler::VectorVar WITH
    n = 7;
    value = [Vst*[hs*drsdp; rs*dhsdp; -1*Ihu];
             Vwt*[hw*drwdp; rw*dhwdp; -1*Ihu]; (md+mr+mdc)*Cp*dTsdp];
  END;

initialization:
  Init, ReInit, Start ISAN Event;
  OnEvent Init DO
    % Initialize state variables.
    new(Vwt) := 1/2*Vd + (1-ar0)*Vr + Vdc + dVwt0;
    new(P)   := P0;
    schedule(ReInit,0.0); % fire immediately after OmSim's init-solver
  END;
  OnEvent ReInit DO
    % Initialize variables dependent upon the initial conditions
    new(ar0)  := ar;
    new(qct0) := qct;
    new(qfw0) := qfw;
    new(qr0)  := qr;
    new(qs0)  := qs;
    new(rs0)  := rs;
    new(rw0)  := rw;
    new(Vwd0) := Vwd-Tsd*(hw-hfw)*qfw/rs/hc;
    schedule(Start,0.0); % fire immediately after re-initialization.
  END;
  OnEvent Start DO
    % Re-Initialize state initializations dependent upon these variables.
    new(Vwt)  := 1/2*Vd + (1-ar0)*Vr + Vdc + dVwt0;
  END;
```

Listing B.12: Boiler2FM.om (*continued*).

```
measurement_equations:
  % Hypothesis 0:  The measurement model in (Åström and Bell, 1988).
  % Hypothesis 1:  The measurement model in (Eborn and Sorlie 1997).
  % The additive constant L0 in each realization is necessary to correct
  % static errors due to out-of-equilibrium state variable initialization.
  dVwd TYPE Real := Vwd-Vwd0;                % [m3]
  dVsd TYPE Real := Vsd-Vsd0;                % [m3]
  dl   TYPE Real := IF Sw1 < 1 THEN   (Vwd + Vsd)/Ad - L0
                    ELSE            (dVwd + dVsd)/Ad + L0; % [m]
realizations:
  % mass flow rate entering the downcomers, [kg/s]
  qdc ISA Variable WITH
    % Hypothesis 0:  The flow rate is approximately constant.
    % Hypothesis 1:  In (Åström and Bell, 1988), a static momentum balance
    %   for the downcomers/risers circuit is given involving one parameter, k.
    % Hypothesis 2:  In (Åström and Bell, 1997), a more complex momentum
    %   balance is derived; the formulation involves two parameters, k and Adc.
    value := IF Sw2 < 1 THEN hypothesis[1]
        ELSE IF Sw2 < 2 THEN hypothesis[2]
        ELSE                 hypothesis[3];
    hypothesis TYPE Column[3] := [sqrt(2*(rw0-rs0)*Vr*ar0/kf);
                                  sqrt(2*(rw -rs )*Vr*ar /kf);
                                  sqrt(2*rw*Adc*(rw-rs)*gc*ar*Vr/kf)]
                                + Delta_qdc*ones(3,1);
    Adc TYPE STATIC Real := 1.4e-4; % [m2], empirically tuned so H2 matches H1
    gc  TYPE STATIC Real := 9.81;   % [m/s2], gravitational constant
  END;
  % vapor mass fraction at the risers outlet, [--]
  xr ISA Variable WITH
    value := xr0 + Delta_xr; % dimensionless, with range 0<xr<1
  END;
  % residence time of vapor below the liquid surface inside the drum, [s]
  Tsd ISA Variable WITH
    value := 0; % Only used in 4th order models; included for initialization.
  END;
  % volume of steam vapor in the drum below the liquid surface
  Vsd ISA Variable WITH
    % The model involves two parameters:  b1 and b2.  With b2 equal
    % to zero (b2=0) the models reduce to the following hypotheses:
    % Hypothesis 0:  Constant volume of steam below the surface.
    % Hypothesis 1:  In (Åström and Bell, 1993), the volume of vapor below
    %   the surface is instantaneously equal to the volume of vapor in the
    %   risers.  To allow for condensation, we add a proportionality constant.
    % Hypothesis 2:  Variation in the submerged vapor volume is proportional
    %   to the volumetric flow rate of the steam phase exiting the risers.
    % Hypothesis 3:  Incorporate feed water mass flow rate, and hence effects
    %   due to condensation, into the model.
    value := IF Sw3 < 1 THEN hypothesis[1]
        ELSE IF Sw3 < 2 THEN hypothesis[2]
        ELSE IF Sw3 < 3 THEN hypothesis[3]
        ELSE IF Sw3 < 4 THEN hypothesis[4]
        ELSE                 hypothesis[5];
    hypothesis TYPE Column[5] := b1*[1; ar*Vr; xr*qr/rs;   ar*Vr;  ar*Vr]
                               + b2*[(qfw-qs)*ones(3,1); qct/rs0; qct/rs];
  END;
  Vsd0 ISA Variable WITH
    value := IF Sw3 < 1 THEN hypothesis[1]
        ELSE IF Sw3 < 2 THEN hypothesis[2]
        ELSE IF Sw3 < 3 THEN hypothesis[3]
        ELSE IF Sw3 < 4 THEN hypothesis[4]
        ELSE                 hypothesis[5];
    hypothesis TYPE Column[5] := b1*[1;ar0*Vr;xr0*qr0/rs0; ar0*Vr;   ar0*Vr]
                               + b2*[(qfw0-qs0)*ones(3,1);    qct0; qct0/rs0];
  END;

connections:
  Water.p   AT Media.Min.p;
  Steam.p   AT Media.Min.p;
  Steam.h   AT Media.Mout.hs;
  Steam.M.T AT Media.Mout.Ts;
auxiliary_equations:
  Water.h    := hfw;
  Steam.M.z  := dl;
END;
```

Listing B.12: Boiler2FM.om (*continued*).

```
Boiler3FM ISA DrumBoiler::Boiler2FM WITH
%%  $Id: Boiler3FM.om,v 1.10 1997/06/27 06:54:33 sorliej Exp $
variables:
  % additional state variable -- steam mass fraction at outlet of risers
  xr ISA Variable; % dimensionless, with range 0<xr<1

  % mass balance for the risers (including time-variation in xr)
  qr TYPE Real := qdc - dMrdp*p' - dMrdx*xr'; % mass flowrate out, [kg/s]

  % under-modelling representation in the risers energy balance
  Delta_reb TYPE Real := Disturbance.V2;

state_equations:
  % 3. Combined mass and energy balances for the risers
  e32.sum*p' + e33*xr' = Q - qdc*xr*hc + Delta_reb;

  e32 ISA DrumBoiler::VectorVar WITH
    n = 8;
    value = [Vr*[    ar*[rs*dhsdp; (1-xr)*hc*drsdp; -1*Ihu];
                 (1-ar)*[rw*dhwdp;     -xr*hc*drwdp; -1*Ihu];
                 (rs + (rw-rs)*xr)*hc*dardp                ]; mr*Cp*dTsdp];
  END;

  e33 TYPE Real := Vr*(rs + (rw-rs)*xr)*hc*dardx;

initialization:
  OnEvent Init DO
    new(xr) := xr0;
  END;
END;
```

Listing B.13: Boiler3FM.om—Definition of the third-order model structure.

```
Boiler4FM ISA DrumBoiler::Boiler3FM WITH
%% $Id: Boiler4FM.om,v 1.23 1997/06/27 08:07:09 sorliej Exp $
variables:
  % additional state variable
  Vsd ISA Base::Variable;  % over-write previous switched definition

  % mass flow rate of steam crossing the liquid surface inside the drum
  qsd  TYPE Real := qr*xr + rs*dVsd/Tsd;          % [kg/s]
% qsd  TYPE Real := qr*xr + rs*dVsd/Tsd - b2*qct; % [kg/s]

  % metal mass of drum below the liquid surface, assuming it is half full
  msd  TYPE Real := md/2; % [kg]

  % redefine to include non-zero initial value for the Init-solver.
  qr0  ISA DiscreteVariable WITH initial := 1; END;

  % under-modelling representation in the control volume's energy balance
  Delta_sdeb TYPE Real := Disturbance.V3;
  Delta_qdc  TYPE Real := 0; % over-write to eliminate inherited binding

ordinary_parameters:
  Vsd0 ISA Parameter WITH default := 8.0; END; % [m3]

state_equations:
  % 4. Combined mass and energy balances for the wet volume inside the drum
  e41*Vwt' + e42.sum*p' + e43*xr' + e44*Vsd' =
    (xr*qr-qsd)/rs + ((hfw-hw)*qfw + Delta_sdeb)/rs/hc;
  %      -dVsd/Tsd + ((hfw-hw)*qfw + Delta_sdeb)/rs/hc; % explicit formulation

  e41 TYPE Real := -P/rs/hc*Ihu;     % [--], nominally 1e-7
  e42 ISA DrumBoiler::VectorVar WITH
    n = 6;
    % The last two elements come from deriving the energy balance in terms
    % of internal energy instead of enthalpy; Sw1 controls their inclusion.
    value = [       Vsd*[  1/rs*drsdp;   1/hc*dhsdp];
                1/rs/hc*[Vwd*rw*dhwdp; msd*Cp*dTsdp];
             -Ihu/rs/hc*[     Vwd+Vsd;   Vr*P*dardp]]; % [m3/MPa]
  END;
  e43 TYPE Real := Vr*e41*dardx; % [m3], nominally 1e-5
  e44 TYPE Real := 1 + e41;      % [--], nominally 1.0

initialization:
  OnEvent Init DO
    new(Vsd) := Vsd0; % Initialize the augmented state variable.
  END;

realizations:
  % over-write dummy definition in Boiler2FM
  Tsd ISA Variable WITH
    % Hypothesis 0:  In (Åström and Bell, 1996), the time constant
    %   is a function of the steam mass flowrate, qs (a controlled signal).
    % Hypothesis 1:  Variation of #0, using only vapor vol. above the surface.
    %   is a function of the steam mass flowrate, qs (a controlled signal).
    % Hypotheses 2:  In (Åström and Bell, 1997), the time constant is
    %   given to be  Tsd = rs*Vsd0/qsd  = rs*(Vsd0-dVsd)/xr/qr
    % Hypotheses 3:  Time-invariant value based on heuristics in #2. Although
    %   both b1 and Vsd0 affect Tsd, only b1 affects the steady-state offset.
    value  = IF Sw3 < 1 THEN hypothesis[1]
        ELSE IF Sw3 < 2 THEN hypothesis[2]
        ELSE IF Sw3 < 3 THEN hypothesis[3]
        ELSE                 hypothesis[4];
    hypothesis TYPE Column[4] := [b1*rs /qs     *(Vd-Vwd);
                                  b1*rs /qs     *(Vd-Vwd-Vsd);
                                  b1*rs /xr /qr *(Vsd0-dVsd);
                                  b1*rs0/xr0/qr0*Vsd0           ];
  END;
END;
```

Listing B.14: Boiler4FM.om—Definition of the fourth-order model structure.

B.2.1 Reduced Order Definitions

```
Boiler1rFM ISA DrumBoiler::Boiler2FM WITH
%% $Id: Boiler1rFM.om,v 1.3 1997/06/27 08:14:19 sorliej Exp $

model_reduction:
  Vwt' = 0.0;

state_equations:
  % 1. Combined global mass and energy balances

  Mxdot ISA DrumBoiler::MatrixVar WITH
    % Over-write inherited matrix definition
    m=n;  n=1;
    value = (e[2,2] - hw*e[1,2])*p';
    rowsum[1] = Q + (hfw-hw)*qfw - hc*qs + Delta_geb;
  END;

END;
```

Listing B.15: Boiler1rFM.om—Reduced first-order structure, assuming the total volume of water in the system is constant.

```
Boiler2rFM ISA DrumBoiler::Boiler3FM WITH
%% $Id: Boiler2rFM.om,v 1.3 1997/06/27 08:15:06 sorliej Exp $

model_reduction:
  Vwt' = 0.0;

state_equations:
  % 1. Combined global mass and energy balances

  Mxdot ISA DrumBoiler::MatrixVar WITH
    % Over-write inherited matrix definition
    m=n;  n=1;
    value = (e[2,2] - hw*e[1,2])*p';
    rowsum[1] = Q + (hfw-hw)*qfw - hc*qs + Delta_geb;
  END;

END;
```

Listing B.16: Boiler2rFM.om—An augmented, reduced second-order model structure.

```
Boiler3rFM ISA DrumBoiler::Boiler4FM WITH
%% $Id: Boiler3rFM.om,v 1.3 1997/06/27 08:21:23 sorliej Exp $

model_reduction:
  Vwt' = 0.0;

state_equations:
  % 1. Combined global mass and energy balances

  Mxdot ISA DrumBoiler::MatrixVar WITH
    % Over-write inherited matrix definition
    m=n;  n=1;
    value = (e[2,2] - hw*e[1,2])*p';
    rowsum[1] = Q + (hfw-hw)*qfw - hc*qs + Delta_geb;
  END;

END;
```

Listing B.17: Boiler3rFM.om—An augmented, reduced third-order model structure.

B.2.2 Alternate State Realization

```
Boiler3wdFM ISA DrumBoiler::Boiler3FM WITH
%%  $Id: Boiler3wdFM.om,v 1.4 1997/06/27 08:13:08 sorliej Exp $
variables:
  % alternate and additional state variables
  Vwd ISA Base::Variable;

  % total volume of water as a function of the new state
  Vwt TYPE Real := Vwd + Vdc + (1 - ar)*Vr; % total volume of water

state_equations:
  % 1. Global energy balance (coupled with xr due to state variable choice)
  % 2. Global mass balance
  % 3. Combined mass and energy balances for the risers

  Mxdot ISA DrumBoiler::MatrixVar WITH
    % Over-writes inherited matrix definition
    m=2; n=3;
    value = [e[1,1]*Vwd', e12a.sum*p', -e[1,1]*Vr*dardx*xr';
             e[2,1]*Vwd', e22a.sum*p', -e[2,1]*Vr*dardx*xr'];
    rowsum[1] = qfw - qs;
    rowsum[2] = Q + qfw*hfw - qs*hs + Delta_geb;
  END;

  e12a ISA DrumBoiler::VectorVar WITH
    n := 2;
    value := [e12.sum; -e[1,1]*Vr*dardp];
  END;

  e22a ISA DrumBoiler::VectorVar WITH
    n := 2;
    value := [e22.sum; -e[2,1]*Vr*dardp];
  END;

initialization:
  OnEvent Init DO
    new(Vwd) := Vd/2;
  END;

END;
```

Listing B.18: Boiler3wdFM.om—An alternate state realization with V_{wd}, the volume of water in the drum, as a state variable.

B.2.3 Time Delay Realizations

```
Boiler3dFM ISA DrumBoiler::Boiler3FM WITH
%%  $Id: Boiler3dFM.om,v 1.4 1997/06/27 08:19:04 sorliej Exp $

  % Over-write inherited def's, replacing qct with the delayed signal.
  Vsd ISA Variable WITH
    value := IF Sw3 < 1 THEN hypothesis[1]
        ELSE                 hypothesis[2];
    hypothesis TYPE Column[2] := b1*[1; ar*Vr] + b2*qctd/rs*ones(2,1);
  END;

  Vsd0 ISA Variable WITH
    value := IF Sw3 < 1 THEN hypothesis[1]
        ELSE                 hypothesis[2];
    hypothesis TYPE Column[2] := b1*[1; ar0*Vr] + b2*qct0/rs0*ones(2,1);
  END;

  % time-delayed value of the total condensation mass flow rate, [kg/s]
  qctd  ISA Base::Variable WITH
    tau ISA Parameter WITH default := 40; END; % delay time constant, [sec]
    Sw  ISA Parameter WITH default := 0;  END; % delay realization switch

  switch_equation:
    value := IF Sw<1 THEN exact
        ELSE IF Sw<2 THEN approx1
        ELSE IF Sw<3 THEN approx2
        ELSE IF Sw<4 THEN approx3
        ELSE              approx4;

  variables:
    exact ISA DrumBoiler::PureDelay WITH
      u := qct;
      T := tau;
    END;

    approx1 ISA DrumBoiler::Pade01 WITH
       u := qct;
      T := tau;
    END;

    approx2 ISA DrumBoiler::Pade11 WITH
      u := qct;
      T := tau;
    END;

    approx3 ISA DrumBoiler::Pade12 WITH
      u := qct;
      T := tau;
    END;

    approx4 ISA DrumBoiler::Pade22 WITH
      u := qct;
      T := tau;
    END;

  END;
END;
```

Listing B.19: Boiler3dFM.om—A variation of the third-order structure that includes realizations (pure and approximate) of a time-delayed signal q_{ct}, the total condensation flow rate.

```
 Boiler4dFM ISA DrumBoiler::Boiler4FM WITH
 %%  $Id: Boiler4dFM.om,v 1.5 1997/06/27 08:28:19 sorliej Exp $

   % Over-write the inherited definition, replacing xr*qr with qsdd.
   qsd  TYPE Real := qsdd + rs*dVsd/Tsd; % [kg/s]

 variables:
   qsdd  ISA Base::Variable WITH
   class_parameter:
     Sw ISA Base::Parameter WITH default := 0; END; % delay realization switch

   switch_equation:
     value := IF Sw<1 THEN exact
         ELSE IF Sw<2 THEN approx1
         ELSE IF Sw<3 THEN approx2
         ELSE IF Sw<4 THEN approx3
         ELSE              approx4;

   variables:
     exact ISA DrumBoiler::PureDelay WITH
       u := xr*qr;
       T := Tsd;
     END;

     approx1 ISA DrumBoiler::Pade01 WITH
        u := xr*qr;
       T := Tsd;
     END;

     approx2 ISA DrumBoiler::Pade11 WITH
       u := xr*qr;
       T := Tsd;
     END;

     approx3 ISA DrumBoiler::Pade12 WITH
       u := xr*qr;
       T := Tsd;
     END;

     approx4 ISA DrumBoiler::Pade22 WITH
       u := xr*qr;
       T := Tsd;
     END;

  END;
END;
```

Listing B.20: Boiler4dFM.om—A variation of the fourth-order structure that includes realizations (pure and approximate) of a time-delayed signal q_{sd}, the vapor flux across the liquid surface in the drum.

```
 Boiler5FM ISA DrumBoiler::Boiler4FM WITH
 %%  $Id: Boiler5FM.om,v 1.5 1997/06/27 08:26:58 sorliej Exp $

   % Over-write the inherited definition, replacing xr*qr with qsdd.
   qsd  TYPE Real := qsdd + rs*dVsd/Tsd; % [kg/s]

 variables:
   qsdd  ISA Base::Variable WITH
     value := delay.value;
     delay ISA Pade01 WITH
       u := xr*qr;
       T := Tsd;
     END;
   END;
 END;
```

Listing B.21: Boiler5FM.om—For equation export, a definition equivalent to Boiler4dFM.om, but with only the Padé(0,1) delay approximation.

B.2.4 Iterative State Variable Initialization

```
Boiler3iFM ISA DrumBoiler::Boiler3FM WITH
%%  $Id: Boiler3iFM.om,v 1.1 1997/06/27 08:22:02 sorliej Exp $

initialization:
  Iter1, Iter2 ISAN Event;

  OnEvent Init DO
    schedule(Iter1,0.0); % fire immediately after OmSim's init-solver
  END;

  OnEvent Iter1 DO
    new(xr) := -ar/dardx + xr/2
      + (1/2/hc/dardx/qdc)*sqrt( hc*qdc*(4*hc*qdc*ar*(ar-dardx*xr)
                                 + hc*qdc*(dardx*xr)^2 + 8*Q*ar*dardx) );
    schedule(Iter2,0.0); % fire immediately
  END;

  OnEvent Iter2 DO
    new(xr) := -ar/dardx + xr/2
      + (1/2/hc/dardx/qdc)*sqrt( hc*qdc*(4*hc*qdc*ar*(ar-dardx*xr)
                                 + hc*qdc*(dardx*xr)^2 + 8*Q*ar*dardx) );
  END;

END;
```

Listing B.22: Boiler3iFM.om—Derivation of the third-order model structure including an iterative initialization of $x_r(0)$ based on first-order Taylor series approximations.

B.3 Simulation Models

```
Oresund2 ISA DrumBoiler::OresundSimIC WITH
%% $Id: Oresund2.om,v 1.20 1997/06/27 08:44:23 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler2FM;

equation_export:
  SMM ISA DrumBoiler::SignalModelMapping WITH
  input_signals:
    U.n  := 5;  U  := [qs1;  qs2;  qf;  qfw;  Tfw ];
    U0.n := 5;  U0 := [qs10; qs20; qf0; qfw0; Tfw0];
    Wv.n := 4;  Wv := [CN1; CN2; CN3; CN4];
    Wy.n := 2;  Wy := [DN1; DN2];
  output_signals:
    Y.n  := 2;  Y  := [dp; dl];
  state_signals:
    X ISA Std::VectorVar WITH
      n := 6;
      value := [LPF1.x; Wp1.W; Wp2.W; Wp3.W; Boiler.Vwt; Boiler.P];
    END;
  parameter_matrix_mapping:
    PM ISA Std::MatrixVar WITH
      m := 23;
      n := 5;
      value := [qs10,               qs20,         qf0,        qfw0,        Tfw0;
                Boiler.mdc,  Boiler.Vd,  Boiler.Vr, Boiler.Vdc,        NaN;
                Tcf,               qfrng,         NaN,         NaN,        NaN;
                Boiler.Sw0, Boiler.Sw1, Boiler.Sw2, Boiler.Sw3,        NaN;
                qscf,                NaN,         NaN,         NaN,        NaN;
                qfcf,                NaN,         NaN,         NaN,        NaN;
                Sigma1,              NaN,         NaN,         NaN,        NaN;
                Sigma2,              NaN,         NaN,         NaN,        NaN;
                Sigma3,              NaN,         NaN,         NaN,        NaN;
                Sigma4,              NaN,         NaN,         NaN,        NaN;
                Sigma5,              NaN,         NaN,         NaN,        NaN;
                Boiler.md,           NaN,         NaN,         NaN,        NaN;
                Boiler.mr,           NaN,         NaN,         NaN,        NaN;
                Boiler.Ad,           NaN,         NaN,         NaN,        NaN;
                Boiler.kf,           NaN,         NaN,         NaN,        NaN;
                Boiler.ks,           NaN,         NaN,         NaN,        NaN;
                Boiler.L0,           NaN,         NaN,         NaN,        NaN;
                Boiler.xi0,          NaN,         NaN,         NaN,        NaN;
                Boiler.b1,           NaN,         NaN,         NaN,        NaN;
                Boiler.b2,           NaN,         NaN,         NaN,        NaN;
                Boiler.dVwt0,        NaN,         NaN,         NaN,        NaN;
                Boiler.P0,           NaN,         NaN,         NaN,        NaN;
                Boiler.xr0,          NaN,         NaN,         NaN,        NaN];
    END;
  END;
END;
```

Listing B.23: Oresund2.om—Simulation model definition for the second-order model structure, including parameterized signal model definitions for equation export (cf. Listing B.9).

```
Oresund3 ISA DrumBoiler::Oresund2 WITH
%% $Id: Oresund3.om,v 1.4 1997/06/27 08:45:04 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler3FM;

equation_export:
  SMM ISA Super::SMM WITH
    X ISA Std::VectorVar WITH
      n := 7;
      value := [LPF1.x; Wp1.W; Wp2.W; Wp3.W; Boiler.Vwt; Boiler.P; Boiler.xr];
    END;
  END;
END;
```

Listing B.24: Oresund3.om—The derived third-order simulation model including overwritten inherited information for equation export.

```
Oresund4 ISA DrumBoiler::Oresund3 WITH
%% $Id: Oresund4.om,v 1.19 1997/06/27 08:41:18 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler4FM;

equation_export:
  SMM ISA Super::SMM WITH
    X ISA Std::VectorVar WITH
      n := 8;
      value := [LPF1.x;        Wp1.W;     Wp2.W;      Wp3.W;
                Boiler.Vwt; Boiler.P; Boiler.xr; Boiler.Vsd];
    END;

    % Over-write inherited definition, replacing b2 with Vsd0.
    PM ISA Std::MatrixVar WITH
      m := 23;
      n := 5;
      value := [qs10,              qs20,        qf0,        qfw0,       Tfw0;
                Boiler.mdc,  Boiler.Vd,  Boiler.Vr,  Boiler.Vdc,        NaN;
                Tcf,              qfrng,        NaN,        NaN,        NaN;
                Boiler.Sw0, Boiler.Sw1, Boiler.Sw2, Boiler.Sw3,         NaN;
                qscf,               NaN,        NaN,        NaN,        NaN;
                qfcf,               NaN,        NaN,        NaN,        NaN;
                Sigma1,             NaN,        NaN,        NaN,        NaN;
                Sigma2,             NaN,        NaN,        NaN,        NaN;
                Sigma3,             NaN,        NaN,        NaN,        NaN;
                Sigma4,             NaN,        NaN,        NaN,        NaN;
                Sigma5,             NaN,        NaN,        NaN,        NaN;
                Boiler.md,          NaN,        NaN,        NaN,        NaN;
                Boiler.mr,          NaN,        NaN,        NaN,        NaN;
                Boiler.Ad,          NaN,        NaN,        NaN,        NaN;
                Boiler.kf,          NaN,        NaN,        NaN,        NaN;
                Boiler.ks,          NaN,        NaN,        NaN,        NaN;
                Boiler.L0,          NaN,        NaN,        NaN,        NaN;
                Boiler.xi0,         NaN,        NaN,        NaN,        NaN;
                Boiler.b1,          NaN,        NaN,        NaN,        NaN;
                Boiler.Vsd0,        NaN,        NaN,        NaN,        NaN;
                Boiler.dVwt0,       NaN,        NaN,        NaN,        NaN;
                Boiler.P0,          NaN,        NaN,        NaN,        NaN;
                Boiler.xr0,         NaN,        NaN,        NaN,        NaN];
    END;
  END;
END;
```

Listing B.25: Oresund4.om—Simulation model definition for the fourth-order model structure; the parameter b2 is replaced by Vsd0 in the equation export parameter mapping.

```
Oresund1r ISA DrumBoiler::Oresund2 WITH
%% $Id: Oresund1r.om,v 1.3 1997/06/27 08:37:35 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler1rFM;

equation_export:
  SMM ISA Super::SMM WITH
    X ISA Std::VectorVar WITH
      n := 5;
      value := [LPF1.x; Wp1.W; Wp2.W; Wp3.W; Boiler.P];
    END;
  END;
END;
```

Listing B.26: Oresund1r.om—Simulation model for the reduced first-order model structure.

```
Oresund2r ISA DrumBoiler::Oresund1r WITH
%% $Id: Oresund2r.om,v 1.3 1997/06/27 08:38:14 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler2rFM;

equation_export:
  SMM ISA Super::SMM WITH
    X ISA Std::VectorVar WITH
      n := 6;
      value := [LPF1.x; Wp1.W; Wp2.W; Wp3.W; Boiler.P; Boiler.xr];
    END;
  END;
END;
```

Listing B.27: Oresund2r.om—Simulation model for the augmented, reduced second-order model structure.

```
Oresund3r ISA DrumBoiler::Oresund4 WITH
%% $Id: Oresund3r.om,v 1.4 1997/06/27 08:39:34 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler3rFM;

equation_export:
  SMM ISA Super::SMM WITH
    X ISA Std::VectorVar WITH
      n := 7;
      value := [LPF1.x; Wp1.W; Wp2.W; Wp3.W; Boiler.P; Boiler.xr; Boiler.Vsd];
    END;
  END;
END;
```

Listing B.28: Oresund3r.om—Simulation model for the reduced third-order model structure.

```
Oresund3wd ISA DrumBoiler::Oresund3 WITH
%% $Id: Oresund3wd.om,v 1.10 1997/06/27 08:45:43 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler3wdFM;

equation_export:
  SMM ISA Super::SMM WITH
    X ISA Std::VectorVar WITH
      n := 7;
      value := [LPF1.x; Wp1.W; Wp2.W;     Wp3.W;
                Boiler.Vwd; Boiler.P; Boiler.xr];
    END;
  END;
END;
```

Listing B.29: Oresund3wd.om—Simulation model for the model structure with an alternate state realization.

```
Oresund3d ISA DrumBoiler::Oresund3 WITH
%% $Id: Oresund3d.om,v 1.2 1997/06/27 08:38:46 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler3dFM;

equation_export:
  %% Note!  This definition is not intended for equation export.
  %%        It is only for simulation testing (via a switch) of
  %%        the various time delay realizations (approximate and
  %%        the exact).  Equation export is not possible because
  %%        of the variable state dimension of these realizations.
END;
```

Listing B.30: Oresund3d.om—Simulation model for the third-order model structure with alternate time-delay realizations of q_{ct}.

```
Oresund4d ISA DrumBoiler::Oresund4 WITH
%% $Id: Oresund4d.om,v 1.3 1997/06/27 08:41:48 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler4dFM;

equation_export:
  %% Note!  This definition is not intended for equation export.
  %%        It is only for simulation testing (via a switch) of
  %%        the various time delay realizations (approximate and
  %%        the exact).  Equation export is not possible because
  %%        of the variable state dimension of these realizations.
  %%        Use Oresund5 and Oresund6 for equation export.
END;
```

Listing B.31: Oresund4d.om—Simulation model for the fourth-order model structure with alternate time-delay realizations of q_{sd}.

```
Oresund5 ISA DrumBoiler::Oresund4 WITH
%%  $Id: Oresund5.om,v 1.5 1997/06/27 08:42:17 sorliej Exp $

  Boiler ISA DrumBoiler::Boiler5FM;

equation_export:
  SMM ISA Super::SMM WITH
    X ISA Std::VectorVar WITH
      n := 8 + Boiler.qsdd.delay.x.n;
      value := [LPF1.x;        Wp1.W;      Wp2.W;       Wp3.W;
                Boiler.Vwt; Boiler.P; Boiler.xr; Boiler.Vsd;
                Boiler.qsdd.delay.x];
    END;
  END;
END;
```

Listing B.32: Oresund5.om—Simulation model for the fourth-order model structure with a Padé(0,1) approximation of the time-delayed q_{sd}.

Appendix C

Annotated IdKit Sessions

This appendix presents the details of the computer-aided parameter optimization investigations of the third, fourth and fifth-order model structures ($\mathcal{M}_3$, $\mathcal{M}_4$, and $\mathcal{M}_5$) respectively. The first section provides background information on the IdKit tools and explains how they were used as building blocks to create project specific tools. The three subsequent sections document the investigations using these tools. Each investigation consists of command script that was run for each of the six data sets; the results of these runs are presented in tabular form. To investigate the influence of the unidentifiable friction factor, all computations were repeated using three fixed values: $k_f = \{0.001, 0.005, 0.01\}$.

C.1 On Batch Processing

A few words on the IdKit tools and the user interface are necessary. For readers familiar with Ljung's *System Identification Tool Box* (SITB) [14], it may be useful to draw conceptual parallels between IdKit and the SITB.

We begin with the concept of a project. Computer-aided system identification involves two things: data and a model structure. An IdKit project is organized in a file-system directory. The data is stored in an ASCII text file. The equations of the model structure are encoded in another text file, as C-language subroutines. The status of the project is recorded in a binary database file (in a hidden sub-directory). The IdKit database is analogous to the SITB's *theta* object. Both are associated to a particular model structure and are "massaged" by the commands of the tool set.

In contrast to the SITB which is implemented as functions in Matlab, the IdKit tools are implemented as UNIX commands. Furthermore, rather than having a set of command-line arguments, the IdKit tools are designed around a "question and answer" dialog [15]. IdKit's commands may be executed either interactively or in batch mode. In the former, the user responds to a series of prompts; in the later, the answers to the prompts are embedded in a command script, i. e. a UNIX shell script. Batch mode operation is the basis of the macro facility provided by IdKit; see [11]. An example of an IdKit macro is shown in listing C.1 on the next page. Specifically note that batch mode operation makes use of so-called "here documents" inside UNIX shell scripts. The syntax of here-documents is as follows:

```
command << delimiter
     ...here-document...    (the standard input to the UNIX command)
delimiter
```

The point to be made is this: although IdKit lacks a command-line argument oriented user interface (which the SITB has), it is possible to construct one. Such an interface is highly desirable to automate repetitive and laborious tasks. Table C.1 on the following page summarizes the set of command macros and command scripts that were developed to aid the investigations. Listings C.2, C.5 and C.6 are included for illustrative purposes. The first provides a simple example of interfacing between IdKit and OmSim. In essence, the IdKit tools are building blocks which are encapsulated inside project specific tools.

Script Name	Description
cm_mkdbase	Create or reinitialize an IdKit project directory's database.
cm_setv	Setup for ALMP validation.
cs_fmtfil	Convert raw ASCII data to IdKit's binary file format.
cs_setd	Set numerical integration time quantum and select dataset.
cs_setf	Setup for ML parameter optimization.
cs_setm	Enter the signal model structure into the project database.
cs_setp	Set the free parameter set and corresponding search constraints.
cs_setp0	Set fixed parameters values and initial guesses of free parameters.
cs_setp0.cf	Set values of calibration factors.
cs_setp0.u0	Set values of initial input conditions.
cs_setp0.x0	Set values of initial state conditions.
cs_sets	Enter scales and ranges of signals in the model.
cs_writep0	Save parameter settings as an IdKit macro and an OmSim OCL script.
cs_writep02ocl	Save initial parameter values as an OmSim OCL script.
cs_writep2ocl	Save parameters resulting from a search as an OmSim OCL script.

Table C.1: Summary of project specific command macros and scripts (cm and cs resp.) written to to aid in automating the investigation.

```
setv > /dev/null <<endsetv
#Validation procedures:
#1:  ALMP Method
#4:  Akaikes Information Criterion
#Validation Procedure:
1
#New data since fitting? (No=0, Yes=1)  Accepted risk type 1:
0                                       0.01
endsetv

```

Listing C.1: cm_setv—UNIX shell script created by IdKit's macro facility.

```
#!/bin/sh
#####################################################################
if test $# -eq 1
then
  filnam="$1"
else
  echo "$0:  ERROR: no filename given on the command line!"
  exit 0
fi

mac $filnam >/dev/null <<EOF
setp  > /dev/null
setp0 > /dev/null
writep0
qmac
EOF
$filnam

# Write the parameter values from the IdKit database
# in the format of an OCL script (to standard output).
echo 'BEGIN
  Simulator s();
  s.reset;
  Model m(s);' > $filnam.ocl

# Append assignements for scalar parameters.
writep0 | sed  -n 's/:/:=/g; s/^/  m./g;        s/$/;/g; 5,11p;' >> $filnam.ocl
writep0 | sed  -n 's/:/:=/g; s/^/  m.Boiler./g; s/$/;/g; 12,$p;' >> $filnam.ocl

# Append the OCL commands that start the simulation and end the block.
echo '
  s.reset;
  s.start;
END;' >> $filnam.ocl

exit 0;
```

Listing C.2: cs_writep0—Command script that saves the parameter values as an IdKit macro and OmSim OCL script; the former also contains the specification of free parameters.

```
1  #!/bin/sh
2  ######################################################################
3  status="OK"
4  if test $# -eq 0; then  Exp="error";
5  else                    Exp="$1"; fi;
6  case "$Exp" in
7  # Calibration for zero mass and k_s values.
8      J)     qscf="0.253";  qfcf="6.205"; ;;
9      F)     qscf="0.253";  qfcf="6.121"; ;;
10     G)     qscf="0.257";  qfcf="6.121"; ;;
11     A|B)   qscf="0.253";  qfcf="5.575"; ;;
12     E)     qscf="0.267";  qfcf="5.612"; ;;
13 # Calibration for non-zero masses and/or non-zero k_s values.
14 #      J|F|G) qscf="0.253";  qfcf="6.205"; ;;
15 #      E)     qscf="0.2665"; qfcf="5.61";  ;;
16 #      A)     qscf="0.257";  qfcf="5.61";  ;;
17 #      B)     qscf="0.254";  qfcf="5.61";  ;;
18     *)     status="";                       ;;
19 esac;
20 if [ "$status" != "OK" ]; then   # An error occurred.
21     echo "$0: ERROR: unknown experiment:  \"$Exp\".";
22     echo "";
23     echo "Valid arg's are E, A, or B (full) and J, F or G (partial load";
24     exit 1;
25 fi;
26 ######################################################################
27 setp0 >/dev/null <<___end_setp0___
28 ######################################################################
29 #Enter origin of parameter vectors:
30 ######################################################################
31 #qs10, qs20, qf0, qfw0, Tfw0
32
33 #mdc, Vd, Vr, Vdc
34
35 #Tcf, qfrng
36
37 #Sw0, Sw1, Sw2, Sw3
38
39 #qscf
40 $qscf
41 #qfcf
42 $qfcf
43 #Sigma1
44
45 #Sigma2
46
47 #Sigma3
48
49 #Sigma4
50
51 #Sigma5
52
53 #md
54
55 #mr
56
57 #Ad
58
59 #kf
60
61 #ks
62
63 #L0
64
65 #xi0
66
67 #b1
68
69 #b2
70
71 #dVwt0
72
73 #P0
74
75 #xr0
76
77 ___end_setp0___
78 ######################################################################
79 writep0 4 5
80 exit 0
```

Listing C.3: cs_setp0.cf—Command script for IdKit's `setp0` command; the dataset specified on the command line affects lines 40 and 42 of the "here-document".

```
1  #!/bin/sh
2  ######################################################################
3  if test $# -eq 0; then
4    Exp="J"
5  else
6    Exp="$*"
7  fi;
8
9  if   test $Exp="E"; then P="10.6089"# MPa == 132.6110 kg/cm2, Exp.E
10 elif test $Exp="A"; then P=" 9.9985"# MPa == 124.9810 kg/cm2, Exp.A
11 elif test $Exp="B"; then P="10.0698"# MPa == 125.8730 kg/cm2, Exp.B
12 elif test $Exp="J"; then P="8.7130" # MPa == 108.9130 kg/cm2, Exp.J
13 elif test $Exp="F"; then P="8.6365" # MPa == 107.9560 kg/cm2, Exp.F
14 elif test $Exp="G"; then P="8.7934" # MPa == 109.9180 kg/cm2, Exp.G
15 else
16   echo "$0: ERROR: unknown experiment; try E,A, or B (full) J,F or G (partial)"
17   exit 0
18 fi;
19
20 xr="0.05"
21 echo "Setting initial conditions for experiment $Exp:  P0=$P, xr0=$xr."
22 ######################################################################
23 setp0 >/dev/null <<endsetp0
24 ######################################################################
25 #Enter origin of parameter vectors:
26 ######################################################################
27 #qs10, qs20, qf0, qfw0, Tfw0
28
29 #mdc, Vd, Vr, Vdc
30
31 #Tcf, qfrng
32
33 #Sw0, Sw1, Sw2, Sw3
34
35 #qscf
36
37 #qfcf
38
39 #Sigma1
40
41 #Sigma2
42
43 #Sigma3
44
45 #Sigma4
46
47 #Sigma5
48
49 #md
50
51 #mr
52
53 #Ad
54
55 #kf
56
57 #ks
58
59 #L0
60
61 #xi0
62
63 #b1
64
65 #b2
66
67 #dVwt0
68
69 #P0
70 $P
71 #xr0
72 $xr
73 endsetp0
74 ######################################################################
75 writep0 20 21 22
```

Listing C.4: cs_setp0.x0—Command script for IdKit's `setp0` command; the dataset specified on the command line affects lines 70 and 72 of the "here-document".

```
1   #!/bin/sh
2   ##################################################################
3   arglist=""
4   if [ $# -gt 0 ]; then
5     stat="OK"
6   fi;
7   while [ "$stat" = "OK" -a  $# -gt 0 ]; do
8     case "$1" in
9       2)
10        dimX=6;
11        states='\Vwt\,\ Total\ Liquid\ Vol\ [m3]       10
12  P\,\ Drum\ Pressure\ [MPa]            10'
13        b2="b2"
14        ;;
15      3)
16        dimX=7;
17        states='Vwt\,\ Total\ Liquid\ Vol\ [m3]      10
18  P\,\ Drum\ Pressure\ [MPa]            10
19  xr\,\ Vapor\ Mass\ Fract\ [--]          0.01'
20        b2="b2"
21        ;;
22      4)
23        dimX=8;
24        states='Vwt\,\ Total\ Liquid\ Vol\ [m3]      10
25  P\,\ Drum\ Pressure\ [MPa]            10
26  xr\,\ Vapor\ Mass\ Fract\ [--]          0.01
27  Vsd\,\ Vapor\ Bubble\ Vol\ [m3]         10'
28        b2="Vsd0"
29        ;;
30      5|5a)
31        dimX=9;
32        states='Vwt\,\ Total\ Liquid\ Vol\ [m3]      10
33  P\,\ Drum\ Pressure\ [MPa]            10
34  xr\,\ Vapor\ Mass\ Fract\ [--]          0.01
35  Vsd\,\ Vapor\ Bubble\ Vol\ [m3]         10
36  qsdd\,\ Pade\ Delay\ State\ [kg/s]      100'
37        b2="Vsd0"
38        ;;
39      -h|-help)
40        stat=""
41        ;;
42      *)
43        arglist="$arglist $1"
44        stat=""
45        ;;
46    esac
47    shift
48  done
49
50  if [ "$stat" != "OK" ]; then   # An error occurred.
51    if [ "$arglist" != "" ]; then
52      echo "$0:  unknown arguments: $arglist"
53      exit 1
54    else
55      echo ""
56      echo "    Use this command-script to set dimensions and names"
57      echo "    for the given order model.  For example:"
58      echo ""
59      echo "        $0 2"
60      echo ""
61      echo "    defines things for the second-order model structure."
62      echo ""
63      exit 2
64    fi;
65  fi;
66  ##################################################################
67  setm > /dev/null <<___end_setm___
68  #The following intersample input behavior is supported:
69  #1:  Zero-order Hold
70  #2:  Linear Interpolation
71  #Select Intersample Input Behavior:
72  2
73  #Timeinvariant?  Input linearization?  Ref. Eps.:  Kalman Eps.:
74  0                0                     1e-15       1e-15
75  #Dimensions of following vectors:
76  #V:   Z:   Y:   Xv:   Xz:   Xy:    Wv:   Wy:   U:   P:
77  0     0    2    0     0     $dimX  4     2     5    23
78  #Model-gain matrix indicators:
79  #Indicate how Y depends on
80  #V:  Z:  Xy:  Wy:  U:
81  0    0   1    1    1
82  #Indicate how Xy depends on
83  #V:  Z:  Xy:  Wv:  Wy:  U:
84  0    0   1    1    0    1
85  #Parameter Vectors:
86  #Name:                                  Dim:  Scale:
87  qs10\,\ qs20\,\ qf0\,\ qfw0\,\ Tfw0     5     0
88  mdc\,\ Vd\,\ Vr\,\ Vdc                  4     0
89  Tcf\,\ qfrng                            2     0
90  Sw0\,\ Sw1\,\ Sw2\,\ Sw3                4     0
91  qscf                                    1     0.1
92  qfcf                                    1     1
93  Sigma1                                  1     1
94  Sigma2                                  1     1
95  Sigma3                                  1     1
96  Sigma4                                  1     1
97  Sigma5                                  1     10
98  md                                      1     1E5
99  mr                                      1     1E5
100 Ad                                      1     10
101 kf                                      1     0.001
102 ks                                      1     1
103 L0                                      1     10
104 xi0                                     1     0.01
105 b1                                      1     1
106 $b2                                     1     1
107 dVwt0                                   1     10
108 P0                                      1     10
109 xr0                                     1     0.01
110 #Y: measurement model output vector:
111 #Name:                                  Scale:
112 P\,\ Drum\ Pressure\ [kg/cm2]           100
113 dl\,\ Level\ Variation\ [mm]            100
114 #e: residual vector:
115 #Name:                                  Scale:
116 Residual\ Drum\ Pressure\ [kg/cm2]      100
117 Residual\ Level\ Variation\ [mm]        100
118 #Xy: Measurement model state vector:
119 #Name:                                  Scale:
120 LPF1\,\ Low\ Pass\ Filter               1
121 WP1\,\ Wiener\ Process\ 1               1
122 WP2\,\ Wiener\ Process\ 2               1
123 WP3\,\ Wiener\ Process\ 3               1
124 $states
125 #U: Input vector:
126 #Name:                                  Scale:
127 qs1\,\ Steam\ Flow\ 1\ [kkg/hr]         100
128 qs2\,\ Steam\ Flow\ 2\ [kkg/hr]         100
129 qf\,\ Fuel\ Flow\ [kkg/hr]              10
130 qfw\,\ FeedWater\ Flow\ [kkg/hr]        100
131 Tfw\,\ FeedWater\ Temp\ [degC]          100
132 ___end_setm___
```

Listing C.5: cs_setm—Command script for IdKit's `setm` command; the model order specified on the command line affects the "here-document" input in lines 77, 106 and 124.

```
#!/bin/sh
#================================================================#
# $Id: cs_setp,v 1.4 1997/06/16 16:27:22 sorliej Exp $
#================================================================#
# Set default parameter mappings:
m_qscf=5;   m_qfcf=5;
m_Sigma1=5; m_Sigma2=5; m_Sigma3=5; m_Sigma4=5; m_Sigma5=5;
m_md=5;     m_mr=5;     m_Ad=1;
m_kf=5;     m_ks=1;     m_L0=1;     m_xi0=5;
m_b1=1;     m_b2=1;
m_dVwt0=1;  m_P0=5;     m_xr0=5;
# Set all parameter indicators "fixed" by default:
i_qscf=0;   i_qfcf=0;
i_Sigma1=0; i_Sigma2=0; i_Sigma3=0; i_Sigma4=0; i_Sigma5=0;
i_md=0;     i_mr=0;     i_Ad=0;
i_kf=0;     i_ks=0;     i_L0=0;     i_xi0=0;
i_b1=0;     i_b2=0;
i_dVwt0=0;  i_P0=0;     i_xr0=0;
#================================================================#
# Parse the command line for parameters to free.
arglist=""
modal=0
quiet=0
stat="OK"
nargs=$#
while [ "$stat" = "OK" -a  $# -gt 0 ]; do
  case "$1" in
    -h|-help)                nargs=`expr $nargs - 1`; stat=""; ;;
    -q|-quiet)               nargs=`expr $nargs - 1`; quiet=1; ;;
    -m|-modal)      modal=1; nargs=`expr $nargs - 1`; quiet=1;
      m_qscf=""; m_qfcf=""; m_Sigma1=""; m_Sigma2="";
      m_Sigma3=""; m_Sigma4=""; m_Sigma5=""; m_md=""; m_mr="";
      m_Ad=""; m_kf=""; m_ks=""; m_L0=""; m_xi0=""; m_b1="";
      m_b2=""; m_dVwt0=""; m_P0=""; m_xr0="";
      i_qscf=""; i_qfcf=""; i_Sigma1=""; i_Sigma2="";
      i_Sigma3=""; i_Sigma4=""; i_Sigma5=""; i_md=""; i_mr="";
      i_Ad=""; i_kf=""; i_ks=""; i_L0=""; i_xi0=""; i_b1="";
      i_b2=""; i_dVwt0=""; i_P0=""; i_xr0="";
      ;;
    *=*)
      lhs=`expr "$1" : '\([a-zA-Z0-9_]*\)=.*'`
      rhs=`expr "$1" : '[a-zA-Z0-9_]*=\(.*\)$'`
      eval "i_$lhs=1";
      case "$lhs" in
        qscf|qfcf)                                 eval "m_$lhs=$rhs"; ;;
        Sigma1|Sigma2|Sigma3|Sigma4|Sigma5)        eval "m_$lhs=$rhs"; ;;
        md|mr|Ad|kf|ks|L0|xi0|b1|dVwt0|P0|xr0) eval "m_$lhs=$rhs"; ;;
        b2|Vsd0)                   eval "i_b2=1"; eval "m_b2=$rhs";    ;;
        *)                              arglist="$arglist $1"; stat=""; ;;
      esac
      case "$rhs" in
        1|5|6)                                  ;;
        *)      arglist="$arglist $1"; stat=""; ;;
      esac
      ;;
    *)  case "$1" in
        qscf|qfcf)                                 eval "i_$1=1"; ;;
        Sigma1|Sigma2|Sigma3|Sigma4|Sigma5)        eval "i_$1=1"; ;;
        md|mr|Ad|kf|ks|L0|xi0|b1|dVwt0|P0|xr0) eval "i_$1=1"; ;;
        b2|Vsd0)                                   eval "i_b2=1"; ;;
        *)                     arglist="$arglist $1"; stat=""; ;;
      esac
      ;;
  esac
  shift
done
if [ "$stat" != "OK" ]; then   # An error occurred.
  if [ "$arglist" != "" ]; then
    echo "$0:  unknown arguments: $arglist"
    exit 1
  else
    echo "    Use this command-script to free parameters for search."
    echo "    The settings are NOT MODAL, i.e. all unspecified parameters"
    echo "    are set \"fixed\" as default.  Thus, you must specify the"
    echo "    COMPLETE set, each time you run the shell-script."
    exit 2
  fi;
fi;
#================================================================#
setp > /tmp/tmp.setp.txt <<___end_setp___
#Number of free parameter sets:
1
#For every p-vector, enter mapping and free components:
#1: Default linear and unbounded space.
#5: Keeps parameter vector >=0.
#6: Keeps parameter vector between  -1. and +1.
#qs10, qs20, qf0, qfw0, Tfw0            dim=5
#Map:    Set1:
5        0
#mdc, Vd, Vr, Vdc                       dim=4
5        0
#Tcf, qfrng                             dim=2
5        0
#Sw0, Sw1, Sw2, Sw3                     dim=4
5        0
#Map:    Set1:
$m_qscf   $i_qscf
$m_qfcf   $i_qfcf
$m_Sigma1 $i_Sigma1
$m_Sigma2 $i_Sigma2
$m_Sigma3 $i_Sigma3
$m_Sigma4 $i_Sigma4
$m_Sigma5 $i_Sigma5
$m_md     $i_md
$m_mr     $i_mr
$m_Ad     $i_Ad
$m_kf     $i_kf
$m_ks     $i_ks
$m_L0     $i_L0
$m_xi0    $i_xi0
$m_b1     $i_b1
$m_b2     $i_b2
$m_dVwt0  $i_dVwt0
$m_P0     $i_P0
$m_xr0    $i_xr0
___end_setp___

if [ $quiet != 1 ]; then
  # Filter the standard-output of the IdKit command, suppressing
  # blank and doubled lines.
  cat /tmp/tmp.setp.txt |\
  sed 's/^\(.*[^ ]\)[ ]*/\1/g; /^$/d; /^Map:.*$/d;' |\
#  sed '8,/^.*dim=1$/d' |\
  uniq
fi;
if [ $modal -eq 0 ]; then
  echo ""
  echo "Number of free parameters is: $nargs"
  echo ""
else
  cat /tmp/tmp.setp.txt |\
  awk '
    BEGIN {n=0}
    {if (($1==1 || $1==5 || $1==6) && $2==1) {n++}}
    END {printf "\nNumber of free parameters is: %d\n\n", n}'
fi;
rm /tmp/tmp.setp.txt
exit 0
```

Listing C.6: cs_setp—A more elaborate example of shell-script programming which encapsulates IdKit's command for partitioning the parameter set into fixed and free subsets, as well as specifying constraints for the parameter search.

C.2 Investigation of $\mathcal{M}_3$

```
#! /bin/sh -v
#--------------------------------------------------------------#
if [ $# -eq 0 ]; then  Exp="J";  kf=0.005;
else                   Exp="$1"; kf=$2;    fi;
#--------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1124/*.c .; mcompile
cs_setm 3
cs_sets 3 $Exp
cs_setp0 -d -q Sigma4=1 Sigma5=20 md=0 mr=0 kf=$kf b1=0 b2=0
cs_setp0 -q Sw0=1 Sw1=1 Sw2=2 Sw3=4
cs_setp0.u0 $Exp
cs_setp0.x0 $Exp
cs_setp0.cf $Exp
cs_setp -q
cs_writep0 "$0_$Exp"-p0_0
#--------------------------------------------------------------#
cs_setp -q qscf qfcf Sigma4 Sigma5 L0 xr0
sensit
cs_setp -q qscf qfcf Sigma4 Sigma5 L0
sensit
cs_setf iterations=20 step=1 reg=0
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_1
#--------------------------------------------------------------#
cs_setp0 -q L0=0
cs_setp  -q xr0
sensit
cs_setf step=0.5
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_2
#--------------------------------------------------------------#
cs_setp -q qscf qfcf Sigma4 Sigma5 L0
sensit
cs_setf step=1
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_3
#--------------------------------------------------------------#
cs_setp -q qscf qfcf Sigma4 Sigma5 ks L0
cm_setv
valid
#--------------------------------------------------------------#
cs_setp0 -q ks=4.8
cs_setp -q qscf qfcf Sigma4 Sigma5 L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_4
#--------------------------------------------------------------#
cs_setp -q qscf qfcf Sigma4 Sigma5 ks L0
cm_setv
valid
#--------------------------------------------------------------#
cs_setp -q qscf qfcf Sigma4 Sigma5 ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_5
#--------------------------------------------------------------#
cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 ks L0
sensit
cm_setv
valid
#--------------------------------------------------------------#
cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_6
#--------------------------------------------------------------#
"$0_$Exp"-p0_5
cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_7
#--------------------------------------------------------------#
"$0_$Exp"-p0_5
cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_8
#--------------------------------------------------------------#
"$0_$Exp"-p0_5
# Initialize positive-valued search with non-zero masses.
cs_setp0 -q md=1e5 mr=1e5
cs_setp -q qscf qfcf Sigma4 Sigma5 md=5 mr=5 ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_9
#--------------------------------------------------------------#
# Continue with an unbounded search, using positive-bounded search
# results as the starting point.  Repeating this tests the globality
# or locality of the result.
cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_10
#--------------------------------------------------------------#
# Check if masses are less than a limit; if so, use previous results.
limit=100000
md='writep0 11 | awk '{printf "%d", $3}''
mr='writep0 12 | awk '{printf "%d", $3}''
if   [ $md -lt $limit ]; then  md=0;"$0_$Exp"-p0_6;
elif [ $mr -lt $limit ]; then  mr=0;"$0_$Exp"-p0_7; fi;
# Then set the free parameters accordingly, adding Ad to the set.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0;;
esac;
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_11
#--------------------------------------------------------------#
cs_setp0 b1=1
cs_setp -m
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_12
#--------------------------------------------------------------#
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1;;
esac;
sensit
cm_setv
valid
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_13
#--------------------------------------------------------------#
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 xi0 b1;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 xi0 b1;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 xi0 b1;;
esac;
cm_setv
valid
#--------------------------------------------------------------#
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1 dVwt0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1 dVwt0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1 dVwt0;;
esac;
cm_setv
valid
#--------------------------------------------------------------#
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1 b2;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1 b2;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1 b2;;
esac;
cm_setv
valid
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_14
#--------------------------------------------------------------#
exit 0
```

Listing C.7: M3_Exp—Command script used to investigate the third-order model structure.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	217, 214, 30.5, 416, 289														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.267	0.2686	–	0.2686	0.2676	0.2673	0.2674	0.2674	0.2674	0.2674	0.2674	0.2673	0.2673	0.2674	0.2674
qfcf	5.612	5.6122	–	–	5.6464	5.6506	5.6515	5.6513	5.6516	5.6515	5.6517	5.6491	5.65	5.6512	5.6513
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	3.08	–	3.076	1.676	1.276	0.1785	0.1784	0.1785	0.1789	0.178	0.1775	0.1777	0.1776	0.1777
Sigma5	20	45.17	–	45.34	31.58	36.51	27.61	29.46	26.79	27.68	26.24	18.54	15.61	13.09	12.99
md	0	–	–	–	–	–	–	3.18e5	−1.63e5	1.87e4	−2.84e5	0	–	–	–
mr	0	–	–	–	–	–	3.19e5	0	4.82e5	3.02e5	6.02e5	3.17e5	3.17e5	3.16e5	3.16e5
Ad	20	–	–	–	–	–	–	–	–	–	–	28.17	27.11	26.4	26.2
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	7.727	8.116	8.119	8.115	8.115	8.117	8.143	8.135	8.159	8.151
L0	0	0.0096	0	−8e−5	0.016	0.023	0.019	0.018	0.019	0.019	0.019	0.015	0.033	0.065	0.075
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	2.722	3.247
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	0.8261
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.61	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0485	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4261.63	4253.44	4261.44	3566.58	3478.97	1869.96	1916.05	1850.21	n.c.	1835.79	1584.41	1462.1	1337.91	1334.77
$\mathcal{L}$	–	2125.81	2125.72	2125.72	1778.29	1733.18	927.981	951.026	917.104	n.c.	909.895	784.218	723.019	659.957	657.387
c.i.	–	−2.3	−0.916	−0.541	−7.76	−0.65	−2.53	−3.03	−3.05	0.132	−3.09	−5.67	−6.45	−5.71	-3.47
time	–	1 : 29.6	40.7	17.8	1 : 12.0	3 : 08.9	2 : 22.7	2 : 23.6	2 : 41.4	9 : 01.5	1 : 20.5	1 : 24.0	1 : 20.7	1 : 28.9	1:06.4

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236, 233, 31.4, 432, 295														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2553	–	0.2553	0.2552	0.2551	0.2551	0.2552	0.2551	0.2551	0.2551	0.2552	0.2552	0.2551	0.2551
qfcf	5.575	5.6203	–	5.6204	5.6211	5.6201	5.6227	5.6231	5.6227	5.6228	5.6226	5.6242	5.6248	5.6227	5.6215
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	3.675	–	3.589	2.823	3.099	0.4851	0.4859	0.4848	0.4856	0.4801	0.4752	0.4751	0.4758	0.4761
Sigma5	20	36.63	–	36.89	36.84	32	32.85	35.48	32.6	32.94	32.17	21.9	22.87	20.37	17.94
md	0	–	–	–	–	–	–	4.25e5	−5.31e4	2.57e4	−1.97e5	0	–	–	–
mr	0	–	–	–	–	–	4.26e5	0	4.79e5	4.03e5	6.23e5	4.19e5	4.21e5	4.16e5	4.19e5
Ad	20	–	–	–	–	–	–	–	–	–	–	28.36	29.04	27.18	27.28
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	3.371	7.067	7.032	7.075	7.064	7.201	7.652	7.676	7.699	7.607
L0	0	0.082	0	−0.0004	0.0008	−0.002	0.0008	0.0016	0.0007	0.0009	0.0005	0.01	−0.01	0.073	0.19
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−2.605	−7.514
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	2.722
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0381	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4249.83	4228.68	4235.92	4062.43	4030.67	2717.91	2774.46	2714.04	2722.76	2699.94	2415.68	2446.95	2366.88	2279.06
$\mathcal{L}$	–	2119.91	2113.34	2112.96	2026.22	2009.31	1351.96	1380.23	1349.02	1353.38	1341.97	1199.84	1215.47	1174.44	1129.53
c.i.	–	−0.197	−0.221	−3.38	−1.79	−0.0111	−2.15	−1.72	−2.32	−3.72	−0.725	−2.14	−8.42	−1.73	-1.31
time	–	1 : 30.7	58.8	36.1	54.6	1 : 46.2	2 : 24.7	2 : 24.9	2 : 43.6	5 : 49.3	54.4	1 : 21.7	1 : 22.9	1 : 29.1	1:39.3

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236, 233, 31.4, 432, 295														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2567	–	0.2567	0.2566	0.2566	0.2567	0.2587	–	0.2567	–	0.2569	0.2569	0.2567	0.2567
qfcf	5.575	5.6509	–	5.6509	5.6556	5.6563	5.6563	5.6563	5.6563	5.6563	–	5.6616	5.6619	5.6583	5.6571
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	0.9261	–	0.9133	0.5009	0.425	0.2224	0.2223	0.222	0.2217	0.2214	0.2247	0.2245	0.2393	0.228
Sigma5	20	22.66	–	22.62	18.42	19.11	20.18	19.87	19.98	19.94	19.89	10.67	10.92	7.124	6.199
md	0	–	–	–	–	–	–	3.84e5	2.69e5	3.48e5	4.2e5	3.85e5	3.91e5	2.86e5	3.45e5
mr	0	–	–	–	–	–	3.78e5	0	1.2e5	5.46e4	−1.77e4	0	–	–	–
Ad	20	–	–	–	–	–	–	–	–	–	–	28.71	29.11	25.42	24.48
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	7.391	8.378	8.296	8.374	8.315	8.355	9.389	9.556	9.933	9.486
L0	0	0.056	0	−0.0003	0.01	0.011	0.01	0.01	0.01	0.01	0.01	0.0071	−0.001	0.11	0.14
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−10.72	−14.09
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	3.733
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0418	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	2913.67	2904.75	2902.34	2322.78	2233.98	1809.71	1797.84	1803.13	1800.62	1798.52	1360.77	1378.05	n.c.	986.009
$\mathcal{L}$	–	1451.83	1451.37	1446.17	1156.39	1110.99	897.854	891.921	893.567	892.31	891.26	672.385	681.025	n.c.	483.005
c.i.	–	−4.37	−0.0909	−3.49	−14.5	−1.62	−0.46	−3.76	−0.369	−2.71	−0.879	−0.735	−1.2	0.517	-3.9
time	–	1 : 11.9	58.7	35.8	1 : 12.0	1 : 24.1	1 : 35.4	2 : 23.2	1 : 48.7	4 : 01.5	51.0	3 : 09.3	1 : 21.1	9 : 50.8	4:30.0

(c) Experiment B, full load, perturbed feed-water flow.

Table C.2: Optimization results for $\mathcal{M}_3$ with $k_f = 0.001$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2546	–	0.2546	0.2563	0.2554	0.2566	0.2565	0.2566	0.2566	0.2566	0.2564	0.2566	0.2567	0.2567
qfcf	6.205	6.2436	–	6.2427	6.2399	6.2396	6.2403	6.2392	6.2414	6.2406	6.2417	6.2348	6.2396	6.2422	6.2409
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	2.874	–	2.685	2.072	2.325	0.3177	0.3168	0.3285	0.3238	0.3167	0.3144	0.3155	0.3146	0.3144
Sigma5	20	35.19	–	36.26	48.07	39.67	33.97	39.96	26.99	33.24	25.69	30.81	24.21	20.49	19.98
md	0	–	–	–	–	–	–	3.91e5	−5.43e5	4.87e3	−6.85e5	0	–	–	–
mr	0	–	–	–	–	–	3.94e5	0	9.4c5	4.57e5	1.08e6	3.91e5	3.94e5	3.92e5	3.9e5
Ad	20	–	–	–	–	–	–	–	–	–	–	26.79	23.63	23.28	24.28
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	2.303	4.399	4.431	4.361	4.383	4.395	4.525	4.487	4.606	4.635
L0	0	0.18	0	−0.0005	−0.004	−0.004	0.0075	0.0063	0.009	0.0078	0.0093	−0.001	0.021	0.043	0.023
x10	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	2.194	1.256
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	−1.789
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.713	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0283	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4044.27	4011.93	4015.46	4031.68	3978.6	2437.95	2552.67	*n.c.*	*n.c.*	2240.53	2364.21	2193.5	2073.87	2057.4
$\mathcal{L}$	–	2017.13	2004.97	2002.73	2010.84	1983.3	1211.97	1269.33	*n.c.*	*n.c.*	1112.26	1174.1	1088.75	1027.93	1018.7
c.i.	–	−4.33	−1.26	−2.85	−2.52	−0.478	−3.02	−3.36	2.12	5.44	−0.705	−3.26	−2.19	−4.21	-8.06
time	–	1 : 11.9	1 : 10.0	36.1	54.1	2 : 48.3	1 : 59.1	1 : 59.0	9 : 01.3	9 : 11.4	1 : 47.6	1 : 20.8	1 : 20.8	1 : 28.3	1:38.0

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2517	–	0.2518	0.2529	0.2527	0.2524	0.2525	0.2524	0.2524	0.2524	0.2524	0.2525	0.2524	0.2525
qfcf	6.121	6.0873	–	6.088	6.0824	6.0918	6.0877	6.0893	6.0876	6.0878	6.0875	6.0882	6.0898	6.0879	6.0903
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	4.67	–	4.302	3.191	3.553	0.406	0.4109	0.4059	0.4058	0.4046	0.4064	0.406	0.4065	0.4047
Sigma5	20	33.08	–	34.96	31.77	18.67	11.78	16.94	11.74	11.83	11.73	11.17	13.32	11.08	9.177
md	0	–	–	–	–	–	–	3.34e5	−1.96e4	1.13e4	−2.97e4	0	–	–	–
mr	0	–	–	–	–	–	3.31e5	0	3.5e5	3.23e5	3.6e5	3.28e5	3.31e5	3.28e5	3.33e5
Ad	20	–	–	–	–	–	–	–	–	–	–	21.73	24.28	21.34	22.82
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	2.51	3.904	3.732	3.922	3.896	3.937	4.05	4.066	4.054	4.022
L0	0	0.2	0	0.001	−0.01	−0.001	−0.007	−0.004	−0.007	−0.007	−0.007	−0.006	−0.002	−0.007	−0.01
x10	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−0.1061	−2.694
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	1.869
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.636	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0258	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4348.76	4326.63	4327.49	4043.97	3741.57	1852.92	2122.9	1852.35	*n.c.*	1851.85	1820.06	1946.07	1816.42	1680.04
$\mathcal{L}$	–	2169.38	2162.32	2158.74	2016.99	1864.79	919.459	1054.45	918.174	*n.c.*	917.923	902.03	965.034	899.212	830.02
c.i.	–	−3.99	−0.807	−0.635	−2.98	−0.582	−3.12	−3.27	−2.74	1.39	−4.32	−1.09	−3.44	−1.65	-4.34
time	–	1 : 36.5	1 : 10.4	41.7	54.4	1 : 24.8	2 : 00.4	2 : 24.3	2 : 16.0	9 : 07.3	54.2	54.2	1 : 21.4	1 : 28.8	1:38.2

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.257	0.2547	–	0.2547	0.2549	0.2549	0.2549	0.2549	0.2549	0.2549	0.2549	0.2552	0.2552	0.2549	0.2549
qfcf	6.121	6.0708	–	6.0705	6.0733	6.0734	6.0709	6.0706	6.0706	6.0705	6.0704	6.0767	6.0774	6.0702	6.0699
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	1.338	–	1.258	0.6559	0.6539	0.2059	–	0.2058	0.2056	0.2054	0.2065	0.2064	0.2091	0.2052
Sigma5	20	16.69	–	16.61	16.71	16.74	16.3	15.35	15.54	15.39	15.13	10.35	10.85	6.673	5.709
md	0	–	–	–	–	–	–	6.06e5	4.81e5	6.02e5	7.66e5	5.88e5	5.96e5	5.48e5	5.95e5
mr	0	–	–	–	–	–	5.96e5	0	1.32e5	3.03e4	−1.42e5	0	–	–	–
Ad	20	–	–	–	–	–	–	–	–	–	–	24.3	24.59	22.03	22.25
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	4.859	4.661	4.573	4.575	4.514	4.525	5.291	5.288	5.332	5.078
L0	0	0.22	0	−0.0005	0.0052	0.0053	0.0039	0.0036	0.0037	0.0036	0.0035	0.0049	−0.01	0.17	0.14
x10	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−8.789	−7.632
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	3.67
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.793	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0239	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	2958.21	2904.91	2910.21	2446.31	2448.3	1600.75	1557.03	1567.7	1560.09	1548.23	1279.44	1312.6	975.9	851.366
$\mathcal{L}$	–	1474.11	1451.47	1450.1	1218.15	1218.15	793.376	771.514	775.848	772.017	766.117	631.721	648.298	478.95	415.683
c.i.	–	−9.63	−0.629	−6.63	−2.74	−0.459	−0.575	−3.85	−0.179	−1.33	−1.43	−1.69	−6.5	−1.6	-4.76
time	–	1 : 11.0	1 : 15.7	35.8	54.1	23.1	1 : 35.6	1 : 59.6	1 : 48.2	4 : 04.1	53.9	1 : 20.9	1 : 20.9	2 : 57.3	1:37.5

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.2: $\mathcal{M}_3$, $k_f = 0.001$ (*continued*).

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	217,214,30.5,416,289														
mdc,...	0,40,38,11														
Tcf,qfrng	100,0														
Sw0,...	1,1,2,4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.267	0.2687	–	0.2687	0.2676	0.2674	0.2674	0.2674	0.2674	0.2674	0.2674	0.2673	0.2674	0.2674	0.2674
qfcf	5.612	5.6424	–	5.6422	5.647	5.6507	5.6519	5.6516	5.6521	5.6519	5.6522	5.6497	5.6508	5.6514	5.6514
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	3.070	–	3.232	1.802	1.423	0.1788	0.1786	0.1787	0.1787	0.1781	0.1776	0.1778	0.1777	0.1777
Sigma5	20	43.71	–	41.87	29.2	34.18	25.45	28.13	23.97	25.58	23.47	17.1	13.66	12.69	12.67
md	0	–	–	–	–	–	–	3.36e5	−2.39e5	2.0e4	−3.41e5	0	–	–	–
mr	0	–	–	–	–	–	3.37e5	0	5.76e5	3.18e5	6.77e5	3.35e5	3.36e5	3.34e5	3.35e5
Ad	20	–	–	–	–	–	–	–	–	–	–	27.46	26.38	26.13	26.07
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	7.313	8.105	8.111	8.105	8.104	8.109	8.133	8.128	8.153	8.15
L0	0	−0.2	0	0.0004	0.017	0.023	0.018	0.017	0.018	0.018	0.019	0.015	0.032	0.045	0.047
xl0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	1.763	1.905
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	0.3081
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.61	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0857	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4237.95	4364.74	4239.91	3562.76	3509.2	1812.38	1883.43	1771.37	1817.66	1756.65	1527.25	1367.11	1315.86	1317.09
$\mathcal{L}$	–	2113.98	2181.37	2114.97	1776.38	1748.6	899.188	934.714	877.686	900.828	870.327	755.626	675.556	648.928	648.546
c.i.	–	−2.58	−0.846	−2.51	−6.82	−0.409	−1.55	−2.05	−2.04	−2.07	−2.18	−5.74	−5.21	−10.1	-7.9
time	–	1 : 31.0	1 : 03.9	54.8	1 : 11.9	3 : 29.7	2 : 22.9	2 : 22.8	2 : 41.5	5 : 51.9	1 : 20.5	1 : 20.5	1 : 25.6	1 : 27.9	1:04.6

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236,233,31.4,432,295														
mdc,...	0,40,38,11														
Tcf,qfrng	100,0														
Sw0,...	1,1,2,4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2553	–	0.2553	0.2552	0.255	0.2552	0.2552	0.2551	0.2552	0.2551	0.2552	0.2553	0.2551	0.255
qfcf	5.575	5.6207	–	5.6205	5.6211	5.6195	5.6228	5.6233	5.6227	5.6228	5.6225	5.6243	5.6251	5.6225	5.6209
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	3.675	–	3.829	3.045	3.439	0.4846	0.4854	0.484	0.4854	0.4793	0.4751	0.4749	0.4757	0.4772
Sigma5	20	36.36	–	36.17	39.03	32.11	34.05	38.1	33.37	34.13	32.86	22.61	23.92	20.87	18.02
md	0	–	–	–	–	–	–	4.44e5	−1.08e5	1.78e4	−2.43e5	0	–	–	–
mr	0	–	–	–	–	–	4.46e5	0	5.52e5	4.31e5	6.87e5	4.39e5	4.42e5	4.35e5	4.37e5
Ad	20	–	–	–	–	–	–	–	–	–	–	28.69	29.64	27.24	27.2
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	2.955	7.081	7.047	7.103	7.082	7.251	7.65	7.689	7.666	7.453
L0	0	−0.1	0	−0.0005	0.0007	−0.003	0.0007	0.0019	0.0004	0.0007	0.0002	0.01	−0.01	0.065	0.18
xl0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−2.294	−6.806
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	3.346
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0709	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4244.55	4262.34	4268.3	4158.44	4107.72	2742.93	2824.81	2729.51	n.c.	2713.75	2438.19	2470.01	2384.16	2284.28
$\mathcal{L}$	–	2117.27	2130.17	2129.15	2074.22	2047.86	1364.46	1405.41	1356.76	n.c.	1348.88	1211.09	1231.5	1183.08	1132.14
c.i.	–	−0.377	−1.09	−2.43	−2.07	−1.33	−1.89	−1.43	−2.19	1.54	−0.0665	−2.19	−7.64	−0.957	-0.579
time	–	1 : 29.8	1 : 03.8	35.7	54.0	2 : 18.9	2 : 23.0	2 : 24.2	2 : 42.0	9 : 03.6	53.9	1 : 20.9	1 : 22.1	1 : 28.3	1:37.5

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236,233,31.4,432,295														
mdc,...	0,40,38,11														
Tcf,qfrng	100,0														
Sw0,...	1,1,2,4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2507	–	0.2567	0.2566	0.2566	0.2567	0.2567	0.2567	0.2567	–	0.2569	0.2569	0.2567	0.2567
qfcf	5.575	5.651	–	5.6509	5.6558	5.6564	5.6564	5.6563	5.6564	–	5.6563	5.6618	5.6622	5.6575	5.6566
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	0.9262	–	0.9616	0.5299	0.4487	0.2224	0.2221	0.222	0.2216	0.2214	0.2243	0.224	0.239	0.227
Sigma5	20	22.9	–	23.03	19.13	19.95	20.78	20.33	20.45	20.41	20.3	10.77	11.09	6.722	6.155
md	0	–	–	–	–	–	–	4.07e5	3.06e5	3.84e5	4.78e5	4.08e5	4.15e5	3.09e5	3.73e5
mr	0	–	–	–	–	–	4.02e5	0	1.08e5	4.32e4	−5.28e4	0	–	–	–
Ad	20	–	–	–	–	–	–	–	–	–	–	28.96	29.44	24.72	24.12
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	7.478	8.334	8.34	8.291	8.367	8.371	9.35	9.48	9.829	9.502
L0	0	−0.2	0	−0.0005	0.0092	0.0099	0.009	0.0088	0.0088	0.0088	0.0088	0.0061	−0.003	0.12	0.14
xl0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−10.74	−12.68
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	3.613
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0762	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	2021.23	3106.24	2952.02	2390.29	2303.95	1830.78	1813.73	1819.67	1816.94	1812.86	1366.74	1387.26	1076.64	977.864
$\mathcal{L}$	–	1455.61	1552.12	1471.01	1190.15	1145.97	908.388	899.866	901.836	900.468	898.428	675.371	685.631	529.321	478.932
c.i.	–	−4.37	−1.26	−7.19	−12.7	−0.742	−0.631	−0.932	−0.525	−1.38	−1.3	−0.972	−1.7	−0.862	-2.94
time	–	1 : 18.5	1 : 10.4	58.4	1 : 13.0	1 : 26.3	1 : 13.3	1 : 37.7	1 : 22.5	3 : 14.0	55.0	3 : 12.9	1 : 22.6	3 : 59.5	2:45.2

(c) Experiment B, full load, perturbed feed-water flow.

Table C.3: Optimization results for $\mathcal{M}_3$ with $k_f = 0.005$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	−	−	−	−	−	−	−	−	−	−	−	−	−	−
qscf	0.253	0.2547	−	0.2547	0.2564	0.2553	0.2566	0.2566	0.2567	0.2566	0.2567	0.2565	0.2567	0.2568	0.2567
qfcf	6.205	6.2443	−	6.2443	6.2412	6.2411	6.2414	6.24	6.243	6.2417	6.2432	6.2376	6.2423	6.2429	6.2416
Sigma1	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma2	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma3	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma4	1	2.876	−	2.879	2.238	2.581	0.3185	0.3172	0.3184	0.3262	0.3166	0.315	0.3152	0.3147	0.3145
Sigma5	20	32.53	−	32.55	45.09	34.76	29.8	38.46	21.66	29.53	21.19	28.02	20.6	20.13	19.52
md	0	−	−	−	−	−	−	4.08e5	−5.5e5	7.28e3	−6.14e5	0	−	−	−
mr	0	−	−	−	−	−	4.13e5	0	9.59e5	4.08e5	1.02e6	4.11e5	4.12e5	4.1e5	4.08e5
Ad	20	−	−	−	−	−	−	−	−	−	−	24.73	22.46	22.71	23.72
kf	0.005	−	−	−	−	−	−	−	−	−	−	−	−	−	−
ks	0	−	−	−	4.8	1.866	4.374	4.422	4.374	4.337	4.415	4.498	4.532	4.607	4.633
L0	0	0.0009	0	−0.0001	−0.004	−0.003	0.0077	0.006	0.0096	0.0079	0.01	0.001	0.023	0.028	0.013
xi0	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
b1	0	−	−	−	−	−	−	−	−	−	−	−	1	1.296	0.6166
b2	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−1.817
dVwt0	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
P0	8.713	−	−	−	−	−	−	−	−	−	−	−	−	−	−
xr0	0.05	−	0.0499	−	−	−	−	−	−	−	−	−	−	−	−
$\|\nu\|$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	−	3988.09	3979.94	3987.93	4041.02	3958.76	2345.53	2525.93	2117.94	n.c.	2100.73	2297.76	2076.98	2061.39	2040.95
$\mathcal{L}$	−	1989.05	1988.97	1989.97	2015.51	1973.38	1165.76	1255.97	1050.97	n.c.	1042.37	1140.88	1030.49	1021.7	1010.47
c.i.	−	−4.89	−0.391	−2.17	−2.39	−0.974	−2.33	−1.52	−3.27	2.35	−2.3	−4.22	−2.04	−3.07	-8.27
time	−	1 : 11.8	23.4	17.8	54.1	2 : 48.4	1 : 59.4	2 : 07.2	2 : 14.0	9 : 01.9	1 : 47.5	1 : 20.7	1 : 20.6	58.6	1:37.2

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	−	−	−	−	−	−	−	−	−	−	−	−	−	−
qscf	0.253	0.2518	−	0.2518	0.2529	0.2525	0.2524	0.2525	0.2524	0.2524	0.2524	0.2524	0.2526	0.2524	0.2525
qfcf	6.121	6.088	−	6.0881	6.0812	6.0925	6.0874	6.0894	6.0868	6.0874	6.0867	6.0882	6.0908	6.0872	6.0896
Sigma1	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma2	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma3	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma4	1	4.672	−	4.627	3.463	3.987	0.4068	0.41	0.4063	0.4074	0.4047	0.4057	0.406	0.406	0.4048
Sigma5	20	31.02	−	31.28	36.5	19.14	13.76	24.57	13.2	13.82	13.2	12.63	16.36	11.92	9.757
md	0	−	−	−	−	−	−	3.51e5	−7.38e4	3.94e3	−8.12e4	0	−	−	−
mr	0	−	−	−	−	−	3.5e5	0	4.21e5	3.49e5	4.29e5	3.47e5	3.5e5	3.45e5	3.49e5
Ad	20	−	−	−	−	−	−	−	−	−	−	22.61	26.91	21.12	22.19
kf	0.005	−	−	−	−	−	−	−	−	−	−	−	−	−	−
ks	0	−	−	−	4.8	2.107	3.848	3.756	3.929	3.844	3.944	4.028	4.075	4.013	3.902
L0	0	0.029	0	0.0002	−0.01	−0.002	−0.007	−0.004	−0.008	−0.007	−0.008	−0.006	−0.0008	−0.008	−0.01
xi0	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
b1	0	−	−	−	−	−	−	−	−	−	−	−	1	−0.4581	−2.26
b2	0	−	−	−	−	−	−	−	−	−	−	−	−	−	1.886
dVwt0	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
P0	8.636	−	−	−	−	−	−	−	−	−	−	−	−	−	−
xr0	0.05	−	0.0461	−	−	−	−	−	−	−	−	−	−	−	−
$\|\nu\|$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	−	4302.96	4292.09	4299.95	4202.68	3842.08	1966.12	2388.68	1937.68	n.c.	1936.98	1906.94	2093.85	1867.63	1724.23
$\mathcal{L}$	−	2146.48	2145.04	2144.98	2096.34	1915.04	976.058	1187.34	960.842	n.c.	960.49	945.468	1038.92	924.817	852.116
c.i.	−	−4.19	−0.723	−4.82	−2.4	−0.0646	−2.13	−1.63	−1.02	2.65	−1.23	−0.327	−1.4	−5.03	-2.3
time	−	1 : 39.6	58.5	39.5	58.9	1 : 33.8	2 : 31.2	2 : 39.5	2 : 29.4	10 : 01.4	59.6	59.6	1 : 29.5	2 : 44.7	1:47.8

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	−	−	−	−	−	−	−	−	−	−	−	−	−	−
qscf	0.257	0.2547	−	0.2547	0.2549	0.2549	0.2549	0.2549	0.2549	0.2549	0.2549	0.2552	0.2553	0.2549	0.2549
qfcf	6.121	6.0711	−	6.071	6.0739	6.0745	6.0714	6.0709	6.071	6.0709	6.0707	6.0772	6.0782	6.0697	6.07
Sigma1	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma2	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma3	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
Sigma4	1	1.338	−	1.322	0.6891	0.6682	0.2056	0.2057	0.2056	0.2055	0.2054	0.2063	0.206	0.2086	0.2052
Sigma5	20	17.05	−	17	17.74	18.2	17.33	15.92	16.08	15.95	15.47	10.57	11.21	6.71	5.716
md	0	−	−	−	−	−	−	6.26e5	5.5e5	6.34e5	8.52e5	6.1e5	6.2e5	5.72e5	6.09e5
mr	0	−	−	−	−	−	6.12e5	0	7.99e4	2.21e4	−2.09e5	0	−	−	−
Ad	20	−	−	−	−	−	−	−	−	−	−	24.49	24.89	21.83	22.27
kf	0.005	−	−	−	−	−	−	−	−	−	−	−	−	−	−
ks	0	−	−	−	4.8	5.286	4.721	4.597	4.607	4.565	4.523	5.272	5.257	5.299	5.061
L0	0	0.045	0	−0.0001	0.0054	0.0061	0.004	0.0036	0.0036	0.0036	0.0034	0.0048	−0.01	0.14	0.11
xi0	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
b1	0	−	−	−	−	−	−	−	−	−	−	−	1	−7.411	−5.931
b2	0	−	−	−	−	−	−	−	−	−	−	−	−	−	3.873
dVwt0	0	−	−	−	−	−	−	−	−	−	−	−	−	−	−
P0	8.793	−	−	−	−	−	−	−	−	−	−	−	−	−	−
xr0	0.05	−	0.0438	−	−	−	−	−	−	−	−	−	−	−	−
$\|\nu\|$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	−	2973.55	2954.68	2962.55	2525.08	2523.87	1643.26	1582.29	1591.19	1585.86	1564.47	1293.19	1335.09	976.766	852.526
$\mathcal{L}$	−	1481.77	1476.34	1476.28	1257.54	1255.94	814.63	784.144	787.595	784.928	774.236	638.595	659.545	479.383	416.263
c.i.	−	−10.7	−1.36	−10.1	−3.05	−0.336	−4.03	−2.82	−3.18	−0.019	−0.274	−1.73	−6.47	−2.82	-3.65
time	−	1 : 16.6	1 : 03.9	36.1	54.0	1 : 24.1	1 : 59.4	1 : 59.4	2 : 23.2	3 : 09.7	53.8	1 : 20.8	1 : 20.7	2 : 56.7	1:37.2

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.3: $\mathcal{M}_3$, $k_f = 0.005$ (*continued*).

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	217, 214, 30.5, 416, 289														
mdc,...	0, 10, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.267	0.2687	–	0.2687	0.2676	0.2674	0.2674	0.2674	0.2674	0.2674	0.2674	0.2673	0.2674	0.2674	–
qfcf	5.612	5.6425	–	5.6422	5.6473	5.6507	5.6521	5.6517	5.6523	5.6521	5.6524	5.65	5.6511	5.6515	–
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	3.079	–	3.316	1.871	1.513	0.1789	0.1786	0.1788	0.1793	0.1782	0.1777	0.1778	0.1777	0.1777
Sigma5	20	43.36	–	40.4	28.37	33.09	24.61	27.68	22.91	24.67	22.44	16.56	13.1	12.56	12.56
md	0	–	–	–	–	–	–	3.45e5	−2.59e5	1.34e4	−3.56e5	0	–	–	–
mr	0	–	–	–	–	–	3.47e5	0	6.05e5	3.35e5	7.02e5	3.45e5	3.45e5	3.44e5	3.44e5
Ad	20	–	–	–	–	–	–	–	–	–	–	27.18	26.14	26.01	26.01
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	7.018	8.1	8.107	8.1	8.1	8.106	8.129	8.128	8.15	8.15
L0	0	−0.3	0	−0.002	0.014	0.02	0.015	0.014	0.016	0.015	0.016	0.013	0.027	0.034	0.034
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	1.514	1.519
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	0.00266
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.61	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.11	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4232.24	4608.22	4232.72	3568.72	3530.3	1788.75	1872	1739.38	n.c.	1724.6	1504.41	1337.19	1308.74	1310.7
$\mathcal{L}$	–	2111.12	2303.11	2111.36	1779.36	1759.15	887.375	928.998	861.691	n.c.	854.298	744.206	660.594	645.371	645.349
c.i.	–	−2.65	−0.245	−1.07	−6.52	−0.058	−1.09	−1.42	−1.58	0.414	−2.13	−6.08	−5.19	−1.58	-4.89
time	–	1 : 30.3	1 : 13.9	53.4	1 : 11.7	3 : 29.1	2 : 44.4	1 : 59.6	2 : 51.3	8 : 59.9	1 : 20.3	1 : 20.4	1 : 23.6	58.4	32.1

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236, 233, 31.4, 432, 295														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2553	–	0.2553	0.2552	0.255	0.2552	0.2552	0.2551	0.2552	0.2551	0.2552	0.2553	0.2551	0.255
qfcf	5.575	5.6209	–	5.6206	5.621	5.6192	5.6228	5.6234	5.6226	5.6228	5.6225	5.6243	5.6253	5.6224	5.6207
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	3.675	–	3.961	3.167	3.608	0.4844	0.485	0.4836	0.4853	0.479	0.4751	0.4749	0.4757	0.4784
Sigma5	20	36.45	–	36.18	40.29	32.54	34.6	39.25	33.78	34.67	33.2	22.93	24.34	21.21	18.41
md	0	–	–	–	–	–	–	4.54e5	−1.21e5	1.58e4	−2.57e5	0	–	–	–
mr	0	–	–	–	–	–	4.56e5	0	5.75e5	4.49e5	7.11e5	4.5e5	4.52e5	4.45e5	4.46e5
Ad	20	–	–	–	–	–	–	–	–	–	–	28.84	29.89	27.32	27.2
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	2.804	7.09	7.057	7.117	7.092	7.274	7.651	7.696	7.649	7.363
L0	0	−0.2	0	−0.0005	0.0006	−0.003	0.0006	0.0019	0.0002	0.00063e	− 5	0.01	−0.01	0.062	0.17
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−2.154	−6.352
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	3.412
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.093	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4246.43	4294.52	4293.1	4209.39	4151.59	2754.06	2845.78	2737.55	n.c.	2720.52	2448.39	2491.43	2395.82	2301.67
$\mathcal{L}$	–	2118.21	2146.26	2141.55	2099.7	2069.8	1370.03	1415.89	1360.77	n.c.	1352.26	1216.19	1237.71	1188.91	1140.83
c.i.	–	−0.445	−1.34	−0.559	−2.28	−1.38	−1.79	−1.37	−2.18	2.31	−4.13	−2.22	−7.34	−0.631	-0.113
time	–	1 : 30.1	1 : 10.1	35.8	54.2	2 : 06.5	2 : 23.9	2 : 23.5	2 : 42.1	9 : 03.9	1 : 33.4	1 : 20.9	1 : 20.9	1 : 28.3	1:37.5

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236, 233, 31.4, 432, 295														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2567	–	0.2567	0.2566	0.2566	0.2567	0.2567	–	–	–	0.2569	0.2569	0.2567	0.2567
qfcf	5.575	5.6512	–	5.6509	5.6559	5.6564	5.6565	5.6564	5.6564	–	5.6564	5.6619	5.6624	5.6574	5.6567
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	0.9262	–	0.988	0.5458	0.4616	0.2224	0.2221	0.2210	0.2215	0.2213	0.2241	0.2238	0.2388	0.227
Sigma5	20	23.06	–	23.19	19.44	20.33	21.03	20.52	20.05	20.6	20.47	10.81	11.14	6.788	6.197
md	0	–	–	–	–	–	–	4.2e5	3.21e5	3.93e5	4.95e5	4.2e5	4.20e5	3.2e5	3.83e5
mr	0	–	–	–	–	–	4.12e5	0	1.05e5	4.52e4	−5.9e4	0	–	–	–
Ad	20	–	–	–	–	–	–	–	–	–	–	29.06	29.57	24.72	24.19
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	7.519	8.37	8.28	8.321	8.359	8.366	9.314	9.451	9.842	9.491
L0	0	−0.3	0	−0.002	0.0073	0.0079	0.0068	0.0067	0.0067	0.0067	0.0066	0.0046	−0.006	0.14	0.16
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−10.39	−11.96
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	3.925
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.099	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	2926.24	3508.64	2976.44	2422.89	2337.81	1839.23	1820.67	1826.37	1823.13	1818.83	1368.59	1389.72	1082.95	982.883
$\mathcal{L}$	–	1458.12	1753.32	1483.22	1206.44	1162.91	912.616	903.335	905.184	903.565	901.417	670.295	686.861	532.475	481.442
c.i.	–	−4.35	−0.398	−5.06	−12.1	−0.337	−1.13	−0.653	−1.23	−1.35	−1.08	−0.041	−1.55	−1.17	-3
time	–	1 : 15.6	1 : 12.9	56.5	1 : 16.0	1 : 28.8	1 : 15.5	1 : 15.5	1 : 25.6	4 : 46.2	56.9	3 : 19.2	1 : 25.3	4 : 09.5	2:53.4

(c) Experiment B, full load, perturbed feed-water flow.

Table C.4: Optimization results for $\mathcal{M}_3$ with $k_f = 0.01$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2547	–	0.2547	0.2564	0.2553	0.2566	0.2566	0.2567	0.2566	0.2567	0.2565	0.2568	0.2568	0.2567
qfcf	6.205	6.2447	–	6.245	6.2418	6.2417	6.2419	6.2403	6.2435	6.2421	6.2437	6.2388	6.2431	6.2432	6.2419
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	2.876	–	2.988	2.331	2.707	0.3188	0.3173	0.3181	0.3271	0.3163	0.3153	0.3148	0.3147	0.3145
Sigma5	20	31.72	–	31.25	44.13	33.17	28.19	38.03	20.48	27.85	20.17	26.9	20.11	20.08	19.34
md	0	–	–	–	–	–	–	4.18e5	−5.04e5	1.15e4	−5.53e5	0	–	–	–
mr	0	–	–	–	–	–	4.23e5	0	9.21e5	4.21e5	9.71e5	4.21e5	4.2e5	4.2e5	4.18e5
Ad	20	–	–	–	–	–	–	–	–	–	–	23.95	22.34	22.42	23.47
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	1.743	4.367	4.421	4.393	4.338	4.438	4.487	4.589	4.607	4.634
L0	0	−0.09	0	−0.0003	−0.005	−0.003	0.0076	0.0056	0.0096	0.0078	0.0099	0.0018	0.023	0.024	0.0094
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	1.053	0.4205
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	−1.906
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.713	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0643	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	3970.2	3979.03	3985.5	4054.74	3959.44	2306.31	2518.38	2076.78	n.c.	2064.17	2269	2058.6	2059.88	2034.44
$\mathcal{L}$	–	1980.1	1988.51	1987.75	2022.37	1973.72	1146.15	1252.19	1030.39	n.c.	1024.08	1126.5	1021.3	1020.94	1007.22
c.i.	–	−4.91	−1.31	−4.29	−2.34	−0.0676	−1.8	−0.535	−3.72	3.75	−3.42	−4.64	−3.23	−6.3	-8.06
time	–	1 : 12.5	1 : 14.0	35.7	54.4	2 : 27.0	1 : 59.0	1 : 59.1	2 : 14.5	9 : 02.2	2 : 04.0	1 : 20.8	1 : 33.0	59.1	1:37.2

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.253	0.2518	–	0.2518	0.2528	0.2525	0.2521	0.2525	0.2523	0.2524	0.2523	0.2524	0.2526	0.2524	0.2525
qfcf	6.121	6.0885	–	6.0882	6.0806	6.0926	6.0872	6.0894	6.0864	6.0872	6.0863	6.0882	6.0913	6.0869	6.0892
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	4.672	–	4.81	3.616	4.22	0.407	0.4093	0.4063	0.4071	0.4047	0.4055	0.4061	0.4058	0.4061
Sigma5	20	30.98	–	30.48	39.18	20.38	15.01	28.29	14.13	15.07	14.12	13.53	17.62	12.51	10.25
md	0	–	–	–	–	–	–	3.6e5	−8.78e4	3.02e3	−9.48e4	0	–	–	–
mr	0	–	–	–	–	–	3.6e5	0	4.44e5	3.61e5	4.52e5	3.57e5	3.6e5	3.54e5	3.57e5
Ad	20	–	–	–	–	–	–	–	–	–	–	23.09	28.18	21.07	21.89
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	1.956	3.839	3.774	3.935	3.839	3.951	4.027	4.078	3.997	3.847
L0	0	−0.07	0	−0.0007	−0.02	−0.002	−0.008	−0.005	−0.009	−0.008	−0.009	−0.006	−0.0009	−0.009	−0.01
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−0.5244	−2.122
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	1.867
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.636	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0596	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	4301.93	4302.01	4309.11	4284.7	3927.7	2028.53	2488.54	1986.05	n.c.	1985.36	1956.08	2147.21	1902.4	1761.86
$\mathcal{L}$	–	2145.96	2150	2149.56	2137.35	1957.85	1007.27	1237.27	985.023	n.c.	984.678	970.042	1065.6	942.201	870.93
c.i.	–	−4.42	−0.568	−3.28	−2.13	−3.32	−1.05	−1.53	−1.1	3.08	−0.279	−7.4	−0.942	−4.99	-1.19
time	–	1 : 39.8	1 : 04.8	30.8	1 : 00.2	1 : 57.1	2 : 12.2	2 : 38.7	2 : 29.6	10 : 01.6	59.8	1 : 29.6	1 : 29.6	2 : 42.1	1:47.4

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
qscf	0.257	0.2547	–	–	0.2549	0.255	0.2549	0.2549	0.2549	0.2549	0.2549	0.2553	0.2553	0.2549	0.2549
qfcf	6.121	6.0713	–	6.0713	6.0742	6.075	6.0716	6.0711	6.0712	6.071	6.0709	6.0775	6.0786	6.0697	6.0702
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	1	1.338	–	1.357	0.7077	0.677	0.2056	0.2056	0.2055	0.2055	0.2055	0.2062	0.2059	0.2086	0.2053
Sigma5	20	17.16	–	17.2	18.24	18.9	17.79	16.17	16.31	16.18	15.57	10.65	11.34	6.836	5.746
md	0	–	–	–	–	–	–	6.37e5	5.8e5	6.61e5	9.0e5	6.21e5	6.32e5	5.81e5	6.15e5
mr	0	–	–	–	–	–	6.21e5	0	5.96e4	1.59e4	−2.47e5	0	–	–	–
Ad	20	–	–	–	–	–	–	–	–	–	–	24.58	25.02	21.83	22.34
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	0	–	–	–	4.8	5.523	4.745	4.608	4.616	4.574	4.512	5.263	5.244	5.294	5.052
L0	0	−0.05	0	−0.0001	0.0053	0.0063	0.0038	0.0034	0.0034	0.0033	0.0031	0.0045	−0.01	0.14	0.1
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0	–	–	–	–	–	–	–	–	–	–	–	1	−6.891	−5.382
b2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	4.064
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.793	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.05	–	0.0571	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	5	1	5	5	6	7	7	8	8	8	8	8	9	10
AIC	–	2978.54	2982.45	2990.28	2564.17	2560.14	1661.76	1593.14	1600.8	n.c.	1569.04	1298.22	1342.71	990.218	856.715
$\mathcal{L}$	–	1484.27	1490.23	1490.14	1277.08	1274.07	823.881	789.568	792.398	n.c.	776.518	641.11	663.355	486.109	418.358
c.i.	–	−1.74	−1.36	−9.67	−3.25	−0.55	−3.61	−2.28	−2.66	1.81	−3.27	−1.72	−6.59	−2.87	-3.08
time	–	58.1	1 : 04.8	36.3	1 : 02.8	2 : 02.5	2 : 08.6	2 : 00.8	2 : 17.8	9 : 08.7	1 : 21.7	1 : 21.7	1 : 21.6	2 : 58.1	1:38.3

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.4: $\mathcal{M}_3$, $k_f = 0.01$ *(continued)*.

C.3 Investigation of $\mathcal{M}_4$

```
#! /bin/sh -v
#--------------------------------------------------------------#
if [ $# -eq 0 ]; then  Exp="J";  kf=0.005;
else                   Exp="$1"; kf=$2;    fi;
#--------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1120/*.c .; mcompile
cs_setm 4
cs_sets 4 $Exp
# Use results of third-order model as default parameter settings.
"../3/kf/$kf/M3_Exp_$Exp-p0_11"
cs_setp0 -q Sw0=1 Sw1=1 Sw2=2 Sw3=0 mr=0 md=0 kf=$kf b1=0.7 Vsd0=8
cs_setp -q
cs_writep0 "$0_$Exp"-p0_0
#--------------------------------------------------------------#
cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0
sensit
cs_setf iterations=20 step=1 reg=0
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_1
#--------------------------------------------------------------#
"$0_$Exp"-p0_0
cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_2
#--------------------------------------------------------------#
"$0_$Exp"-p0_0
cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_3
#--------------------------------------------------------------#
"$0_$Exp"-p0_0
# Initialize positive-valued search with non-zero masses.
cs_setp0 -q md=1e5 mr=1e5
cs_setp -q qscf qfcf Sigma4 Sigma5 md=5 mr=5 Ad ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_4
#--------------------------------------------------------------#
# Continue with an unbounded search, using positive-bounded search
# results as the starting point.  Repeating this tests the
# globality or locality of the result.
cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_5
#--------------------------------------------------------------#
# Check if masses are less than a limit; if so use previous results.
limit=100000
md=`writep0 11 | awk '{printf "%d", $3}'`
mr=`writep0 12 | awk '{printf "%d", $3}'`
if   [ $md -lt $limit ]; then  md=0;"$0_$Exp"-p0_1;
elif [ $mr -lt $limit ]; then  mr=0;"$0_$Exp"-p0_2; fi;
# Then set the free parameters accordingly.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0;;
esac;
# Then re-fit the data to prepare for an ALMP test. Note that this
# set of free parameters duplicates that of the 1st, 2nd or 3rd
# fit.  By repeating the fit with non-zero mass from the start, we
# test the globality/locality of the results.
setf -o
time fit -d0 -d1
ackest
cs_writep0 "$0_$Exp"-p0_6
#--------------------------------------------------------------#
# Perfom the ALMP test with b1 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1;;
esac;
cm_setv
valid
sensit
#--------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Perfom the ALMP test with dVwt0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 dVwt0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 dVwt0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 dVwt0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Fit b1 and log the AIC test result.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5;;
esac;
cs_setd 0.5 $Exp
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_7
#--------------------------------------------------------------#
# Fit Vsd0 and log the AIC test result.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1 Vsd0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1 Vsd0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1 Vsd0;;
esac;
sensit
# Before fitting Vsd0, fix b1 because of cross coupling with Vsd0.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_8
#--------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1121/*.c .; mcompile
cs_setm 4
cs_sets 4 $Exp
# Use results of 6-th experiment to start; this sets the free param's.
"$0_$Exp"-p0_6
cs_setp0 -q Sw0=1 Sw1=1 Sw2=2 Sw3=1 b1=0.7
cs_setf iterations=20 step=1 reg=0
# Fit without timing to determine if the mass distribution is
# affected by the switch in the hypothesis.
fit
ackest
md=`writep0 11 | awk '{printf "%d", $3}'`
mr=`writep0 12 | awk '{printf "%d", $3}'`
if   [ $md -lt $limit ]; then  md=0; "$0_$Exp"-p0_1;
elif [ $mr -lt $limit ]; then  mr=0; "$0_$Exp"-p0_2; fi
cs_setp0 -q Sw0=1 Sw1=1 Sw2=2 Sw3=1 b1=0.7
# The set of free parameters is set by the macro "$0_$Exp"-p0_6
# Use the command script to query the dimension of the set.
cs_setp -m
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_9
#--------------------------------------------------------------#
# Perfom the ALMP test with b1 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Perfom the ALMP test with dVwt0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 dVwt0;;
```

Listing C.8: M4_Exp—Command script used to investigate the fourth-order model structure.

```
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 dVwt0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 dVwt0;;
esac;
setv -o
valid
sensit
#---------------------------------------------------------------------#
# Fit bl and log the AIC test result.
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 bl=5;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 bl=5;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 bl=5;;
esac;
cs_setd 0.5 $Exp
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_10
#---------------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1122/*.c .; mcompile
cs_setm 4
cs_sets 4 $Exp
# Use results of 6-th experiment to start; this sets the free param's.
"$0_$Exp"-p0_6
cs_setp0 -q Sw0=1 Sw1=1 Sw2=2 Sw3=2 bl=1
cs_setf iterations=20 step=1 reg=0
# Fit without timing to determine if the mass distribution is
# affected by the switch in the hypothesis.
fit
ackest
md='writep0 11 | awk '{printf "%d", $3}''
mr='writep0 12 | awk '{printf "%d", $3}''
if   [ $md -lt $limit ]; then  md=0; "$0_$Exp"-p0_1;
elif [ $mr -lt $limit ]; then  mr=0; "$0_$Exp"-p0_2; fi
cs_setp0 -q Sw0=1 Sw1=1 Sw2=2 Sw3=2 bl=1
# The set of free parameters is set by the macro "$0_$Exp"-p0_6
# Use the command script to query the dimension of the set.
cs_setp -m
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_11
#---------------------------------------------------------------------#
# Perfom the ALMP test with bl free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 bl;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 bl;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 bl;;
esac;
setv -o
valid
sensit
#---------------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
setv -o
valid
sensit
#---------------------------------------------------------------------#
# Perfom the ALMP test with dVwt0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 dVwt0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 dVwt0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 dVwt0;;
esac;
setv -o
valid
sensit
#---------------------------------------------------------------------#
# Fit bl and log the AIC test result.
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 bl=5;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 bl=5;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 bl=5;;
esac;
cs_setd 0.5 $Exp
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_12
#---------------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1123/*.c .; mcompile
cs_setm 4
cs_sets 4 $Exp
# Use results of 6-th experiment to start; this sets the free param's.
"$0_$Exp"-p0_6
cs_setp0 -q Sw0=1 Sw1=1 Sw2=2 Sw3=3 bl=1
cs_setf iterations=20 step=1 reg=0
# Fit without timing to determine if the mass distribution is
# affected by the switch in the hypothesis.
fit
ackest
md='writep0 11 | awk '{printf "%d", $3}''
mr='writep0 12 | awk '{printf "%d", $3}''
if   [ $md -lt $limit ]; then  md=0; "$0_$Exp"-p0_1;
elif [ $mr -lt $limit ]; then  mr=0; "$0_$Exp"-p0_2; fi
cs_setp0 -q Sw0=1 Sw1=1 Sw2=2 Sw3=3 bl=1
# The set of free parameters is set by the macro "$0_$Exp"-p0_6
# Use the command script to query the dimension of the set.
cs_setp -m
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_13
#---------------------------------------------------------------------#
# Perfom the ALMP test with bl free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 bl;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 bl;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 bl;;
esac;
setv -o
valid
sensit
#---------------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
setv -o
valid
sensit
#---------------------------------------------------------------------#
# Perfom the ALMP test with dVwt0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 dVwt0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 dVwt0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 dVwt0;;
esac;
setv -o
valid
sensit
#---------------------------------------------------------------------#
# Fit bl and log the AIC test result.
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 bl=5;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 bl=5;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 bl=5;;
esac;
cs_setd 0.5 $Exp
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_14
#---------------------------------------------------------------------#
exit 0
```

Listing C.8 M4_Exp (*continued*).

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	217, 214, 30.5, 416, 289														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2673	0.2674	0.2674	0.2674	0.2674	0.2674	0.2674	0.2674	0.2674	0.2674	0.2674	0.2673	0.2674	0.2673	0.2674
qfcf	5.6491	5.6511	5.6514	5.6515	5.6514	5.6516	5.6511	5.6523	5.6523	5.651	5.6527	5.6504	5.6525	5.6497	5.6516
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.1775	0.1779	0.1779	0.1779	0.1781	0.1779	0.178	0.1761	0.1763	0.1779	0.1763	0.1778	0.1765	0.1776	0.1764
Sigma5	18.54	12.25	11.41	11.08	11.45	10.86	11.39	8.841	8.837	13.38	8.505	14.53	7.863	16.77	9.719
md	0	–	3.18e5	4.77e5	3.03e5	5.85e5	3.19e5	3.17e5	3.17e5	3.18e5	3.17e5	3.17e5	3.18e5	3.17e5	3.19e5
mr	0	3.17e5	0	−1.59e5	1.74e4	−2.68e5	0	–	–	–	–	–	–	–	–
Ad	28.17	29.36	29.19	29.15	29.2	29.12	29.19	30.7	30.7	30.08	32.78	26.9	25.28	27.64	25.87
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	8.143	8.107	8.11	8.115	8.11	8.118	8.11	8.123	8.123	8.12	8.132	8.121	8.104	8.134	8.114
L0	0.015	0.021	0.021	0.021	0.021	0.022	0.021	0.024	0.024	0.026	0.018	0.028	0.066	0.017	0.022
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.209	–	0.7	1.316	1	1.988	1	4.149
Vsd0	8	–	–	–	–	–	–	–	7.735	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.61	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0185	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	1289.6	1238.44	1220.01	1244.05	1205.71	1238.34	1051.72	1051.72	1353.04	1023.92	1411.62	968.358	1513.61	1119.7
$\mathcal{L}$	–	636.802	611.222	601.007	613.023	593.855	611.172	516.86	516.859	668.519	502.958	697.812	475.179	748.805	550.851
c.i.	–	−1.63	−1.38	−1.12	−0.669	−3.7	−2.73	−4.23	−1.51	−6.98	−5.23	−6.01	−5.22	−5.06	-1.21
time	–	1 : 42.2	1 : 43.0	1 : 53.5	4 : 02.9	1 : 25.1	25.4	3 : 46.3	56.3	1 : 17.5	4 : 17.5	1 : 29.7	8 : 48.2	1 : 39.5	7:22.5

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236, 233, 31.4, 432, 295														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2552	0.2551	0.2551	0.2551	0.2551	0.2551	–	0.2551	–	0.2552	0.2551	0.2552	0.2551	0.2552	0.2551
qfcf	5.6242	5.6231	5.6228	5.623	5.623	5.6231	5.6231	5.6217	5.6217	5.6235	5.6214	5.6234	5.6214	5.6234	5.6217
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4752	0.4756	0.476	0.4756	0.4756	0.4756	0.4756	0.4758	0.4759	0.4755	0.4765	0.4754	0.476	0.4755	0.4757
Sigma5	21.9	19.45	19.93	19.56	19.49	19.44	19.45	18.38	18.35	20.05	17.81	20.19	18.02	20.19	18.47
md	0	–	4.15e5	1.17e5	5.5e4	−1.46e4	0	–	–	–	–	–	–	–	–
mr	0	4.17e5	0	3.01e5	3.65e5	4.34e5	4.2e5	4.22e5	4.22e5	4.19e5	4.23e5	4.19e5	4.22e5	4.19e5	4.2e5
Ad	28.36	29.66	29.28	29.54	29.59	29.67	29.65	31.74	31.76	30.1	34.85	27.79	26.83	27.74	26.87
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	7.652	7.727	7.793	7.745	7.726	7.72	7.72	7.796	7.794	7.703	7.846	7.693	7.805	7.691	7.769
L0	0.01	0.0063	0.0054	0.0061	0.0062	0.0063	0.0063	0.0013	0.0014	0.011	0.027	0.0078	0.021	0.0076	0.0014
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.585	–	0.7	2.062	1	2.562	1	3.196
Vsd0	8	–	–	–	–	–	–	–	7.226	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0381	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	2331.44	2349.39	2337.19	2334.75	2332.84	2331.35	2293.2	2291.9	2353.04	2271.11	2358.03	2279.19	2357.81	2296.32
$\mathcal{L}$	–	1157.72	1166.7	1159.6	1158.37	1157.42	1157.68	1137.6	1136.95	1168.52	1126.56	1171.02	1130.59	1170.9	1139.16
c.i.	–	−1.07	−1.04	−1.35	−1.05	−4.99	−0.843	−0.959	−6.25	−3.26	−4.12	−2.43	−6.98	−2.31	-3.23
time	–	1 : 50.8	1 : 44.3	1 : 56.6	2 : 26.6	58.2	26.0	3 : 52.3	1 : 56.5	50.9	7 : 31.7	59.5	8 : 50.6	1 : 07.8	5:00.9

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236, 233, 31.4, 432, 295														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2569	0.2568	0.2568	0.2568	–	–	–	0.2568	–	0.2568	0.2567	0.2569	0.2567	0.2569	0.2567
qfcf	5.6616	5.6602	5.6603	5.6602	5.6602	–	5.6602	5.6588	5.6588	5.6608	5.6586	5.6608	5.6586	5.6609	5.6588
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2247	0.2284	0.2293	0.2281	0.2274	0.2279	0.2275	0.2252	0.2249	0.2273	0.2243	0.227	0.2244	0.2268	0.2252
Sigma5	10.67	7.297	7.465	7.328	7.346	7.26	7.316	5.72	5.724	8.215	5.393	8.683	5.297	8.938	5.722
md	0	–	3.49e5	4.95e4	4.04e4	−8.84e4	0	–	–	–	–	–	–	–	–
mr	0	3.57e5	0	3.08e5	3.33e5	4.57e5	3.72e5	3.95e5	3.92e5	3.76e5	3.94e5	3.72e5	3.98e5	3.71e5	3.91e5
Ad	28.71	29.57	29.61	29.59	29.56	29.56	29.58	30.67	30.69	30.17	32.52	27.87	26.1	27.95	26.27
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	9.389	9.755	9.769	9.812	9.786	9.788	9.886	9.463	9.502	9.737	9.375	9.792	9.357	9.796	9.515
L0	0.0071	0.006	0.006	0.006	0.0059	0.0059	0.0059	0.0037	0.0037	0.0095	0.022	0.0091	0.028	0.0066	0.0039
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.391	–	0.7	1.653	1	2.393	1	3.51
Vsd0	8	–	–	–	–	–	–	–	7.876	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0418	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	1100.5	1119.7	1104.55	1103.92	1097.51	1099.84	917.809	917.537	1182.66	872.588	1221.32	859.747	1241.8	917.428
$\mathcal{L}$	–	542.25	551.85	543.276	542.96	539.754	541.92	449.905	449.769	583.331	427.294	602.658	420.873	612.9	449.714
c.i.	–	−1.89	−1.83	−0.113	−3.18	−1.57	−0.974	−0.148	−1.97	−0.435	−0.291	−1.02	−2.98	−0.247	-3.14
time	–	2 : 18.5	2 : 10.5	3 : 24.2	3 : 55.1	1 : 01.7	52.5	3 : 55.2	57.8	1 : 42.3	10 : 20.8	1 : 29.9	13 : 15.7	1 : 40.2	11:10.1

(c) Experiment B, full load, perturbed feed-water flow.

Table C.5: Optimization results for $\mathcal{M}_4$ with $k_f = 0.001$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2564	0.2565	0.2567	0.2567	0.2567	0.2567	0.2567	0.2567	0.2567	0.2566	0.2567	0.2565	0.2567	0.2564	0.2566
qfcf	6.2348	6.2409	6.2414	6.2414	–	6.2414	6.2414	6.2414	–	6.2418	6.2417	6.2396	6.2414	6.2366	6.2391
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.3144	0.3201	0.3145	0.3147	0.3147	0.3146	0.3145	0.3104	0.3103	0.318	0.3102	0.3182	0.3102	0.3151	0.3107
Sigma5	30.81	9.469	7.937	7.936	7.936	7.917	7.922	7.857	7.851	10.35	8.638	16	6.137	24.61	7.912
md	0	–	3.89e5	3.46e5	3.51e5	3.7e5	3.91e5	3.88e5	3.88e5	3.97e5	3.89e5	3.95e5	3.9e5	3.92e5	3.96e5
mr	0	3.93e5	0	4.47e4	4.09e4	2.11e4	0	–	–	–	–	–	–	–	–
Ad	26.79	27.2	27.97	27.84	27.84	27.9	27.97	28.37	28.35	27.86	29.88	23.4	24.14	25.31	25.07
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.525	4.246	4.608	4.553	4.558	4.583	4.61	4.681	4.68	4.357	4.631	4.331	4.59	4.468	4.548
L0	−0.0015	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.026	0.03	0.027	0.05	0.0035	0.011
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
bl	0.7	–	–	–	–	–	–	0.7331	–	0.7	0.8277	1	1.438	1	3.061
Vsd0	8	–	–	–	–	–	–	–	7.423	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.713	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0283	–	–	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	1529.09	1389.45	1391.91	1392.05	1391.1	1389.46	1376.01	1375.32	1589.57	1443.72	1903.27	1197.88	2206.06	1380.6
$\mathcal{L}$	–	756.546	686.727	686.956	687.026	686.55	686.728	679.004	678.66	786.783	712.86	943.633	589.94	1095.03	681.298
c.i.	–	−1.8	−8.14	−6.68	−0.0978	−5.69	−1.69	−3.7	−7.68	−3.46	−4.17	−6.48	−5.16	−4.33	-3.32
time	–	2 : 16.0	2 : 08.0	2 : 22.6	2 : 23.5	56.9	25.5	1 : 53.4	1 : 53.2	1 : 19.0	2 : 52.3	2 : 03.5	5 : 31.4	2 : 26.9	9:17.2

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2524	0.2523	0.2522	0.2524	0.2523	0.2524	0.2523	0.2524	–	0.2523	0.2524	0.2524	0.2524	0.2524	0.2524
qfcf	6.0882	6.0845	6.0826	6.088	6.0845	6.0881	6.0845	6.0876	–	6.0849	6.0876	6.086	6.0875	6.0863	6.0876
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4064	0.4063	0.4078	0.4044	0.4071	0.4044	0.4063	0.4025	0.4025	0.4061	0.4025	0.4057	0.4023	0.4062	0.4024
Sigma5	11.17	20.21	29.83	10.16	20.33	10.1	20.23	11.11	11.1	17.43	11.11	14.05	11.01	13.71	11.02
md	0	–	3.28e5	−5.56e5	4.79e3	−5.71e5	0	–	–	–	–	–	–	–	–
mr	0	3.32e5	0	8.87e5	3.27e5	9.03e5	3.32e5	3.28e5	3.28e5	3.32e5	3.28e5	3.31e5	3.28e5	3.3e5	3.28e5
Ad	21.73	23.08	25.33	26.04	23.09	26.2	23.08	21.5	21.5	23.34	21.71	20.07	21.15	20.04	21.12
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.05	4.082	4.108	3.928	4.085	3.925	4.081	4.034	4.034	4.075	4.034	4.058	4.033	4.073	4.036
L0	−0.0059	−0.01	−0.01	−0.006	−0.01	−0.006	−0.01	−0.007	−0.007	0.0027	−0.006	0.0063	−0.006	−0.009	−0.007
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
bl	0.7	–	–	–	–	–	–	0.0732	–	0.7	0.1123	1	0.2914	1	0.2388
Vsd0	8	–	–	–	–	–	–	–	7.819	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.636	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0258	–	–	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	2246.53	2528.92	1751.15	n.c.	1745.84	2246.52	1810.4	1810.47	2138.78	1810.68	1983.26	1804.6	1966.67	1805.43
$\mathcal{L}$	–	1115.27	1256.46	866.573	n.c.	863.022	1115.26	896.202	896.235	1061.39	896.338	983.628	893.299	075.336	893.713
c.i.	–	−3.54	−3.28	−0.743	0.318	−2	−2.76	−3.73	−2.29	−6.06	−3.63	−8.11	−0.389	−0.0791	-0.491
time	–	2 : 12.9	2 : 39.1	1 : 58.8	9 : 58.6	1 : 58.8	26.4	3 : 56.7	58.9	1 : 16.3	3 : 46.0	2 : 22.9	3 : 43.8	1 : 59.5	4:31.2

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2552	0.255	0.255	0.255	0.255	0.255	–	0.255	0.255	0.255	0.255	0.2551	0.255	0.2551	0.255
qfcf	6.0767	6.0719	6.0723	6.072	6.0719	6.0719	–	6.0724	6.0724	6.0729	6.0723	6.0738	6.0723	6.0742	6.0722
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2065	0.2057	0.207	0.2056	0.205	0.2051	0.2051	0.2064	0.2063	0.2061	0.2061	0.2075	0.2063	0.2077	0.2062
Sigma5	10.35	6.05	6.08	6.04	6.049	6.043	6.044	5.939	5.931	5.906	5.836	6.369	5.784	6.854	5.795
md	0	–	5.68e5	2.68e5	1.75e5	1.73e5	1.71e5	9.36e4	3.02e4	0	–	1.08e5	8.85e4	0	–
mr	0	5.8e5	0	3.18e5	4.23e5	4.27e5	4.29e5	4.99e5	5.63e5	5.88e5	5.96e5	4.68e5	5.04e5	5.75e5	5.93e5
Ad	24.3	26.3	26.3	26.28	26.27	26.26	26.26	26.05	26.05	27.09	27.41	23.35	22.90	23.45	22.99
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	5.291	5.041	5.184	5.105	5.08	5.069	5.069	5.139	5.13	5.207	5.105	5.329	5.121	5.347	5.111
L0	0.0049	−0.004	−0.004	−0.004	−0.004	−0.004	−0.001	−0.003	−0.003	0.01	0.012	0.0074	0.013	0.0006	−0.003
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
bl	0.7	–	–	–	–	–	–	0.6287	–	0.7	0.7717	1	1.259	1	1.602
Vsd0	8	–	–	–	–	–	–	–	7.921	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.793	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0239	–	–	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	8	9	9	9	9	10	10	8	9	9	10	8	9
AIC	–	890.362	898.612	890.954	890.286	890.153	890.14	883.913	882.845	875.176	868.384	936.3	864.689	987.624	863.792
$\mathcal{L}$	–	437.181	441.321	436.477	436.143	436.076	436.07	431.956	431.423	429.588	425.192	459.15	422.344	485.812	422.896
c.i.	–	−1.06	−1.31	−1.38	−0.5	−3.17	−5.1	−0.783	−5.98	−7.17	−11.5	−0.907	−5.01	−3.96	-4.69
time	–	1 : 50.2	1 : 43.8	1 : 55.4	1 : 56.2	28.8	28.7	2 : 06.5	2 : 06.3	1 : 16.4	2 : 49.6	32.9	6 : 06.9	1 : 40.2	6:11.3

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.5: $\mathcal{M}_4$, $k_f = 0.001$ *(continued)*.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	217, 214, 30.5, 416, 289														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2673	0.2674	0.2674	0.2674	–	0.2674	0.2674	0.2674	–	0.2674	0.2675	0.2674	0.2674	0.2673	0.2674
qfcf	5.6497	5.6516	5.6518	5.6518	–	5.6518	5.6518	5.6525	–	5.6515	5.6528	5.6508	5.6527	5.6502	5.652
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.1776	0.1781	0.1781	0.1781	0.1782	0.1782	0.1782	0.1765	0.1765	0.1781	0.1765	0.1779	0.1767	0.1777	0.1766
Sigma5	17.1	10.92	10.58	10.6	10.61	10.48	10.57	8.664	8.66	12.51	8.435	13.67	7.817	15.77	9.02
md	0	–	3.36e5	3.19e5	2.99e5	4.4e5	3.37e5	3.36e5	3.36e5	3.36e5	3.36e5	3.36e5	3.37e5	3.35e5	3.37e5
mr	0	3.38e5	0	1.7e4	3.74e4	−1.03e5	0	–	–	–	–	–	–	–	–
Ad	27.46	28.86	28.8	28.8	28.8	28.78	28.79	30.1	30.1	29.62	32.07	26.46	25.14	27.1	25.59
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	8.133	8.09	8.093	8.093	8.092	8.094	8.092	8.109	8.109	8.104	8.116	8.107	8.089	8.122	8.098
L0	0.015	0.02	0.021	0.021	0.021	0.021	0.021	0.023	0.023	0.026	0.045	0.027	0.059	0.016	0.021
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.116	–	0.7	1.271	1	1.904	1	3.793
Vsd0	8	–	–	–	–	–	–	–	7.681	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.61	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0857	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	1207.91	1185.54	1189.15	1189.68	1181.44	1185.37	1037.81	1037.81	1305.7	1018.52	1368.43	965.006	1470.23	1066.91
$\mathcal{L}$	–	595.956	584.768	585.577	585.841	581.718	584.686	509.904	509.905	644.85	500.26	676.217	473.503	727.115	524.456
c.i.	–	−0.729	−0.731	−0.846	−1.04	−2.61	−2.61	−6	−1.14	−6.38	−4.67	−5.52	−5.39	−4.67	-0.282
time	–	1 : 55.8	1 : 48.1	2 : 02.4	2 : 56.5	1 : 00.4	26.7	4 : 13.4	59.4	1 : 17.7	4 : 47.5	1 : 30.5	8 : 51.6	1 : 41.0	7:31.4

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236, 233, 31.4, 432, 295														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2552	0.2552	0.2551	0.2552	0.2552	–	0.2552	0.2551	0.2551	0.2552	0.2551	0.2552	0.2551	0.2552	0.2551
qfcf	5.6243	5.6232	5.6231	5.6231	5.6232	–	5.6232	5.6216	–	5.6236	5.6212	5.6235	5.6213	5.6235	5.6216
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4751	0.4754	0.4755	0.4754	0.4755	0.4755	0.4755	0.4758	0.4759	0.4753	0.4766	0.4753	0.4761	0.4753	0.4756
Sigma5	22.61	20.02	20.23	20.1	20.05	20.04	20.01	18.68	18.64	20.67	17.95	20.83	18.29	20.88	18.76
md	0	–	4.36e5	1.78e5	7.39e4	3.74e4	0	–	–	–	–	–	–	–	–
mr	0	4.37e5	0	2.6e5	3.65e5	4.02e5	4.4e5	4.42e5	4.42e5	4.39e5	4.43e5	4.39e5	4.42e5	4.39e5	4.4e5
Ad	28.69	29.93	29.7	29.83	29.87	29.9	29.91	32.24	32.26	30.4	35.56	28.07	26.94	28.04	26.99
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	7.65	7.723	7.751	7.734	7.715	7.722	7.715	7.802	7.799	7.698	7.857	7.69	7.816	7.683	7.764
L0	0.01	0.0064	0.0059	0.0062	0.0063	0.0064	0.0064	0.0008	0.0008	0.011	0.029	0.0094	0.027	0.0079	0.0008
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.697	–	0.7	2.18	1	2.658	1	3.571
Vsd0	8	–	–	–	–	–	–	–	7.224	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0709	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	2351.92	2359.36	2356.58	2355.05	2354.75	2351.79	2304.6	2303.31	2374.61	2277.2	2380.03	2289.72	2381.78	2307.33
$\mathcal{L}$	–	1167.96	1171.68	1169.29	1168.52	1168.38	1167.89	1143.3	1142.66	1179.3	1129.6	1182.01	1135.86	1182.89	1144.67
c.i.	–	−0.69	−0.673	−0.957	−0.122	−0.18	−0.735	−1.08	−6.39	−3.22	−4.68	−2.24	−6.37	−2.64	-2.23
time	–	1 : 44.7	1 : 43.9	1 : 57.3	1 : 56.7	29.0	26.1	3 : 49.7	1 : 53.8	54.0	8 : 04.3	1 : 00.7	8 : 51.6	1 : 07.0	4:56.8

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	236, 233, 31.4, 432, 295														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2569	0.2568	0.2568	0.2568	–	–	0.2568	0.2568	0.2568	0.2569	0.2568	0.2569	0.2567	0.2569	0.2568
qfcf	5.6618	5.6605	5.6605	5.6605	5.6604	5.6604	5.6605	5.659	–	5.6609	5.6588	5.661	5.6588	5.6611	5.6589
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2243	0.228	0.2284	0.2276	0.227	0.2272	0.227	0.2251	0.2249	0.2267	0.2243	0.2265	0.2243	0.2264	0.225
Sigma5	10.77	7.552	7.647	7.596	7.593	7.561	7.571	5.818	5.822	8.483	5.453	8.942	5.355	9.222	5.821
md	0	–	3.73e5	1.26e5	5.79e4	−8.29e3	0	–	–	–	–	–	–	–	–
mr	0	3.77e5	0	2.58e5	3.4e5	4.04e5	3.93e5	4.17e5	4.14e5	3.92e5	4.17e5	3.94e5	4.2e5	3.93e5	4.13e5
Ad	28.96	29.85	29.87	29.85	29.81	29.82	29.85	31.01	31.02	30.49	32.9	28.13	26.25	28.22	26.44
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	9.35	9.716	9.723	9.733	9.689	9.735	9.847	9.473	9.508	9.79	9.353	9.721	9.363	9.725	9.516
L0	0.0061	0.005	0.005	0.005	0.005	0.005	0.005	0.0026	0.0026	0.0085	0.022	0.0085	0.029	0.0056	0.0028
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.434	–	0.7	1.695	1	2.437	1	3.652
Vsd0	8	–	–	–	–	–	–	–	7.861	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0762	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	1123.72	1134.06	1128.59	1126.57	1124.82	1123.02	929.697	929.396	1203.73	880.217	1240.92	867.388	1262.7	929.339
$\mathcal{L}$	–	553.858	559.028	555.293	554.287	553.409	553.512	455.849	455.698	593.865	431.109	612.46	424.694	623.35	455.67
c.i.	–	−1.52	−1.5	−4.18	−0.325	−0.738	−0.643	−0.0765	−2.07	−0.362	−3.27	−1.85	−2.68	−0.754	-3.19
time	–	2 : 08.2	2 : 07.7	3 : 19.6	8 : 08.7	57.1	51.1	3 : 47.8	56.6	1 : 16.9	11 : 21.0	1 : 34.2	13 : 54.1	1 : 40.4	11:39.7

(c) Experiment B, full load, perturbed feed-water flow.

Table C.6: Optimization results for $\mathcal{M}_4$ with $k_f = 0.005$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2565	0.2567	0.2568	0.2567	0.2567	–	0.2567	0.2567	0.2567	0.2567	0.2567	0.2566	0.2567	0.2565	0.2565
qfcf	6.2376	6.2421	6.2423	6.2422	6.2422	–	–	6.242	6.242	6.2426	6.242	6.2413	6.2422	6.2391	6.2386
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.315	0.3162	0.3152	0.315	0.315	0.3151	0.3151	0.3104	0.3104	0.3176	0.3107	0.3195	0.3106	0.3163	0.3136
Sigma5	28.02	8.041	8.393	8.012	8.008	7.991	7.991	7.669	7.626	9.831	7.604	13.1	6.473	21.15	11.62
md	0	–	4.04e5	1.43e5	1.19e5	1.16e5	1.15e5	−6.21e4	−7.75e4	2.4e5	−1.31e5	0	–	–	–
mr	0	4.09e5	0	2.65e5	2.9e5	2.93e5	2.95e5	4.7e5	4.86e5	1.72e5	5.39e5	4.14e5	4.08e5	4.11e5	4.06e5
Ad	24.73	27.07	27.77	27.29	27.25	27.24	27.24	28.11	28.03	27.31	29.87	22.66	23.69	23.72	24.66
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.498	4.429	4.743	4.544	4.521	4.52	4.519	4.566	4.52	4.366	4.504	4.279	4.531	4.414	4.309
L0	0.001	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.026	0.033	0.027	0.048	0.0061	0.011
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	0.8104	–	0.7	0.9198	1	1.45	1	3.256
Vsd0	8	–	–	–	–	–	–	–	8.054	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.713	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0499	–	–	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	8	9	9	9	9	10	10	9	10	8	9	8	9
AIC	–	1402.79	1431.6	1399.64	1399.14	1399.03	1399.02	n.c.	1357.06	1553.48	1355.84	1762.92	1237.19	2099.8	1663.6
$\mathcal{L}$	–	693.395	707.799	690.818	690.57	690.515	690.508	n.c.	668.532	767.738	667.919	873.461	609.595	1041.9	822.798
c.i.	–	−4.4	−0.519	−0.206	−1.16	−3.37	−5.95	0.13	−0.0221	−5.08	−0.67	−0.166	−5.6	−5.16	-3.63
time	–	2 : 10.3	1 : 43.1	1 : 55.2	1 : 55.7	28.8	29.0	21 : 04.3	1 : 03.5	56.7	3 : 06.8	1 : 30.4	5 : 32.1	2 : 13.7	8:40.7

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2524	0.2523	0.2522	0.2524	0.2523	0.2524	0.2523	0.2524	–	0.2523	0.2524	0.2523	0.2524	0.2523	0.2524
qfcf	6.0882	6.0839	6.0822	6.0864	6.0842	6.0866	6.0839	6.0869	–	6.0845	6.0869	6.0856	6.0869	6.086	6.0869
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4057	0.4062	0.4079	0.4046	0.4061	0.4045	0.4061	0.4019	0.4019	0.4058	0.4019	0.4056	0.4019	0.4057	0.4019
Sigma5	12.63	18.27	23.81	12.13	18.01	11.86	18.28	12.04	12.03	15.82	12.05	13.14	11.85	12.75	11.77
md	0	–	3.46e5	−5.92e5	2.31e3	−6.44e5	0	–	–	–	–	–	–	–	–
mr	0	3.48e5	0	9.39e5	4.03e5	9.92e5	3.49e5	3.46e5	3.46e5	3.48e5	3.46e5	3.47e5	3.46e5	3.46e5	3.46e5
Ad	22.61	22.87	23.14	24.85	23.13	25.11	22.87	22.04	22.05	23.4	22.48	20.37	21.32	20.29	21.17
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.028	4.075	4.108	3.98	4.071	3.969	4.074	4.013	4.013	4.062	4.012	4.04	4.011	4.034	4.007
L0	−0.0058	−0.01	−0.01	−0.008	−0.01	−0.008	−0.01	−0.007	−0.007	0.0021	−0.006	0.0054	−0.004	−0.009	−0.007
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	0.1543	–	0.7	0.2339	1	0.5409	1	0.5068
Vsd0	8	–	–	–	–	–	–	–	7.701	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.636	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0461	–	–	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	2173.45	2366.98	1880.48	n.c.	1861.12	2173.44	1867.83	1867.82	2068.73	1868.37	1935.01	1856.25	1913.56	1851.64
$\mathcal{L}$	–	1078.73	1175.49	931.24	n.c.	921.56	1078.72	924.915	924.912	1028.36	925.186	959.506	919.127	948.78	916.772
c.i.	–	−3.68	−1.38	−0.00982	6.11	−1.91	−2.7	−5.25	−1.3	−6.65	−4.91	−0.942	−1.59	−1.04	-3.02
time	–	2 : 10.9	2 : 18.6	1 : 57.1	9 : 51.1	1 : 57.7	26.2	3 : 53.2	57.9	1 : 21.6	3 : 58.9	1 : 30.0	3 : 18.5	1 : 40.9	3:42.8

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2552	0.255	0.255	0.255	0.255	0.255	0.255	0.255	–	0.2551	0.255	0.2551	0.255	0.2551	0.255
qfcf	6.0772	6.0727	6.0729	6.0727	6.0726	6.0725	6.0725	6.0728	–	6.0737	6.0726	6.0745	6.0726	6.075	6.0726
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2063	0.2063	0.2073	0.2061	0.2054	0.2054	0.2053	0.2063	0.2063	0.2068	0.2061	0.2078	0.2062	0.2079	0.2061
Sigma5	10.57	6.081	6.16	6.112	6.104	6.097	6.095	6.083	6.083	6.18	5.946	6.825	5.898	7.529	5.946
md	0	–	5.83e5	2.52e5	7.84e4	5.07e4	0	–	–	–	–	–	–	–	–
mr	0	5.92e5	0	3.47e5	5.35e5	5.64e5	6.14e5	6.13e5	6.13e5	6.02e5	6.14e5	5.93e5	6.12e5	5.91e5	6.1e5
Ad	24.49	26.51	26.52	26.5	26.48	26.48	26.48	26.38	26.39	27.33	27.86	23.55	23.09	23.69	23.1
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	5.272	5.132	5.227	5.171	5.137	5.127	5.121	5.158	5.16	5.285	5.128	5.361	5.134	5.372	5.14
L0	0.0048	−0.004	−0.004	−0.004	−0.004	−0.004	−0.004	−0.003	−0.003	0.01	0.013	0.0097	0.017	0.0008	−0.003
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	0.6687	–	0.7	0.8195	1	1.315	1	1.779
Vsd0	8	–	–	–	–	–	–	–	7.894	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.793	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0438	–	–	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	895.92	908.994	900.953	897.91	897.895	895.047	899.116	899.114	910.075	882.130	984.95	876.57	1055.89	882.251
$\mathcal{L}$	–	439.96	446.497	441.476	439.955	439.948	439.524	440.558	440.557	447.038	432.069	484.475	429.285	519.943	432.126
c.i.	–	−0.619	−0.716	−0.93	−2.88	−0.636	−2.46	−4.87	−3.37	−5.62	−6.46	−5.08	−3.18	−2.58	-0.00441
time	–	2 : 18.5	2 : 11.7	2 : 26.5	3 : 04.6	36.4	1 : 05.9	2 : 25.9	1 : 12.8	1 : 16.8	2 : 49.2	1 : 31.6	4 : 20.0	2 : 00.3	5:55.9

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.6: $\mathcal{M}_4$, $k_f = 0.005$ (*continued*).

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10, ...	217, 214, 30.5, 416, 289														
mdc, ...	0, 40, 38, 11														
Tcf, qfrng	100, 0														
Sw0, ...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2673	0.2674	0.2674	0.2674	0.2674	0.2674	–	0.2674	–	0.2674	0.2675	0.2674	0.2675	0.2673	0.2674
qfcf	5.65	5.6518	5.652	5.6519	5.652	5.652	–	5.6527	–	5.6516	5.6529	5.651	5.6528	5.6504	5.6521
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.1777	0.1782	0.1782	0.1782	0.1784	0.1783	0.1783	0.1765	0.1765	0.1781	0.1765	0.178	0.1768	0.1778	0.1767
Sigma5	16.56	10.47	10.35	10.38	10.36	10.33	10.33	8.669	8.665	12.26	8.48	13.39	7.882	15.42	8.809
md	0	–	3.46e5	2.33e5	2.84e5	3.4e5	3.46e5	3.45e5	3.45e5	3.46e5	3.45e5	3.45e5	3.46e5	3.45e5	3.46e5
mr	0	3.46e5	0	1.13e5	6.19e4	5.9e3	0	–	–	–	–	–	–	–	–
Ad	27.18	28.67	28.65	28.65	28.64	28.61	28.61	29.87	29.87	29.44	31.81	26.29	25.08	26.9	25.48
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	8.129	8.083	8.087	8.085	8.085	8.085	8.085	8.104	8.103	8.098	8.11	8.1	8.083	8.117	8.091
L0	0.013	0.018	0.018	0.018	0.018	0.018	0.018	0.02	0.02	0.023	0.041	0.024	0.054	0.014	0.019
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.082	–	0.7	1.244	1	1.868	1	3.65
Vsd0	8	–	–	–	–	–	–	–	7.688	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.61	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.11	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	1178.5	1169.7	1174.43	1172.82	1171.6	1169.48	1038.81	1038.51	1291.35	1022.69	1353.9	971.313	1454.52	1050.36
$\mathcal{L}$	–	581.25	576.848	578.213	577.412	576.799	576.711	510.406	510.257	637.677	502.346	668.949	476.656	719.26	516.179
c.i.	–	−0.352	−0.413	−0.623	−3.95	−6.13	−2.53	−0.0922	−1.2	−6.14	−1.69	−5.37	−5.54	−4.57	-0.0624
time	–	1 : 42.6	1 : 42.4	1 : 54.4	2 : 23.9	57.7	25.5	2 : 51.1	56.8	1 : 16.2	4 : 41.8	1 : 29.1	8 : 44.4	1 : 49.8	7:55.7

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10, ...	236, 233, 31.4, 432, 295														
mdc, ...	0, 40, 38, 11														
Tcf, qfrng	100, 0														
Sw0, ...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2552	0.2552	0.2552	0.2552	0.2552	0.2552	0.2552	0.2551	0.2551	0.2552	0.2551	0.2552	0.2551	0.2552	0.2551
qfcf	5.6243	5.6232	5.6231	5.6232	5.6232	–	5.6232	5.6216	5.6216	5.6236	5.6212	5.6236	5.6212	5.6236	5.6215
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4751	0.4753	0.4754	0.4753	0.4755	0.4754	0.4754	0.4758	0.4759	0.4753	0.4767	0.4753	0.4762	0.4753	0.4756
Sigma5	22.93	20.32	20.46	20.38	20.33	20.33	20.3	18.86	18.82	20.97	18.07	21.14	18.45	21.2	18.94
md	0	–	4.47e5	1.96e5	8.57e4	5.88e4	0	–	–	–	–	–	–	–	–
mr	0	4.47e5	0	2.53e5	3.64e5	3.91e5	4.5e5	4.52e5	4.52e5	4.5e5	4.54e5	4.49e5	4.53e5	4.49e5	4.51e5
Ad	28.84	30.06	29.91	29.09	30.01	30.03	30.01	32.47	32.49	30.54	35.88	28.21	27	28.18	27.05
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	7.651	7.724	7.738	7.73	7.71	7.722	7.715	7.807	7.804	7.699	7.865	7.691	7.824	7.683	7.765
L0	0.01	0.0065	0.0061	0.0063	0.0064	0.0064	0.0065	0.0006	0.0006	0.011	0.03	0.0099	0.029	0.0070	0.0005
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.744	–	0.7	2.228	1	2.696	1	3.71
Vsd0	8	–	–	–	–	–	–	–	7.221	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.093	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	2362.21	2367.36	2366.27	2364.91	2364.84	2362.05	2311.43	2310.15	2385.05	2281.85	2390.56	2296.35	2392.84	2314.05
$\mathcal{L}$	–	1173.1	1175.68	1174.13	1173.45	1173.42	1173.02	1146.72	1146.08	1184.53	1131.92	1187.28	1139.18	1188.42	1148.02
c.i.	–	−0.533	−0.527	−0.791	−0.953	−0.78	−0.666	−1.2	−6.35	−3.21	−4.79	−2.15	−6.15	−2.69	-1.99
time	–	1 : 59.1	1 : 52.6	2 : 04.9	2 : 05.6	31.1	28.1	4 : 09.0	2 : 05.1	50.9	7 : 31.8	1 : 04.2	9 : 24.9	1 : 10.1	4:56.3

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10, ...	236, 233, 31.4, 432, 295														
mdc, ...	0, 40, 38, 11														
Tcf, qfrng	100, 0														
Sw0, ...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2569	0.2568	0.2568	0.2568	0.2568	–	0.2568	0.2568	–	0.2569	0.2568	0.2569	0.2568	0.2569	0.2568
qfcf	5.6619	5.6606	5.6606	5.6606	5.6605	5.6605	5.6606	5.659	5.6591	5.661	5.6588	5.6611	5.6588	5.6612	5.659
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2241	0.2278	0.228	0.2273	0.2267	0.227	0.2268	0.225	0.2248	0.2265	0.2242	0.2263	0.2243	0.2262	0.225
Sigma5	10.81	7.657	7.72	7.696	7.695	7.677	7.677	5.849	5.851	8.593	5.471	9.043	5.368	9.325	5.849
md	0	–	3.85e5	1.56e5	7.19e4	3.03e4	0	–	–	–	–	–	–	–	–
mr	0	3.87e5	0	2.39e5	3.37e5	3.78e5	4.04e5	4.28e5	4.25e5	4.04e5	4.28e5	4.05e5	4.32e5	4.04e5	4.23e5
Ad	29.06	29.97	29.98	29.96	29.93	29.94	29.97	31.16	31.18	30.61	33.08	28.24	26.32	28.34	26.52
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	9.314	9.693	9.698	9.711	9.657	9.714	9.826	9.475	9.507	9.757	9.354	9.688	9.363	9.692	9.514
L0	0.0046	0.0034	0.0034	0.0034	0.0034	0.0034	0.0034	0.0009	0.0009	0.0069	0.02	0.007	0.028	0.0041	0.0011
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	1.455	–	0.7	1.716	1	2.456	1	3.701
Vsd0	8	–	–	–	–	–	–	–	7.858	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.099	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	1133.01	1139.72	1137.09	1135.53	1134.78	1132.3	933.215	932.904	1212.24	882.401	1248.3	868.9	1270.07	932.574
$\mathcal{L}$	–	558.505	561.862	559.547	558.765	558.391	558.15	457.608	457.452	598.119	432.201	616.152	425.45	627.034	457.287
c.i.	–	−1.29	−1.28	−3.78	−0.155	−0.682	−0.5	−0.058	−2.14	−0.592	−3.12	−2.4	−2.56	−1.06	-3.2
time	–	2 : 17.8	2 : 17.5	3 : 43.4	8 : 01.3	1 : 03.7	54.9	4 : 14.0	1 : 03.3	1 : 16.8	11 : 24.6	1 : 30.7	13 : 19.6	1 : 45.1	11:43.1

(c) Experiment B, full load, perturbed feed-water flow.

Table C.7: Optimization results for $\mathcal{M}_4$ with $k_f = 0.01$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2565	0.2567	0.2568	0.2568	0.2568	0.2567	0.2567	0.2568	0.2568	0.2567	0.2568	0.2566	0.2568	0.2566	0.2565
qfcf	6.2388	6.2426	6.2427	6.2426	–	6.2426	6.2126	6.2426	–	6.2429	6.2427	6.2421	6.2427	6.2401	6.2395
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.3153	0.3148	0.3158	0.3148	0.3147	0.3151	0.3148	0.3103	0.3103	0.3171	0.3103	0.3194	0.3103	0.3169	0.315
Sigma5	26.9	8.154	8.868	8.166	8.182	8.085	8.11	8.077	8.066	9.494	8.248	12.08	6.876	19.69	10.24
md	0	–	4.13e5	1.42e4	2.52e4	−7.45e4	0	–	–	–	–	–	–	–	–
mr	0	4.17e5	0	4.03e5	3.95e5	4.93e5	4.18e5	4.17e5	4.17e5	4.21e5	4.18e5	4.24e5	4.17e5	4.22e5	4.17e5
Ad	23.95	27.1	27.68	27.12	27.13	27.01	27.1	27.58	27.56	27.09	29.09	22.37	23.5	23.09	24.15
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.487	4.569	4.792	4.58	4.585	4.527	4.571	4.61	4.631	4.386	4.627	4.284	4.606	4.39	4.257
L0	0.0018	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.013	0.025	0.03	0.027	0.045	0.0069	0.012
x10	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	0.7184	–	0.7	0.846	1	1.406	1	3.106
Vsd0	8	–	–	–	–	–	–	–	7.315	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.713	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0613	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	1409.63	1472.58	1413	n.c.	1407.37	1409.63	1395.66	1391.69	1525.59	1410.73	1704.07	1280.02	2049.52	1576.41
$\mathcal{L}$	–	696.815	728.292	697.501	n.c.	694.686	696.815	688.829	688.347	754.797	696.366	844.035	631.009	1016.76	779.203
c.i.	–	−6.61	−0.145	−0.287	0.156	−3.43	−1.56	−3.92	−6.92	−3.75	−4.85	−0.779	−4.95	−6.34	-3.89
time	–	2 : 13.2	1 : 46.1	2 : 00.8	10 : 02.3	1 : 00.3	26.8	1 : 59.1	2 : 00.0	1 : 18.1	2 : 50.6	1 : 33.0	5 : 34.1	2 : 29.1	8:46.7

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2524	0.2522	0.2522	0.2523	0.2522	0.2523	0.2522	0.2521	–	0.2523	0.2524	0.2523	0.2524	0.2523	0.2524
qfcf	6.0882	6.0837	6.0823	6.0854	6.0837	6.0857	6.0837	6.0866	–	6.0814	6.0866	6.0855	6.0865	6.0859	6.0866
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4055	0.4063	0.4075	0.4052	0.4062	0.405	0.4062	0.4018	0.4018	0.4059	0.4018	0.4057	0.4017	0.4056	0.4017
Sigma5	13.53	17.82	21.54	13.7	17.94	13.32	17.83	12.71	12.73	15.59	12.75	13.29	12.51	12.88	12.37
md	0	–	3.55e5	−5.35e5	1.25e4	−6.13e5	0	–	–	–	–	–	–	–	–
mr	0	3.58e5	0	8.91e5	3.46e5	9.7e5	3.58e5	3.56e5	3.56e5	3.57e5	3.56e5	3.56e5	3.56e5	3.56e5	3.55e5
Ad	23.09	22.97	22.9	24.1	22.95	24.36	22.96	22.38	22.38	23.61	22.9	20.65	21.49	20.53	21.27
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.027	4.075	4.102	4.018	4.075	4.009	4.075	4.014	4.014	4.061	4.014	4.042	4.013	4.026	4.003
L0	−0.006	−0.01	−0.02	−0.01	−0.01	−0.009	−0.01	−0.008	−0.008	0.0016	−0.006	0.0047	−0.003	−0.009	−0.008
x10	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	0.1879	–	0.7	0.2812	1	0.6297	1	0.6166
Vsd0	8	–	–	–	–	–	–	–	7.669	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.636	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0596	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	2155.62	2204.34	1966.03	2161.82	1946.05	2155.61	1907.91	1907.9	2058.49	1908.46	1943.21	1895.08	1920.71	1887.01
$\mathcal{L}$	–	1069.81	1139.17	974.015	1071.91	964.024	1069.8	944.956	944.949	1021.25	945.23	963.603	938.538	952.355	934.503
c.i.	–	−3.53	−1.91	−3.32	−2.63	−1.85	−2.67	−4.83	−1.11	−6.92	−4.6	−1.65	−2.19	−1.62	-3.97
time	–	2 : 20.3	2 : 16.7	2 : 24.1	5 : 48.5	1 : 55.7	26.4	4 : 09.4	58.2	1 : 18.4	3 : 52.2	1 : 32.2	3 : 24.7	1 : 41.4	4:08.5

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
qs10,...	122, 121, 17.3, 222, 245														
mdc,...	0, 40, 38, 11														
Tcf,qfrng	100, 0														
Sw0,...	1, 1, 2, 0	–	–	–	–	–	–	–	–	1, 1, 2, 1	–	1, 1, 2, 2	–	1, 1, 2, 3	–
qscf	0.2553	0.255	0.255	0.255	0.255	0.255	–	0.255	–	0.2551	0.255	0.2551	0.255	0.2551	0.255
qfcf	6.0775	6.073	6.0732	6.073	6.0729	6.0729	6.0729	6.073	–	6.074	6.0728	6.0748	6.0728	6.0754	6.0727
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2062	0.2066	0.2074	0.2063	0.2056	0.2057	0.2056	0.2064	0.2064	0.207	0.2062	0.2079	0.2063	0.2079	0.2062
Sigma5	10.65	6.13	6.195	6.162	6.157	6.149	6.146	6.161	6.16	6.336	6.004	7.052	5.96	7.825	6.02
md	0	–	5.92e5	2.64e5	7.93e4	5.13e4	0	–	–	–	–	–	–	–	–
mr	0	5.09e5	0	3.43e5	5.42e5	5.7e5	6.22e5	6.22e5	6.22e5	6.1e5	6.24e5	6.02e5	6.22e5	6.01e5	6.19e5
Ad	24.58	26.62	26.63	26.61	26.59	26.58	26.59	26.56	–	27.44	28.08	23.64	23.15	23.8	23.16
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–	–	–
ks	5.263	5.173	5.246	5.203	5.175	5.166	5.162	5.172	5.171	5.314	5.139	5.374	5.144	5.377	5.15
L0	0.0045	−0.004	−0.004	−0.004	−0.004	−0.004	−0.004	−0.004	−0.004	0.01	0.014	0.01	0.019	0.0007	−0.004
x10	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	–	–	–	–	–	0.6904	–	0.7	0.8404	1	1.34	1	1.85
Vsd0	8	–	–	–	–	–	–	–	7.888	8	–	–	–	–	–
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.793	–	–	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0571	–	–	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	8	9	9	9	8	9	9	8	9	8	9	8	9
AIC	–	902.814	913.42	907.702	904.847	904.817	901.937	908.619	908.394	928.883	889.16	1008.82	884.235	1083.75	891.106
$\mathcal{L}$	–	443.407	448.71	444.851	443.424	443.409	442.969	445.31	445.197	456.442	435.58	496.41	433.118	533.876	436.553
c.i.	–	−0.375	−0.427	−0.694	−1.99	−0.648	−2.32	−0.386	−3.27	−5.21	−5.21	−4.6	−4.63	−2.29	-0.0821
time	–	1 : 44.0	1 : 42.7	1 : 54.5	2 : 24.1	28.3	51.9	58.1	1 : 01.2	1 : 16.8	2 : 49.5	1 : 30.7	5 : 59.6	1 : 42.5	5:02.9

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.7: $\mathcal{M}_4$, $k_f = 0.01$ (*continued*).

C.4 Investigation of $\mathcal{M}_5$

```
#! /bin/sh -v
#--------------------------------------------------------------#
if [ $# -eq 0 ]; then  Exp="J";  kf=0.005;
else                   Exp="$1"; kf=$2;    fi;
#--------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1120/*.c .; mcompile
cs_setm 5
cs_sets 5 $Exp
# Use results of fourth-order investigation as initial guesses.
"../4/kf/$kf/M4_Exp_$Exp-p0_6"
cs_writep0 "$0_$Exp"-p0_0
#--------------------------------------------------------------#
# Fit without timing to determine if the mass distribution is
# affected by the switch in the model structure.
cs_setf iterations=20 step=1 reg=0
fit -d0 -d1
ackest
limit=100000
md='writep0 11 | awk '{printf "%d", $3}''
mr='writep0 12 | awk '{printf "%d", $3}''
if   [ $md -lt $limit ]; then  md=0;
elif [ $mr -lt $limit ]; then  mr=0; fi
# Then set the free parameters accordingly.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0;;
esac;
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_1
#--------------------------------------------------------------#
# Perfom the ALMP test with b1 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1;;
esac;
cm_setv
valid
sensit
#--------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Perfom the ALMP test with dVwt0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 dVwt0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 dVwt0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 dVwt0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Fit b1 and log the AIC test result.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5;;
esac;
cs_setd 0.5 $Exp
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_2
#--------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5 Vsd0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5 Vsd0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5 Vsd0;;
esac;
setv -o
valid
sensit
# Fit Vsd0 and log the AIC test result.
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_3
#--------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1121/*.c .; mcompile
cs_setm 5
cs_sets 5 $Exp
# Use results of fourth-order investigation as initial parameter guesses.
"../4/kf/$kf/M4_Exp_$Exp-p0_9"
# Fit without timing to determine if the mass distribution is
# affected by the switch in the model structure.
setf -o
fit -d0 -d1
ackest
md='writep0 11 | awk '{printf "%d", $3}''
mr='writep0 12 | awk '{printf "%d", $3}''
if   [ $md -lt $limit ]; then  md=0;
elif [ $mr -lt $limit ]; then  mr=0; fi
# Then set the free parameters accordingly.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0;;
esac;
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_4
#--------------------------------------------------------------#
# Perfom the ALMP test with b1 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Perfom the ALMP test with dVwt0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 dVwt0;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 dVwt0;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 dVwt0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------#
# Fit b1 and log the AIC test result.
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5;;
esac;
cs_setd 0.5 $Exp
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_5
#--------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
    0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5 Vsd0=5;;
    *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5 Vsd0=5;;
    *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5 Vsd0=5;;
esac;
setv -o
valid
sensit
# Fit Vsd0 and log the AIC test result.
setf -o
time fit -d0 -d1
```

Listing C.8: M5_Exp—Command script used to investigate the fourth-order model structure.

```
ackest
sensit
cs_writep0 "$0_$Exp"-p0_6
#--------------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1122/*.c .; mcompile
cs_setm 5
cs_sets 5 $Exp
# Use results of fourth-order investigation as initial parameter guesses.
"../4/kf/$kf/M4_Exp_$Exp-p0_11"
# Fit without timing to determine if the mass distribution is
# affected by the switch in the model structure.
setf -o
fit -d0 -d1
ackest
md=`writep0 11 | awk '{printf "%d", $3}'`
mr=`writep0 12 | awk '{printf "%d", $3}'`
if   [ $md -lt $limit ]; then  md=0;
elif [ $mr -lt $limit ]; then  mr=0; fi
# Then set the free parameters accordingly.
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0;;
esac;
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_7
#--------------------------------------------------------------------#
# Perfom the ALMP test with b1 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------------#
# Perfom the ALMP test with dVwt0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 dVwt0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 dVwt0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 dVwt0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------------#
# Fit b1 and log the AIC test result.
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5;;
esac;
cs_setd 0.5 $Exp
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_8
#--------------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5 Vsd0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5 Vsd0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5 Vsd0;;
esac;
setv -o
valid
sensit
# Fit Vsd0 and log the AIC test result.
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_9
#--------------------------------------------------------------------#
cs_setd 1.0 $Exp
rm *.c .ikbase/*exe; ln -s mdl/1121/*.c .; mcompile
cs_setm 5
cs_sets 5 $Exp
# Use results of fourth-order investigation as initial parameter guesses.
"../4/kf/$kf/M4_Exp_$Exp-p0_13"
# Fit without timing to determine if the mass distribution is
# affected by the switch in the model structure.
setf -o
fit -d0 -d1
ackest
md=`writep0 11 | awk '{printf "%d", $3}'`
mr=`writep0 12 | awk '{printf "%d", $3}'`
if   [ $md -lt $limit ]; then  md=0;
elif [ $mr -lt $limit ]; then  mr=0; fi
# Then set the free parameters accordingly.
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0;;
esac;
sensit
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_10
#--------------------------------------------------------------------#
# Perfom the ALMP test with b1 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 Vsd0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 Vsd0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 Vsd0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------------#
# Perfom the ALMP test with dVwt0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 dVwt0;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 dVwt0;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 dVwt0;;
esac;
setv -o
valid
sensit
#--------------------------------------------------------------------#
# Fit b1 and log the AIC test result.
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5;;
esac;
cs_setd 0.5 $Exp
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_11
#--------------------------------------------------------------------#
# Perfom the ALMP test with Vsd0 free
case "$md,$mr" in
     0,*)  cs_setp -q qscf qfcf Sigma4 Sigma5      mr=1 Ad ks L0 b1=5 Vsd0=5;;
     *,0)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1      Ad ks L0 b1=5 Vsd0=5;;
     *,*)  cs_setp -q qscf qfcf Sigma4 Sigma5 md=1 mr=1 Ad ks L0 b1=5 Vsd0=5;;
esac;
setv -o
valid
sensit
# Fit Vsd0 and log the AIC test result.
setf -o
time fit -d0 -d1
ackest
sensit
cs_writep0 "$0_$Exp"-p0_12
#--------------------------------------------------------------------#
exit 0
```

Listing C.8 M5_Exp (*continued*).

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10, ...	217, 214, 30.5, 416, 289												
mdc, ...	0, 40, 38, 11												
Tcf, qfrng	100, 0												
Sw0, ...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2074	–	0.2074	0.2074	0.2074	0.2074	–	0.2073	0.2074	0.2075	0.2073	0.2074	0.2074
qfcf	5.6514	5.6514	5.6524	5.6524	5.651	5.6528	–	5.6503	5.6520	5.6528	5.6497	5.6517	5.6517
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.178	0.178	0.1763	0.1764	0.1779	0.1763	0.1763	0.1778	0.1765	0.1765	0.1770	0.1765	0.1763
Sigma5	11.39	11.87	9.442	9.373	13.66	8.974	8.969	14.78	8.488	8.079	10.92	10.07	10.52
md	3.19e5	3.19e5	3.18e5	3.18e5	3.18e5	3.18e5	3.18e5	3.17e5	3.19e5	3.19e5	3.17e5	3.2e5	3.19e5
mr	0	–	–	–	–	–	–	–	–	–	–	–	–
Ad	29.19	29.44	31.4	31.58	30.23	33.40	33.45	27.01	25.74	25.5	27.7	26.58	26.58
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–
ks	8.11	8.116	8.132	8.125	8.123	8.142	8.142	8.123	8.117	8.11	8.135	8.124	8.139
L0	0.021	0.021	0.025	0.025	0.026	0.05	0.05	0.028	0.067	0.076	0.017	0.023	0.023
x10	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.242	1.295	0.7	1.375	1.369	1	2.026	3.349	1	4.179	1.161
Vsd0	8	–	–	2.479	8	–	7.915	8	–	2.809	8	–	26.78
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.61	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0485	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1267.48	1098.79	*n.c.*	1367.53	1002.15	1004.15	1423.77	1022.82	*n.c.*	1519.78	1186.76	1178.34
$\mathcal{L}$	–	625.738	540.396	*n.c.*	675.763	522.075	522.075	703.886	502.41	*n.c.*	751.89	584.382	579.168
c.i.	–	−8.98	−2.7	0.535	−8.18	−5.2	−5.04	−7.29	−4.46	5.09	−7.9	−4.23	-3.68
time	–	34.5	5 : 04.5	28 : 28.0	37.3	6 : 22.6	1 : 23.8	40.0	11 : 53.0	35 : 25.8	47.0	11 : 32.4	5:22.2

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10, ...	236, 233, 31.4, 432, 295												
mdc, ...	0, 40, 38, 11												
Tcf, qfrng	100, 0												
Sw0, ...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2551	0.2551	0.2551	0.2551	0.2552	0.2551	0.2551	0.2552	0.2551	0.255	0.2552	0.2551	0.2551
qfcf	5.6231	5.6231	5.622	5.622	5.6235	5.6212	5.6214	5.6234	5.6213	5.62	5.6234	5.6217	5.6217
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4756	0.4756	0.4754	0.4754	0.4755	0.4759	0.4763	0.4755	0.4756	0.4776	0.4755	0.4754	0.4755
Sigma5	19.45	19.49	18.06	18.05	20.07	17.58	15.45	20.25	18.13	15.99	20.23	18.61	18.58
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	4.2e5	4.2e5	4.21e5	4.21e5	4.2e5	4.23e5	4.23e5	4.19e5	4.22e5	4.27e5	4.19e5	4.2e5	4.2e5
Ad	29.05	29.81	31.85	31.95	30.19	36.45	58.64	27.84	27.48	27.07	27.78	27.33	27.37
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–
ks	7.72	7.703	7.7	7.691	7.694	7.731	7.796	7.681	7.705	7.866	7.68	7.681	7.673
L0	0.0063	0.0063	0.0024	0.0024	0.011	0.028	0.043	0.0078	0.021	0.052	0.0076	0.0013	0.0013
x10	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.375	1.386	0.7	2.131	4.6	1	2.572	6.891	1	3.058	4.427
Vsd0	8	–	–	5.318	8	–	16.2	8	–	0.7898	8	–	5.557
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0381	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	2332.91	2303.39	2304.7	2353.77	2260.88	2170.93	2359.92	2282.72	2197.69	2359.35	2301.5	2302.27
$\mathcal{L}$	–	1158.45	1142.69	1142.35	1108.88	1121.44	1075.47	1171.96	1132.36	1088.85	1171.67	1141.75	1141.14
c.i.	–	−7.83	−3.98	−2.51	−7.71	−7.18	−2.52	−5.75	−1.36	−1.11	−7.74	−1.16	-1.76
time	–	34.8	5 : 09.3	2 : 50.1	34.5	10 : 07.3	23 : 56.0	39.6	10 : 22.9	30 : 58.6	44.7	6 : 40.7	3:34.5

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10, ...	236, 233, 31.4, 432, 295												
mdc, ...	0, 40, 38, 11												
Tcf, qfrng	100, 0												
Sw0, ...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2568	0.2568	0.2568	–	0.2568	0.2567	0.2567	0.2569	0.2567	0.2567	0.2569	0.2568	–
qfcf	5.6602	5.6601	5.6588	5.6589	5.6606	5.6586	5.6585	5.6607	5.6586	5.6586	5.6608	5.6588	5.6588
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2275	0.2275	0.2252	0.2249	0.2271	0.2242	0.2236	0.2271	0.2244	0.2235	0.2268	0.2253	0.2251
Sigma5	7.316	7.33	6.116	6.103	8.215	5.675	5.602	8.673	5.678	5.165	8.936	6.167	6.154
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	3.72e5	3.74e5	3.93e5	3.92e5	3.72e5	3.97e5	3.97e5	3.75e5	3.98e5	4.06e5	3.73e5	3.89e5	3.92e5
Ad	29.58	29.52	30.31	30.3	30.17	32.12	35.65	27.83	26.09	25.88	27.92	26.33	26.32
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–
ks	9.886	9.863	9.467	9.465	9.824	9.309	9.202	9.727	9.351	9.081	9.762	9.517	9.45
L0	0.0059	0.0058	0.0037	0.0037	0.0094	0.021	0.025	0.009	0.026	0.041	0.0066	0.0039	0.0039
x10	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.273	1.259	0.7	1.591	2.288	1	2.299	5.092	1	3.208	7.699
Vsd0	8	–	–	1.935	8	–	12.87	8	–	1.55	8	–	3.317
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0418	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1101.05	965.712	*n.c.*	1181.98	908.516	899.965	1220.69	909.621	*n.c.*	1241.24	971.675	n.c.
$\mathcal{L}$	–	542.523	473.856	*n.c.*	582.989	445.258	439.982	602.346	445.811	*n.c.*	612.619	476.837	n.c.
c.i.	–	−2.13	−1.14	1.09	−1.19	−2.89	−1.44	−1.49	−2.66	5.7	−1.63	−3.66	0.353
time	–	33.9	5 : 01.4	27 : 43.1	34.5	10 : 11.6	15 : 23.6	38.8	17 : 20.0	32 : 45.9	46.5	16 : 01.0	38:38.1

(c) Experiment B, full load, perturbed feed-water flow.

Table C.8: Optimization results for $\mathcal{M}_5$ with $k_f = 0.001$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2567	0.2567	0.2567	0.2567	0.2566	0.2567	0.2567	0.2565	0.2567	0.2567	0.2564	0.2566	0.2567
qfcf	6.2414	6.2411	6.241	6.241	6.2416	6.2413	6.2411	6.2394	6.241	6.2411	6.2365	6.2386	6.2389
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.3145	0.3146	0.3103	0.3103	0.3172	0.3101	0.3102	0.3176	0.3101	0.3103	0.3151	0.3109	0.3109
Sigma5	7.922	9.363	9.239	9.157	11.37	9.729	9.136	16.63	7.155	7.022	24.91	8.824	8.604
md	3.91e5	3.94e5	3.92e5	3.92e5	3.97e5	3.92e5	3.91e5	3.95e5	3.91e5	3.94e5	3.92e5	3.98e5	3.96e5
mr	0	–	–	–	–	–	–	–	–	–	–	–	–
Ad	27.97	28.92	29.53	29.62	28.58	31.02	28.48	23.82	25.25	25.13	25.53	26.8	26.65
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.01	4.623	4.695	4.69	4.404	4.642	4.674	4.357	4.679	4.639	4.473	4.66	4.729
L0	0.013	0.013	0.013	0.013	0.025	0.03	0.025	0.026	0.049	0.054	0.0033	0.01	0.0099
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.7425	0.757	0.7	0.8354	0.5045	1	1.465	1.988	1	3.197	0.7722
Vsd0	8	–	–	2.252	8	–	0.4227	8	–	4.466	8	–	30.66
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.713	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0283	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1509.62	1492.21	1488.05	1655.16	1528.8	n.c.	1929.06	1308.28	1297.12	2213.37	1459.54	1444.58
$\mathcal{L}$	–	746.81	737.105	734.023	819.579	755.401	n.c.	956.531	645.139	638.562	1098.69	720.77	712.289
c.i.	–	−8.48	−2.17	−0.23	−6.61	−2.45	4.58	−4.94	−0.0527	−3.17	−5.35	−3.7	-3.87
time	–	34.6	2 : 32.0	7 : 00.6	34.2	3 : 46.2	27 : 59.4	39.0	7 : 18.8	14 : 29.9	45.8	11 : 53.1	9:16.1

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2523	0.2523	0.2524	0.2524	0.2523	0.2524	0.2524	0.2524	0.2524	0.2524	0.2524	0.2524	0.2524
qfcf	6.0845	6.0848	6.0876	6.0877	6.0852	6.0876	6.0877	6.0861	6.0876	6.0876	6.0864	6.0876	6.0877
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4063	0.4069	0.4025	0.4025	0.4063	0.4025	–	0.4058	0.4024	0.4023	0.406	0.4025	0.4025
Sigma5	20.23	15.13	11.11	11.07	14.58	11.11	11.08	12.3	11.02	10.98	12.81	11.02	11
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	3.32e5	3.31e5	3.28e5	3.28e5	3.31e5	3.28e5	3.28e5	3.3e5	3.28e5	3.28e5	3.3e5	3.28e5	3.28e5
Ad	23.08	22.4	21.5	21.59	23.02	21.71	21.58	20.05	21.15	21.16	19.99	21.12	21.22
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.081	4.102	4.034	4.033	4.082	4.033	4.033	4.054	4.032	4.03	4.066	4.035	4.034
L0	−0.011	−0.01	−0.007	−0.006	0.0032	−0.006	−0.006	0.0065	−0.005	−0.005	−0.009	−0.007	−0.006
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.07209	0.06588	0.7	0.1107	0.07376	1	0.2973	0.4999	1	0.2408	0.5011
Vsd0	8	–	–	2.425	8	–	3.405	8	–	4.686	8	–	3.554
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.636	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0258	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	2038.86	1811.14	n.c.	2011.37	1811.37	1812.24	1888.07	1805.18	1804.1	1918.08	1805.57	n.c.
$\mathcal{L}$	–	1011.43	896.572	n.c.	997.685	896.683	896.119	936.035	893.591	892.05	951.038	893.785	n.c.
c.i.	–	−6.91	−1.87	0.619	−6.88	−1.11	−0.0236	−6.35	−2.1	−0.166	−7.5	−3.01	0.127
time	–	33.9	7 : 36.4	27 : 43.8	33.9	6 : 18.8	4 : 10.2	41.6	8 : 40.5	6 : 36.0	44.1	6 : 33.0	35:59.0

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.255	0.2549	0.255	0.255	0.255	0.255	0.255	0.2551	0.255	0.255	0.2551	0.255	0.255
qfcf	6.0719	6.0713	6.0723	6.0723	6.0726	6.072	6.072	6.0736	6.0721	6.0719	6.074	6.0721	6.0721
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2051	0.2046	0.2061	0.206	0.2057	0.2057	0.2057	0.2072	0.206	0.2057	0.2075	0.206	0.206
Sigma5	6.044	6.358	6.098	6.084	5.843	5.798	5.786	6.364	5.915	5.451	6.832	5.98	5.971
md	1.71e5	7.97e4	–	–	0	–	–	6.36e4	–	–	0	–	–
mr	4.29e5	5.32e5	5.19e5	5.19e5	5.93e5	6.02e5	6.03e5	5.16e5	5.35e5	5.37e5	5.76e5	5.96e5	5.96e5
Ad	26.26	26.11	25.82	25.8	26.97	27.22	28.28	23.28	22.92	22.79	23.41	22.94	22.94
kf	0.001	–	–	–	–	–	–	–	–	–	–	–	–
ks	5.069	4.945	5.106	5.111	5.15	5.045	5.034	5.29	5.075	5.038	5.332	5.081	5.073
L0	−0.0038	−0.005	−0.003	−0.003	0.01	0.011	0.013	0.0071	0.011	0.033	0.0004	−0.003	−0.003
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.5912	0.5843	0.7	0.7616	0.9149	1	1.226	3.607	1	1.517	2.138
Vsd0	8	–	–	2.252	8	–	10.48	8	–	0.7794	8	–	5.67
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.793	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0239	–	–	–	–	–	–	–	–	–	–	–	–
$\|\nu\|$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	923.027	900.062	n.c.	865.983	862.602	863.029	932.448	877.637	n.c.	984.734	885.78	886.406
$\mathcal{L}$	–	453.514	441.031	n.c.	424.992	422.301	421.514	458.224	429.819	n.c.	484.367	433.89	433.203
c.i.	–	−1.74	−0.943	0.776	−5.58	−7.19	−2.41	−2.44	−5.87	4.15	−5.64	−5.29	-0.475
time	–	34.2	2 : 34.5	27 : 49.3	34.9	3 : 52.6	10 : 00.0	41.8	7 : 45.0	31 : 07.3	43.8	6 : 30.5	3:45.3

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.8: $\mathcal{M}_5$, $k_f = 0.001$ (*continued*).

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	217, 214, 30.5, 410, 289												
mdc,...	0, 40, 38, 11												
Tcf.qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2674	0.2674	0.2674	0.2674	0.2674	0.2675	0.2675	0.2674	0.2674	0.2675	0.2673	0.2674	–
qfcf	5.6518	5.6518	5.6525	–	5.6514	5.6528	5.6528	5.6508	5.6527	5.6528	5.6502	5.6519	5.6519
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.1782	0.1782	0.1765	0.1765	0.178	0.1764	–	0.1779	0.1767	0.1767	0.1777	0.1766	0.1764
Sigma5	10.57	10.97	9.147	9.084	12.75	8.783	8.771	13.89	8.279	7.952	15.91	9.904	9.794
md	3.37e5	3.37e5	3.36e5	3.37e5	3.36e5	3.36e5	3.36e5	3.36e5	3.37e5	3.37e5	3.35e5	3.38e5	3.37e5
mr	0	–	–	–	–	–	–	–	–	–	–	–	–
Ad	28.79	28.99	30.6	30.78	29.73	32.61	31.82	26.55	25.49	25.3	27.16	26.15	26.16
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–
ks	8.092	8.098	8.114	8.105	8.107	8.122	8.121	8.109	8.096	8.09	8.124	8.104	8.118
L0	0.021	0.021	0.023	0.023	0.026	0.046	0.044	0.026	0.06	0.069	0.016	0.021	0.021
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.138	1.193	0.7	1.296	1.181	1	1.937	3.19	1	3.785	1.2
Vsd0	8	–	–	2.15	8	–	6.621	8	–	2.945	8	–	23.75
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.01	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0857	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1212.05	1076.50	n.c.	1318.84	1017.28	1019.28	1379.52	1005.72	n.c.	1470.25	1133.74	1127.51
$\mathcal{L}$	–	598.024	520.207	n.c.	651.418	514.638	514.638	681.762	493.861	n.c.	730.127	557.809	553.753
c.i.	–	−8.68	−4.62	0.784	−8.18	−5.24	−0.016	−7.28	−4.79	5.45	−7.65	−6.22	-4.31
time	–	34.2	4 : 59.2	27 : 45.3	33.9	6 : 10.1	1 : 22.4	38.9	11 : 35.8	32 : 27.6	43.5	11 : 20.1	5:15.7

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	236, 233, 31.4, 432, 295												
mdc,...	0, 40, 38, 11												
Tcf.qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2552	0.2552	0.2551	–	0.2552	0.255	0.2551	0.2552	0.2551	0.255	0.2552	0.2551	0.2551
qfcf	5.6232	5.6232	5.6218	–	5.6230	5.621	5.6213	5.6235	5.6212	5.6199	5.6235	5.6215	5.6215
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4755	0.4754	0.4754	0.4754	0.4753	0.4759	0.4762	0.4753	0.4758	0.4784	0.4753	0.4754	0.4754
Sigma5	20.01	20.05	18.7	18.7	20.7	17.10	15.26	20.88	18.25	10.2	20.92	18.61	18.6
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	4.4e5	4.4e5	4.42e5	4.42e5	4.4e5	4.45e5	4.43e5	4.39e5	4.44e5	4.49e5	4.39e5	4.41e5	4.41e5
Ad	29.91	30.09	32.99	33.04	30.49	38.09	60.08	28.13	27.71	27.23	28.08	27.5	27.55
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–
ks	7.715	7.7	7.695	7.696	7.69	7.73	7.771	7.679	7.712	7.9	7.674	7.671	7.66
L0	0.0061	0.0065	0.0016	0.0016	0.011	0.033	0.045	0.0095	0.029	0.054	0.0079	0.0003	0.0003
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.043	1.048	0.7	2.35	4.672	1	2.749	6.998	1	3.754	5.061
Vsd0	8	–	–	7.318	8	–	16.07	8	–	0.7567	8	–	5.961
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–		–
xr0	0.0709	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	2352.7	2304.93	2306.87	2376.45	2256.45	2162.01	2381.94	2287.59	2208.38	2383.24	2301.06	2303.07
$\mathcal{L}$	–	1168.35	1143.47	1143.44	1170.72	1119.23	1071.01	1182.97	1134.8	1094.19	1183.62	1141.53	1141.53
c.i.	–	−7.75	−1.05	−3	−7.54	−0.242	−1.64	−5.83	−4.46	−0.0745	−7.87	−3.02	-0.332
time	–	34.0	5 : 02.6	1 : 22.6	34.3	8 : 57.4	22 : 24.3	44.2	11 : 26.3	34 : 45.7	44.1	11 : 28.0	1:50.4

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	236, 233, 31.4, 432, 295												
mdc,...	0, 40, 38, 11												
Tcf.qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2568	0.2568	0.2568	0.2568	0.2569	0.2567	0.2567	0.2569	0.2567	0.2567	0.2569	0.2568	–
qfcf	5.6605	5.6604	5.6589	5.6589	5.6608	5.6587	5.6586	5.661	5.6587	5.6587	5.6611	5.6589	–
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.227	0.227	0.2249	0.2246	0.2268	0.224	0.2235	0.2266	0.2242	0.2234	0.2263	0.225	0.2249
Sigma5	7.571	7.564	6.061	6.048	8.467	5.627	5.581	8.931	5.603	5.131	9.218	6.097	6.083
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	3.93e5	3.95e5	4.15e5	4.14e5	3.97e5	4.2e5	4.2e5	3.96e5	4.2e5	4.28e5	3.95e5	4.11e5	4.13e5
Ad	29.85	29.78	30.66	30.64	30.42	32.52	35.44	28.09	26.17	25.99	28.2	26.4	26.39
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–
ks	9.847	9.827	9.424	9.442	9.704	9.285	9.198	9.677	9.317	9.084	9.697	9.483	9.419
L0	0.005	0.0049	0.0026	0.0026	0.0084	0.021	0.024	0.0084	0.027	0.042	0.0056	0.0027	0.0027
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.357	1.34	0.7	1.653	2.228	1	2.372	5.073	1	3.447	8.307
Vsd0	8	–	–	1.991	8	–	12.18	8	–	1.628	8	–	3.303
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0762	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1122.35	958.36	n.c.	1202.77	901.835	896.694	1240.1	899.208	n.c.	1262.05	902.475	n.c.
$\mathcal{L}$	–	553.176	470.18	n.c.	593.387	441.917	438.347	612.052	440.604	n.c.	623.024	472.238	n.c.
c.i.	–	−1.8	−0.571	1.04	−0.931	−2.32	−2.26	−2.15	−2.46	5.63	−2.11	−3.54	0.368
time	–	33.9	5 : 01.1	27 : 45.1	34.6	10 : 24.2	15 : 31.9	40.0	17 : 50.4	33 : 13.7	43.6	14 : 34.6	35:40.2

(c) Experiment B, full load, perturbed feed-water flow.

Table C.9: Optimization results for $\mathcal{M}_5$ with $k_f = 0.005$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qsl0,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2567	0.2568	0.2568	0.2568	0.2567	0.2568	0.2568	0.2566	0.2566	0.2566	0.2565	0.2564	0.2566
qfcf	6.2422	6.2424	6.2425	–	6.2431	6.2429	6.2428	6.2405	6.2398	6.2404	6.2386	6.2352	6.239
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.3151	0.3158	0.3104	0.3104	0.316	0.3103	0.3103	0.3167	0.3101	0.311	0.3158	0.3099	0.31
Sigma5	7.991	8.837	8.76	8.645	9.964	9.132	8.953	15.2	12.14	10.21	21.92	16.13	13.55
md	1.15e5	5.58e5	5.6e5	5.6e5	6.24e5	6.21e5	6.2e5	0	–	–	–	–	–
mr	2.95e5	−1.53e5	–	–	−2.13e5	–	–	4.11e5	4.05e5	4.06e5	4.11e5	4.05e5	4.05e5
Ad	27.24	28.21	27.58	27.61	27.53	28.68	27.01	23.92	26.38	25.39	24.34	29.64	26.88
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.519	4.813	4.687	4.677	4.451	4.625	4.648	4.308	4.578	4.468	4.439	4.527	4.645
L0	0.013	0.013	0.013	0.013	0.027	0.029	0.026	0.024	0.037	0.045	0.0053	0.0052	0.0065
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.6669	0.6782	0.7	0.7642	0.537	1	1.384	3.341	1	3.092	0.1291
Vsd0	8	–	–	1.957	8	–	2.454	8	–	0.8625	8	–	125.3
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.713	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0499	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1470.89	1454.29	1446.61	1557.65	1507	n.c.	1862.33	1687.68	1567.64	2123.21	1891.01	1768.53
$\mathcal{L}$	–	727.447	718.145	713.307	770.827	744.502	n.c.	923.163	834.838	773.819	1053.61	936.503	874.264
c.i.	–	−1.48	−2.32	−3.72	−1.52	−7.8	5.54	−5.81	−7.84	−1.24	−6.81	−1.01	-1.51
time	–	34.5	2 : 34.2	8 : 26.6	34.7	3 : 50.8	28 : 17.3	39.5	7 : 19.7	31 : 06.6	45.1	8 : 08.4	12:33.9

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qsl0,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2523	0.2523	0.2524	0.2524	0.2523	0.2524	0.2524	0.2523	0.2524	0.2524	0.2524	0.2524	0.2524
qfcf	6.0839	6.0844	6.0868	6.087	6.0849	6.0868	6.0868	6.0858	6.0864	6.0865	6.0861	6.0868	6.087
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4061	0.407	0.4019	0.4018	0.4062	0.4019	0.4019	0.4058	0.4018	0.4017	0.4057	0.4019	0.4018
Sigma5	18.28	14.03	12.04	11.94	13.48	12.05	11.98	11.91	11.78	11.69	12.08	11.75	11.63
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	3.49e5	3.48e5	3.46e5	3.46e5	3.47e5	3.46e5	3.46e5	3.46e5	3.46e5	3.46e5	3.46e5	3.46e5	3.46e5
Ad	22.87	22.75	22.03	22.31	23.36	22.51	22.19	20.53	20.94	21.02	20.31	21.02	21.19
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.074	4.103	4.013	4.006	4.072	4.012	4.009	4.042	4.013	4.008	4.026	4.005	3.999
L0	−0.012	−0.01	−0.008	−0.007	0.0026	−0.006	−0.006	0.0056	−0.0005	0.0045	−0.009	−0.008	−0.008
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.1729	0.1972	0.7	0.2587	0.1946	1	0.7463	1.368	1	0.586	3.736
Vsd0	8	–	–	0.7834	8	–	2.603	8	–	3.422	8	–	1.362
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.636	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0461	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1985	1868.35	n.c.	1954.81	1868.61	1866.93	1865.46	1852.16	1848.3	1875.02	1850.39	n.c.
$\mathcal{L}$	–	984.501	925.173	n.c.	969.404	925.306	923.463	924.732	917.078	914.148	929.509	916.196	n.c.
c.i.	–	−6.98	−1.49	2.41	−7.07	−2.06	−2.09	−6.05	−0.925	−2.62	−8.3	−1.41	2.4
time	–	34.4	8 : 54.5	27 : 51.9	36.1	8 : 00.0	11 : 59.8	38.7	7 : 13.0	21 : 36.1	46.0	6 : 44.9	36:42.5

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qsl0,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.255	0.255	0.255	0.255	0.255	0.255	0.255	0.2551	0.255	–	0.2551	0.255	0.255
qfcf	6.0725	6.0721	6.0725	6.0725	6.0735	6.0722	6.0722	6.0743	6.0723	6.0723	6.0749	6.0723	6.0723
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2053	0.2049	0.206	0.2059	0.2064	0.2057	0.2057	0.2076	0.2059	0.2057	0.2079	0.2058	0.2059
Sigma5	6.095	6.027	6.004	5.991	6.014	5.76	5.757	6.736	5.833	5.477	7.461	5.917	5.904
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	6.14e5	6.23e5	6.18e5	6.18e5	6.05e5	6.21e5	6.22e5	5.94e5	6.18e5	6.2e5	5.92e5	6.14e5	6.16e5
Ad	26.48	26.28	26.18	26.16	27.2	27.69	28.23	23.47	22.96	22.87	23.65	22.99	22.98
kf	0.005	–	–	–	–	–	–	–	–	–	–	–	–
ks	5.121	5.022	5.088	5.092	5.246	5.046	5.037	5.344	5.064	5.044	5.367	5.078	5.062
L0	−0.0038	−0.004	−0.004	−0.003	0.01	0.013	0.014	0.0096	0.017	0.035	0.0007	−0.003	−0.003
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.6578	0.6504	0.7	0.8215	0.8994	1	1.304	3.364	1	1.745	2.466
Vsd0	8	–	–	2.315	8	–	9.343	8	–	1.059	8	–	5.656
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.793	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0138	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	885.457	888.455	n.c.	880.253	857.722	859.475	974.808	867.257	n.c.	1049.13	877.507	877.909
$\mathcal{L}$	–	434.728	435.228	n.c.	436.626	419.861	419.738	479.404	424.629	n.c.	516.564	429.753	428.954
c.i.	–	−4.8	−3.31	0.716	−5.56	−3.57	−0.81	−5.44	−4.65	3.81	−4.87	−0.257	-0.421
time	–	36.3	2 : 41.0	29 : 39.2	34.8	3 : 52.2	4 : 14.9	41.2	7 : 22.5	33 : 12.7	43.9	7 : 37.2	3:33.5

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.9: $\mathcal{M}_5$, $k_f = 0.005$ (*continued*).

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10, ...	217, 214, 30.5, 416, 289												
mdc, ...	0, 40, 38, 11												
Tcf, qfrng	100, 0												
Sw0, ...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2674	0.2674	0.2674	0.2674	0.2674	0.2675	0.2675	0.2674	0.2675	0.2675	0.2673	0.2674	–
qfcf	5.652	5.6519	5.6526	–	5.6516	5.6529	5.6528	5.6509	5.6527	5.6529	5.6504	5.652	5.652
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.1783	0.1783	0.1765	0.1766	0.1781	0.1765	0.1765	0.178	0.1768	0.1768	0.1778	0.1766	0.1765
Sigma5	10.33	10.7	9.087	9.035	12.47	8.769	8.71	13.59	8.265	7.98	15.56	9.634	9.535
md	3.46e5	3.46e5	3.46e5	3.46e5	3.46e5	3.46e5	3.46e5	3.45e5	3.47e5	3.47e5	3.45e5	3.47e5	3.46e5
mr	0	–	–	–	–	–	–	–	–	–	–	–	–
Ad	28.64	28.82	30.3	30.46	29.55	32.29	30.66	26.37	25.38	25.22	26.95	25.98	25.99
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–
ks	8.085	8.09	8.106	8.099	8.1	8.114	8.109	8.103	8.088	8.083	8.118	8.095	8.109
L0	0.018	0.018	0.02	0.021	0.023	0.042	0.039	0.024	0.055	0.064	0.014	0.019	0.019
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.103	1.149	0.7	1.268	1.014	1	1.901	3.099	1	3.639	1.203
Vsd0	8	–	–	2.435	8	–	3.985	8	–	3.062	8	–	22.88
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.61	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.11	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1194.37	1072.49	n.c.	1303.62	1046.37	1046.76	1364.43	1004.91	n.c.	1460.41	1114.18	1108.59
$\mathcal{L}$	–	589.183	527.246	n.c.	643.809	511.185	513.381	674.217	493.455	n.c.	722.206	548.089	544.297
c.i.	–	−8.61	−0.225	1.05	−8.17	−5.22	−0.433	−7.29	−4.96	5.3	−7.59	−6.99	−4.49
time	–	34.0	3 : 50.4	28 : 51.2	34.7	6 : 30.4	11 : 28.9	39.7	11 : 40.2	32 : 47.0	44.4	11 : 33.1	5:21.4

(a) Experiment E, full load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10, ...	236, 233, 31.4, 432, 295												
mdc, ...	0, 40, 38, 11												
Tcf, qfrng	100, 0												
Sw0, ...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2552	0.2552	0.2551	0.2551	0.2552	0.255	0.2551	0.2552	0.2551	0.255	0.2552	0.2551	0.2551
qfcf	5.6232	5.6233	5.6218	5.6217	5.6230	5.621	5.6212	5.6236	5.6212	5.6199	5.6236	5.6214	–
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4754	0.4754	0.4755	0.4754	0.4753	0.4759	0.4701	0.4753	0.4757	0.479	0.4753	0.4754	0.4754
Sigma5	20.3	20.33	18.8	18.8	21	17.48	15.21	21.19	18.38	16.32	21.25	18.09	18.08
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	4.5e5	4.5e5	4.53e5	4.53e5	4.5e5	4.56e5	4.53e5	4.5e5	4.55e5	4.6e5	4.49e5	4.52e5	4.52e5
Ad	30.04	30.22	33.44	33.5	30.63	38.77	60.81	28.26	27.82	27.3	28.22	27.59	27.63
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–
ks	7.715	7.701	7.098	7.703	7.691	7.733	7.765	7.68	7.723	7.917	7.674	7.67	7.601
L0	0.0005	0.0066	0.0014	0.0013	0.011	0.035	0.046	0.0099	0.031	0.055	0.008	−0.00049e	− 5
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.738	1.756	0.7	2.432	4.711	1	2.811	7.035	1	4.012	4.928
Vsd0	8	–	–	8.754	8	–	16.03	8	–	0.7444	8	–	6.543
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	9.998	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.093	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	2362.86	2308.73	2310.57	2385.89	2257.2	2159.21	2392.44	2292.62	2214.12	2394.26	2304.16	2306.17
$\mathcal{L}$	–	1173.43	1145.36	1145.29	1184.95	1119.6	1069.6	1188.22	1137.31	1097.06	1189.13	1143.08	1143.08
c.i.	–	−7.99	−0.673	−2.76	−7.41	−0.278	−1.31	−5.79	−1.83	−2.96	−7.97	−3.57	−1.02
time	–	34.6	5 : 06.7	1 : 23.7	35.4	9 : 16.7	23 : 52.5	40.2	16 : 09.2	33 : 49.0	51.7	13 : 20.6	1:56.2

(b) Experiment A, full load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10, ...	236, 233, 31.4, 432, 295												
mdc, ...	0, 40, 38, 11												
Tcf, qfrng	100, 0												
Sw0, ...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2568	0.2568	0.2568	–	0.2569	0.2567	0.2567	0.2569	0.2567	0.2568	0.2569	0.2568	0.2568
qfcf	5.6606	5.6605	5.659	5.659	5.6609	5.6587	5.6587	5.6611	5.6588	5.6588	5.6612	5.6589	–
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2268	0.2268	0.2248	0.2246	0.2266	0.2239	0.2235	0.2263	0.2241	0.2233	0.2261	0.2249	0.2248
Sigma5	7.677	7.663	6.057	6.044	8.576	5.62	5.578	9.031	5.585	5.123	9.321	6.088	6.074
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	4.04e5	4.05e5	4.26e5	4.24e5	4.08e5	4.29e5	4.31e5	4.07e5	4.31e5	4.39e5	4.05e5	4.22e5	4.24e5
Ad	29.97	29.9	30.81	30.8	30.55	32.71	35.5	28.2	26.22	26.04	28.31	26.45	26.45
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–
ks	9.826	9.806	9.414	9.438	9.681	9.319	9.202	9.653	9.31	9.087	9.668	9.472	9.413
L0	0.0034	0.0033	0.0008	0.0009	0.0069	0.02	0.023	0.0069	0.027	0.041	0.0041	0.001	0.001
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	1.385	1.367	0.7	1.676	2.224	1	2.396	5.051	1	3.515	8.527
Vsd0	8	–	–	1.987	8	–	11.99	8	–	1.67	8	–	3.28
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	10.07	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.099	–	–	–	–	–	–	–	–	–	–	–	–
|ν|	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1131.06	957.656	n.c.	1211.14	900.529	896.291	1247.38	896.714	n.c.	1269.35	961.15	n.c.
$\mathcal{L}$	–	557.529	469.828	n.c.	597.571	441.264	438.147	615.691	439.357	n.c.	626.675	471.575	n.c.
c.i.	–	−1.76	−0.398	1.05	−1.14	−3.41	−1.57	−2.54	−2.41	5.59	−2.36	−4.16	0.387
time	–	34.9	5 : 15.6	27 : 51.1	34.9	11 : 38.5	9 : 58.9	40.0	17 : 16.4	32 : 43.2	44.9	18 : 24.1	36:39.5

(c) Experiment B, full load, perturbed feed-water flow.

Table C.10: Optimization results for $\mathcal{M}_5$ with $k_f = 0.01$ fixed.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2567	0.2567	0.2567	0.2567	0.2567	0.2567	0.2567	0.2566	0.2567	0.2566	0.2566	0.2564	0.2566
qfcf	6.2426	6.2405	6.2408	–	6.2414	6.2409	6.2408	6.2412	6.2406	6.2411	6.2396	6.2367	6.2396
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.3148	0.3144	0.3102	0.3102	0.3151	0.3102	0.3102	0.3167	0.3102	0.3106	0.3164	0.3102	0.31
Sigma5	8.14	12.83	12.72	12.72	12.66	12.36	12.32	14.14	11.81	10.17	20.47	15.28	13.2
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	4.18e5	4.15e5	4.16e5	4.16e5	4.18e5	4.16e5	4.16e5	4.21e5	4.15e5	4.16e5	4.21e5	4.15e5	4.15e5
Ad	27.1	30.2	29.32	29.3	29.25	30.95	29.81	23.57	25.73	24.88	23.69	28.32	26.36
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.571	4.647	4.587	4.584	4.512	4.579	4.579	4.401	4.584	4.497	4.417	4.505	4.627
L0	0.013	0.0097	0.0099	0.0099	0.022	0.024	0.022	0.024	0.035	0.044	0.0061	0.0059	0.0068
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.6575	0.6563	0.7	0.7844	0.6399	1	1.332	3.262	1	2.824	0.1479
Vsd0	8	–	–	7.776	8	–	4.404	8	–	0.9626	8	–	107.6
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.713	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0643	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1735.64	1721.34	1723.19	1727.51	1701.14	1700.57	1810.39	1668.19	n.c.	2075.12	1853.05	1749.51
$\mathcal{L}$	–	859.821	851.67	851.596	855.753	841.568	840.286	897.196	825.097	n.c.	1029.56	917.524	864.753
c.i.	–	−6.03	−1.01	−4.02	−6.36	−3.24	−0.0147	−6.29	−7.83	4.82	−6.47	−1.63	-2.4
time	–	34.5	2 : 35.0	1 : 24.6	34.8	3 : 52.9	8 : 31.4	39.3	7 : 20.2	34 : 51.9	43.8	8 : 15.5	12:42.2

(d) Experiment J, partial load, perturbed steam flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.2522	0.2523	0.2524	0.2524	0.2523	0.2524	–	0.2523	0.2523	0.2523	0.2523	0.2524	0.2524
qfcf	6.0837	6.0842	6.0864	6.0865	6.0848	6.0864	6.0864	6.0857	6.086	6.0861	6.086	6.0863	6.0866
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.4062	0.4072	0.4018	0.4017	0.4063	0.4018	0.4017	0.4058	0.4018	0.4017	0.4050	0.4017	0.4016
Sigma5	17.83	14.04	12.71	12.53	13.52	12.71	12.62	12.29	12.32	12.23	12.31	12.28	12.05
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	3.58e5	3.57e5	3.56e5	3.56e5	3.56e5	3.56e5	3.56e5	3.56e5	3.56e5	3.56e5	3.55e5	3.55e5	3.56e5
Ad	22.96	23.04	22.34	22.73	23.67	22.96	22.51	20.86	21.01	21.09	20.58	20.93	21.23
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–
ks	4.075	4.109	4.018	4.008	4.074	4.016	4.012	4.047	4.023	4.017	4.02	4.001	3.991
L0	−0.013	−0.01	−0.009	−0.008	0.0021	−0.006	−0.006	0.0049	0.0021	0.0084	−0.009	−0.009	−0.008
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.2355	0.2801	0.7	0.3393	0.2496	1	0.8962	1.565	1	0.7915	9.35
Vsd0	8	–	–	0.8444	8	–	2.202	8	–	3.495	8	–	0.7625
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.036	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0596	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	1985.74	1906.64	n.c.	1957.41	1906.76	1903.92	1887.81	1884.48	1881.2	1888.71	1882.14	n.c.
$\mathcal{L}$	–	984.869	944.32	n.c.	970.704	944.378	941.901	935.907	933.24	930.598	936.354	932.07	n.c.
c.i.	–	−7.03	−0.994	2.23	−7.21	−1.56	−0.913	−7.34	−1.03	−1.9	−8.78	−0.722	3.21
time	–	34.9	9 : 02.9	28 : 15.4	33.9	8 : 10.3	11 : 21.7	40.8	4 : 33.3	25 : 34.7	44.8	4 : 58.5	36:17.7

(e) Experiment F, partial load, perturbed fuel flow.

Θ	0	1	2	3	4	5	6	7	8	9	10	11	12
qs10,...	122, 121, 17.3, 222, 245												
mdc,...	0, 40, 38, 11												
Tcf,qfrng	100, 0												
Sw0,...	1, 1, 2, 0	–	–	–	1, 1, 2, 1	–	–	1, 1, 2, 2	–	–	1, 1, 2, 3	–	–
qscf	0.255	0.255	0.255	0.255	0.2551	0.255	–	0.2551	0.255	0.255	0.2551	0.255	0.255
qfcf	6.0729	6.0725	6.0726	6.0727	6.0738	6.0724	6.0724	6.0747	6.0725	6.0724	6.0753	6.0724	6.0724
Sigma1	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma2	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma3	0	–	–	–	–	–	–	–	–	–	–	–	–
Sigma4	0.2056	0.2051	0.2059	0.2059	0.2067	0.2057	0.2057	0.2078	0.2059	0.2057	0.2079	0.2058	0.2059
Sigma5	6.146	5.984	6.007	5.994	6.141	5.76	5.758	6.94	5.826	5.556	7.748	5.911	5.897
md	0	–	–	–	–	–	–	–	–	–	–	–	–
mr	6.22e5	6.3e5	6.28e5	6.28e5	6.13e5	6.32e5	6.32e5	6.03e5	6.28e5	6.3e5	6.01e5	6.24e5	6.26e5
Ad	26.59	26.39	26.36	26.34	27.32	27.9	28.36	23.57	22.99	22.93	23.76	23.02	23.01
kf	0.01	–	–	–	–	–	–	–	–	–	–	–	–
ks	5.162	5.072	5.094	5.095	5.284	5.051	5.043	5.361	5.068	5.056	5.374	5.08	5.064
L0	−0.0039	−0.004	−0.004	−0.004	0.01	0.013	0.014	0.01	0.018	0.034	0.0006	−0.004	−0.004
xi0	0	–	–	–	–	–	–	–	–	–	–	–	–
b1	0.7	–	0.6861	0.6784	0.7	0.8461	0.9147	1	1.336	2.915	1	1.833	2.593
Vsd0	8	–	–	2.286	8	–	9.319	8	–	1.618	8	–	5.65
dVwt0	0	–	–	–	–	–	–	–	–	–	–	–	–
P0	8.793	–	–	–	–	–	–	–	–	–	–	–	–
xr0	0.0571	–	–	–	–	–	–	–	–	–	–	–	–
$\lvert\nu\rvert$	0	8	9	10	8	9	10	8	9	10	8	9	10
AIC	–	881.162	888.799	n.c.	905.369	857.732	859.681	996.833	866.439	n.c.	1076.38	876.703	877.072
$\mathcal{L}$	–	432.581	435.399	n.c.	444.685	419.866	419.841	490.417	424.22	n.c.	530.192	429.351	428.536
c.i.	–	−4.63	−5.32	0.749	−5.55	−1.94	−0.426	−5.69	−4.32	3.66	−4.71	−0.211	-0.394
time	–	34.2	2 : 31.2	28 : 05.8	35.0	3 : 53.2	1 : 26.0	40.2	7 : 13.5	32 : 18.7	43.7	6 : 30.0	3:31.2

(f) Experiment G, partial load, perturbed feed-water flow.

Table C.10: $\mathcal{M}_5$, $k_f = 0.01$ (*continued*).

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