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Application Study in the K2 Project

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Abstract

The K2 model database is a set of Omola libraries used for modelling of thermal power plants. In this study it is used to model a heat recovery steam generation plant, HRSG. Using object-oriented methodology the plant structure is decomposed into plant sections and the sections are then further decomposed into units. This decomposition is supported by Omola and the structure of the K2 model database. The HRSG model is then used to simulate different operating conditions.

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1. Introduction

This application study is part of the K2 project at the Department of Automatic Control, Lund Institute of Technology. The K2 project is focused on the development of a general model library for modelling of power generation systems, but also include a number of side effects concerning large model databases, version control, static solver and user interface. The tool used is the object-oriented modelling language Omola and the simulation environment OmSim. An Omola Tutorial is found in [Andersson, 1993] and a more detailed discusstion is found in [Andersson, 1994] The K2 project is financed in three different research programs: Sydkraft, NUTEK power systems program and NUTEK complex systems program.

The aim of this application study is to be able to simulate a small power plant, a so called *heat recovery steam generation plant*, HRSG. Flue gas from a gas turbine is fed into a pan where the heat is recovered by boiling water. The produced steam is used to drive a steam turbine in order to produce electric power. Remaining energy in the steam heats up water used for district heating in apartments.

Heat Recovery Steam Generation Plant

The HRSG plant configuration, studied in this report, is seen in Figure 1. Condensate water is pumped from the condenser to the deaerator via a preheater in the pan. Feedwater is then pumped from the deaerator to the drum via an economizer which heats up the water to boiling temperature. The water in the drum is circulated through the evaporator and the two phases water and steam then flashes, separates, into the drum. Saturated steam is extracted from the drum and passes two superheaters to produce superheated steam before it enters the steam turbine. In the turbine the steam flow expands to low

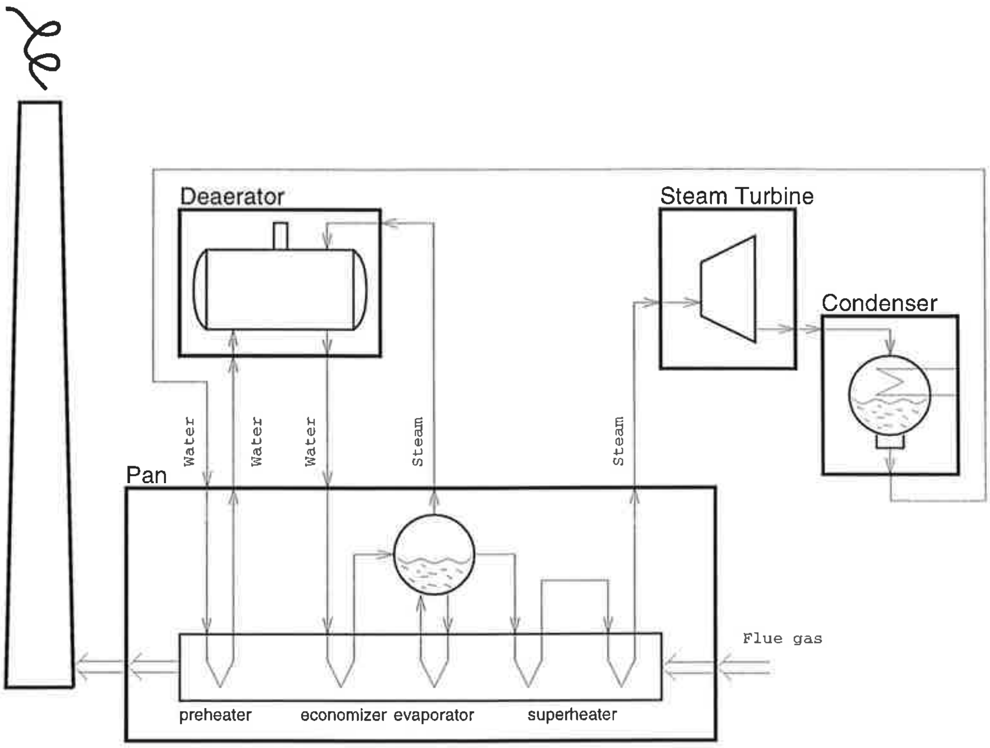

Figure 1. The configuration of a heat recovery steam generation plant.

pressure and it is then condensed to water again in the condenser and can be recirculated to the deaerator.

Structuring of the Model

The classes used in the modelling of the application has been structured according to the guidelines in [Nilsson, 1993]. The plant can be viewed in a top-down fashion on different levels of complexity, called granularity levels; flowsheet, unit and subunit level, see Figure 2. On the flowsheet level the plant itself and the sections of the plant are described. The unit level is where the building blocks performing unit operations, like pumps, tanks and heat exchangers are described and the subunit level is the lowest level where balance equations, functions and basic components are used for the behavioral description. These different levels will be dealt with in the following sections.

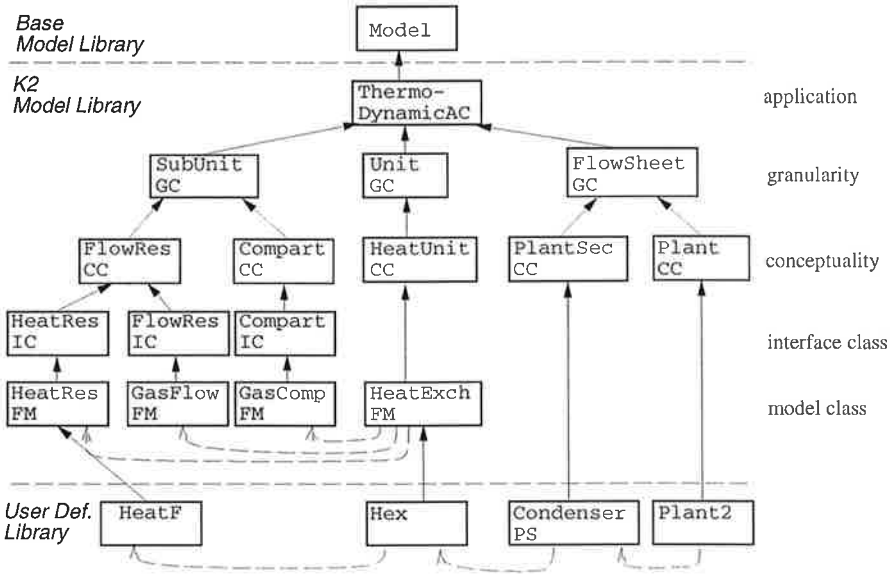

Figure 2. Structuring guidelines of the model library. The suffices AC (Application Class), GC, CC and IC mark that these are classes used as super classes for structuring purposes only while the classes with suffix FM (Full Model) are complete and can be used in simulations.

2. Flowsheet models

On the flowsheet level the different sections of the plant are described. These sections are constructed from unit models, like pumps, tanks and heat exchangers. The four sections of the studied HRSG plant are described in the following; deaerator, pan, steam turbine and condenser.

Deaerator Section

The deaerator contains water and is pressurized to keep the water at a temperature slightly over 100 ℃. This is to minimize the amount of oxygen and other gases in the feedwater. Condensate water enters the tank after it has been preheated in the pan. The level in the tank is controlled by a valve on the inflow. Another valve is used to control the tank pressure by the way of drawing a small amount of steam from the boiler drum. The feedwater pump

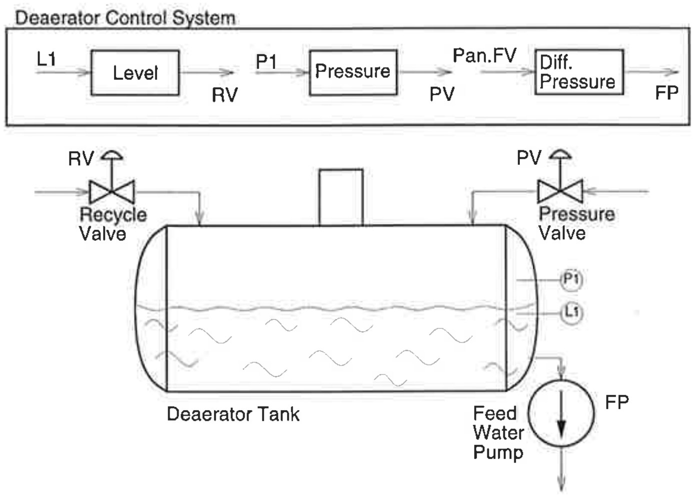

Figure 3. The deaerator configuration.

is used to raise the pressure of the feedwater before it enters the pan. The pumping power is governed by a feedforward from the feed valve controller of the boiler to ensure that the pressure drop over the valve does not increase when the valve is closed.

Pan Section

The pan section consists of preheater, economizer, boiler and superheater. Condensate water is preheated by the flue gas in the preheater, which is the last heat exchanger of five in the flue gas pathway. Before the feedwater enters the boiler it passes a heat exchanger called the economizer, where it is heated up to boiling temperature. In the boiler water is evaporated and then the saturated steam is passed through the superheater where it is heated up further. The layout of the pan is shown in Figure 4.

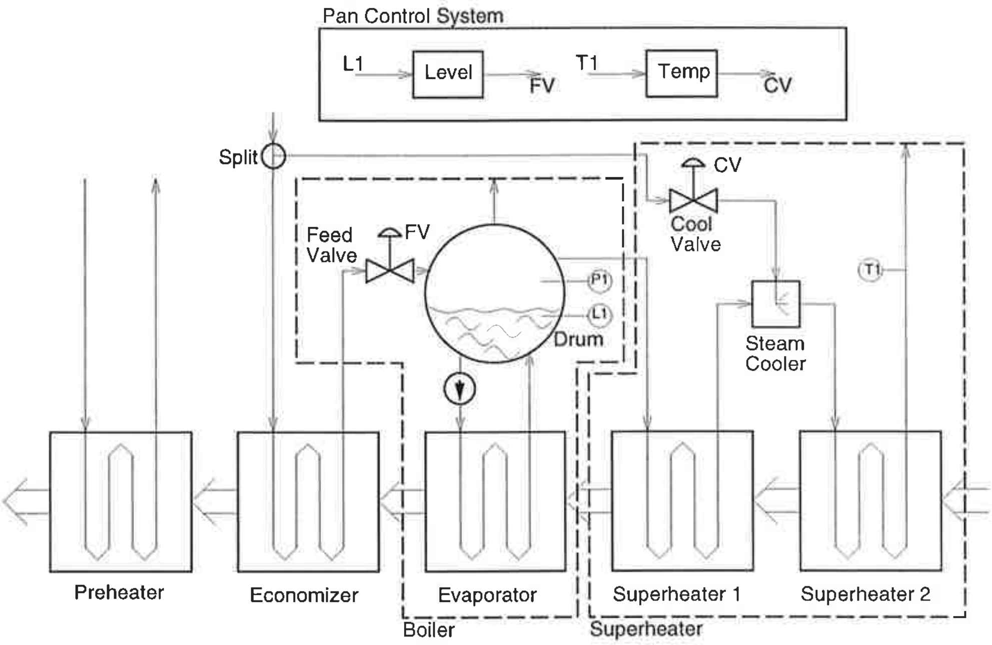

Figure 4. The pan section configuration with the internal structure in boiler and superheater.

Boiler Feedwater enters the boiler drum through the feed valve which is used to control the water level in the drum. Water is circulated with a pump through the evaporator in order to generate steam. When the mixture of water and steam from the evaporator enters the boiler drum it flashes, separates in two phases. The saturated steam produced leaves the drum to the following superheater. A small amount of the steam is recirculated to the deaerator and used for pressure control.

Superheater The superheater is composed of two heat exchangers with a spray cooler between them. In the superheater the saturated steam from the boiler is heated up to close to the temperature of the flue gas entering the pan, approximately 500 ℃. With the spray cooler the temperature of the steam leaving the superheater can be controlled. A small amount of feedwater is sprayed into the superheated steam flow from the first heat exchanger, thereby decreasing the steam temperature.

Steam Turbine Section

The superheated steam is expanded in the steam turbine producing electrical energy. The produced output power is proportional to the steam flow through the turbine and the enthalpy drop over the turbine. The throttle valve and the bypass valve are used to control the turbine inflow pressure and also the pressure upstream to the boiler drum. The bypass valve makes it possible to bypass steam directly to the condenser. It is only open during startup and large pressure transients.

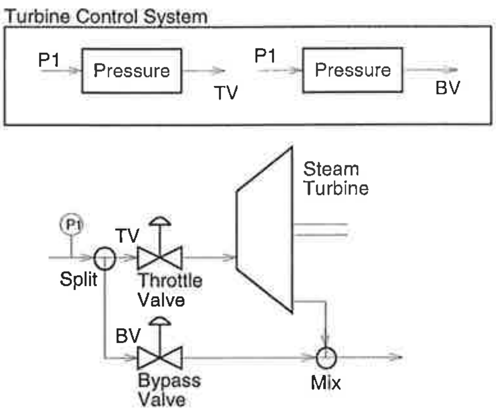

Figure 5. The steam turbine configuration.

Condenser Section

Waste heat in the steam from the turbine is removed by cooling with district-heating water in the condenser and the steam condenses to water. It is then immediately pumped out by the condenser pump to the deaerator. Only a small amount of water is kept in the condenser drum. Make-up water is instead supplied by the buffer tank, which is kept at atmospheric pressure. With the two water valves the logic controller can be used to keep the condenser level and the condensate water pressure within limits.

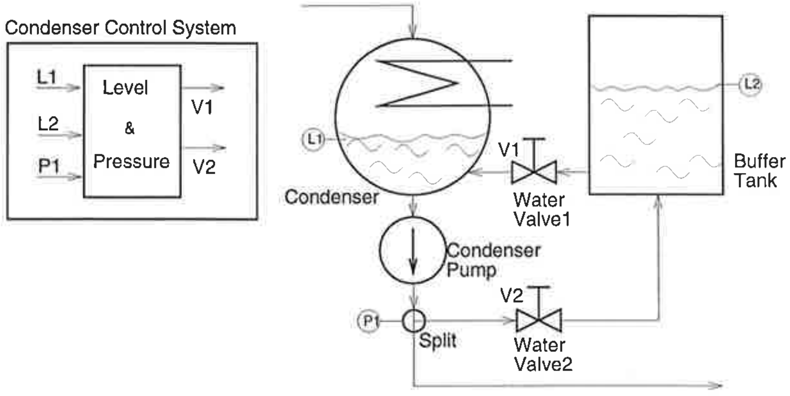

Figure 6. The condenser configuration.

3. Unit Models

The hierarchical structure and function of the HRSG sections was discussed in the previous section. The sections are built from processing units. The units used in the HRSG plant can be listed as follows:

6 Heat exchangers
3 Pressurized tanks
1 Atmospheric tank
1 Steam turbine
3 Pumps
8 Control valves
1 Steam cooler
4 Mixers and splitters

All processing units are decomposed into subunits. These subunits can be categorized into two major groups namely *compartments* and *flow resistors*. Dynamic mass and energy balances, expressed as pressure and enthalpy, are described in compartment models. The media and heat flow between compartments are described by flow resistors. There are compartments and flow resistors for one-phase media, like water, steam or flue gas, and there are also two-phase compartments for the mixture of water and steam. The modelling of the subunits is further described in [Nilsson and Eborn, 1994].

There are also additional units for the control of the plant:

6 SISO controllers
1 Logic controller
10 Sensors

These units are discussed in more detail in the following subsections.

Heat units

The heat units are mainly different types of heat exchanger models, each one composed of two compartments describing the two sides of the unit. The two compartments describe the dynamics of the media on the primary and secondary side. The five heat exchangers in the pan all have flue gas on one side and water or steam on the other. In the condenser there is a heat exchanger with water on one side and condensing steam on the other.

The heat interaction between the two compartments is described by a heat flow resistor and on each compartment outflow there are flow resistors.

The configuration of the economizer in the pan section can be seen in Figure 7.

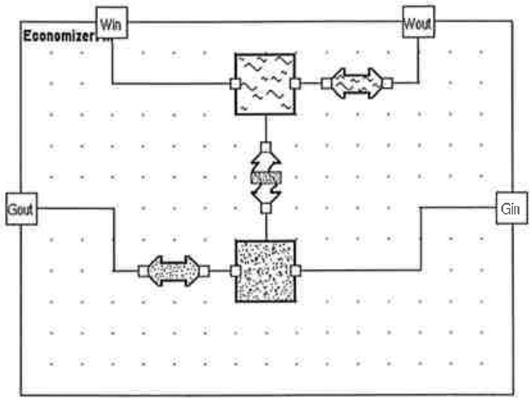

Figure 7. The configuration of a heat exchanger.

Tank models

The boiler drum, condenser drum and the deaerator tank are pressurized tanks modelled as two-phase compartment models. In the condenser section there is also a buffer tank. This tank is assumed to be at atmospheric pressure and is modelled as an open water compartment with volume dynamics instead of pressure dynamics.

Flow units

The flow units used in the HRSG model are; pumps, valves, mixers, splitters and spray coolers. The graphical icons of these are shown in Figure 8.

Pumps and valves are modelled as flow resistors. Both kinds are static descriptions of the relation between pressures and medium flow. The valves are pressure drop descriptions for water or steam. The pump model uses a relation between the pressure 'drop' (negative in this case) and the applied pumping power.

The remaining flow units contain no flow description but simply describe a junction of several flows of the same medium, possibly of different phases. In a mixer two flows of the same media and phase is mixed and the resulting enthalpy is calculated. In a splitter one flow is split in two flows with the same enthalpy. A steam cooler sprays a small water flow into a large steam flow to decrease the steam temperature. The cooler is modelled as a two-phase mixer. These three units are supposed to be connected to two flow resistors, in the mixer case at the inflow and for the splitter at the outflow.

Figure 8. Different kinds of flow units.

Turbine

The turbine in the HRSG plant is a steam turbine, modelled as a steam compartment and a critical expansion flow resistor. The compartment accounts for the volume dynamics in the turbine and also creates a small lag between the inflow and the outflow. It also has the function of breaking up the large algebraic system which would be created if the dynamics of the turbine volume were neglected. The enthalpy drop in the turbine is calculated with an isentropical thermal efficiency approximation since no steam table function for calculating the enthalpy from entropy and pressure has been implemented.

Controllers

The SISO-controllers used in the plant are analog PID-controllers although the derivative action is never used. The controller models are taken from a control equipment database described in [Nilsson, 1993]. In the condenser system there is also a special logic controller built from analog and digital blocks like comparators and AND operators. These logic components are also taken from the control database.

4. Simulations.

To study how the models in the K2 library perform in simulations a prototype setup has been assembled. The model is called `Plant2` and belongs to the `K2Plants` library in the k2appdb data base. The model as seen in the graphical editor is shown in Figure 9.

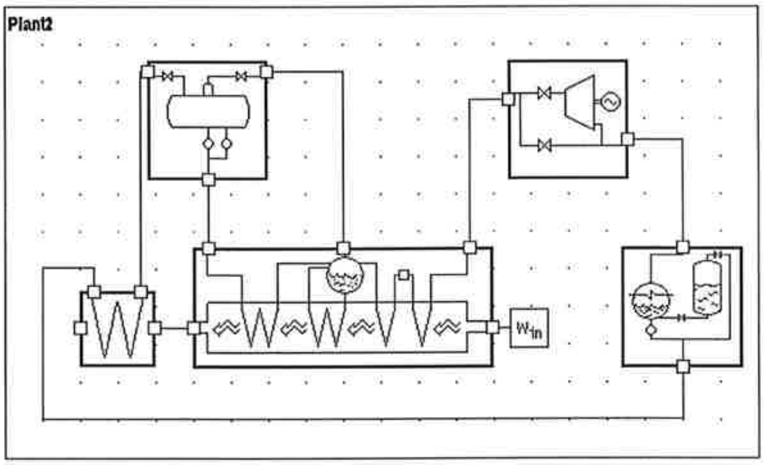

Figure 9. The prototype 2 setup.

The plant is assumed to receive a flue-gas flow of 350 kg/s at h =627 kJ/kg, T = 500 ℃ from the gas turbine. The initial state of the plant is assumed to be steady which gives a circulation flow that is a little larger than 40 kg/s. To start the simulation you also need initial values of most of the 61 dynamic and algebraic state variables. These are listed together with the parameter values in Appendix A. In the following simulations some deviations from the steady state have been studied. They have all been performed on a SPARCstation 5 with 32 MBytes of memory. Memory is an issue since the instantiated model used for the simulations takes about 40 MBytes and extensive use of virtual memory would slow down the instantiation of the model very much.

The plots from the simulations show the main variables affected: flows, pressures, control valve positions, powers and total efficiency. There are three or four major independent flows through the system: condensate water flowing from the condenser to the deaerator, feedwater flowing to the boiler drum, steam flowing through the superheater and possibly also the turbine flow differing from the steam flow if the bypass valve in the turbine system is open. The pressure plots are taken in the boiler drum and just before and after the pan. The control variables that can be seen are from the turbine throttle controller and the level controllers in the deaerator and the boiler drum. In some of the simulations also the controls of the bypass controller and the pressure controller of the deaerator are shown. The powers are defined as: the total heat content of the flue gas flowing through the pan, P_{tot}, the heat flow absorbed by the water and steam and the electrical output power of the steam turbine, P_{out}. The total efficiency of the HRSG can then be defined as P_{out}/P_{tot}. The difference between the two consists of: excess heat lost through the chimney, low temperature heat transferred to cooling water in the condenser and losses in the turbine and generator. Since the parameters of the plant have not been chosen very carefully the losses through the chimney are substantial; the temperature of the flue gas leaving the chimney is 163 ℃.

Turbine control setpoint changes

The steam turbine system consists of a steam turbine and a bypass leading hot steam directly to the condenser. The pressure before the turbine is controlled with two PI-controllers and control valves, the throttle valve and the bypass valve. In the initial state the throttle valve opening is about 89% and the bypass valve is closed. The bypass is used during the startup procedure and to reduce sudden peaks in steam pressure. During normal operation the bypass valve is closed.

Case 1: The behaviour of the plant when the turbine pressure setpoints are changed is studied in two simulations. First the turbine pressure setpoint is increased with 10% from 50 to 55 bars. During this operation the turbine controllers remain in their operating region and the regulated pressure reaches the setpoint after 50 s. When the throttle valve starts to close the pressures increase rapidly and the flows decrease for a while before they settle at a flow rate slightly lower than before the setpoint change. The reduced flow rate makes the total efficiency go down a little and it also causes lower pressure in the condenser drum. The simulation is completed after 160 CPU-seconds and the results are shown in the Figures 10-12.

Case 2: In a second simulation the pressure setpoint is decreased with 10% to 45 bars. The flow through the turbine increases rapidly first and then settles at a slightly higher flow rate than before. The bypass valve also opens for a short period of time but closes again when the pressure goes under 46 bars, which is the setpoint of the bypass valve controller. The regulated pressure does not reach the lower setpoint since the throttle valve saturates after 38 seconds. The total efficiency goes up ever so little due to the higher flow rate although this also causes a slightly higher back pressure in the turbine. The results are shown in the Figures 13-15. The total CPU-time required for this simulation is 200 seconds.

Flue-gas flow variations

Supervisory load control of the gas turbine will cause the flue-gas flow and thus the heat flow into the pan to increase or decrease. The effects of this have been studied in this section.

Case 1:

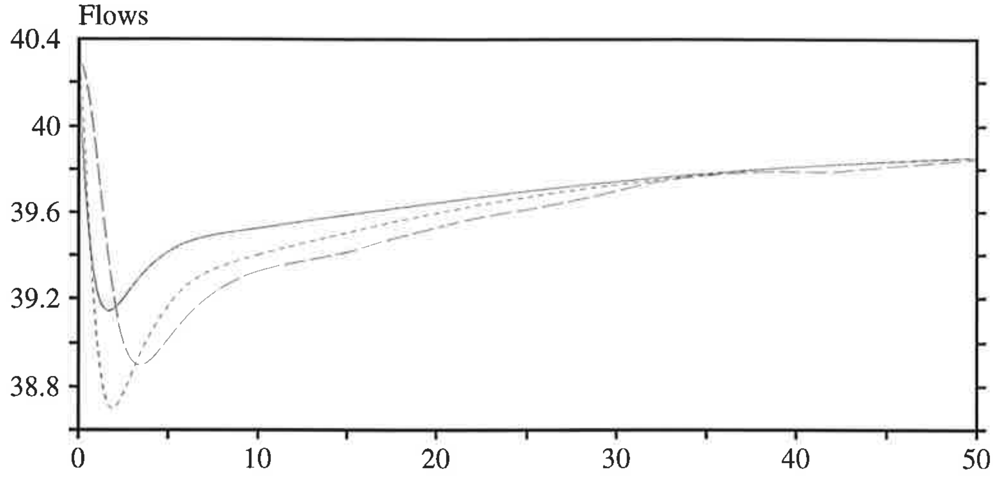

Figure 10. Flow changes when the turbine pressure demand is increased. (Solid line - steam, dashed - condensate, dotted - feedwater, dash-dotted - turbine flow.)

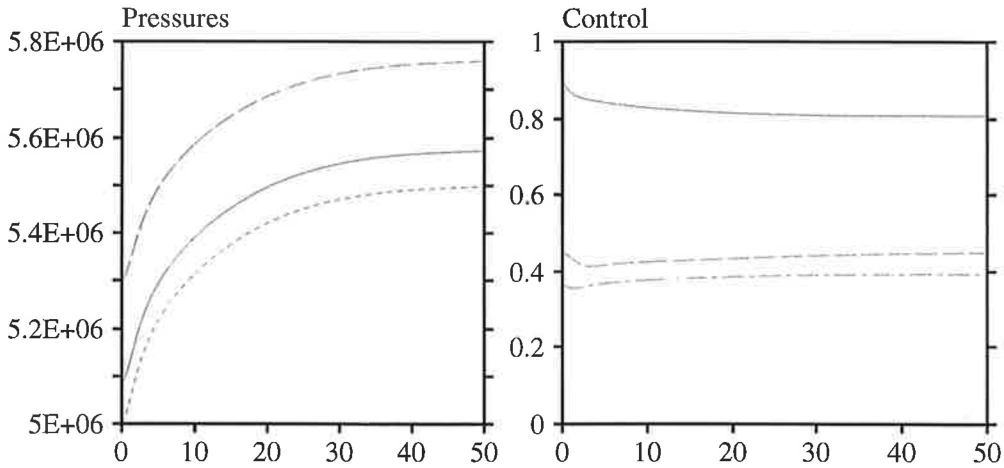

Figure 11. Pressures in the pan and the main control variables with increasing turbine pressure. (Solid line - throttle valve, dashed - deaer.valve, dash-dotted - boiler valve.)

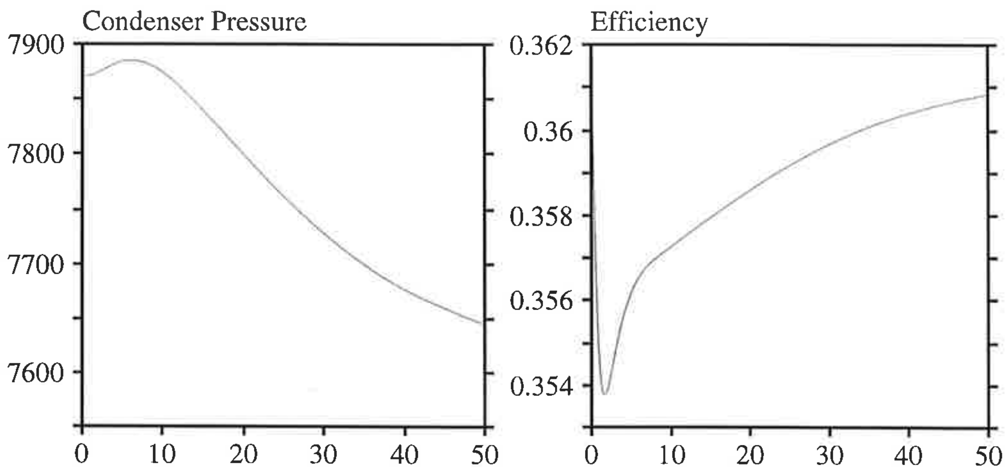

Figure 12. Condenser drum pressure and the total efficiency (P_{out}/P_{tot}) when the turbine pressure demand is increased.

Case 2:

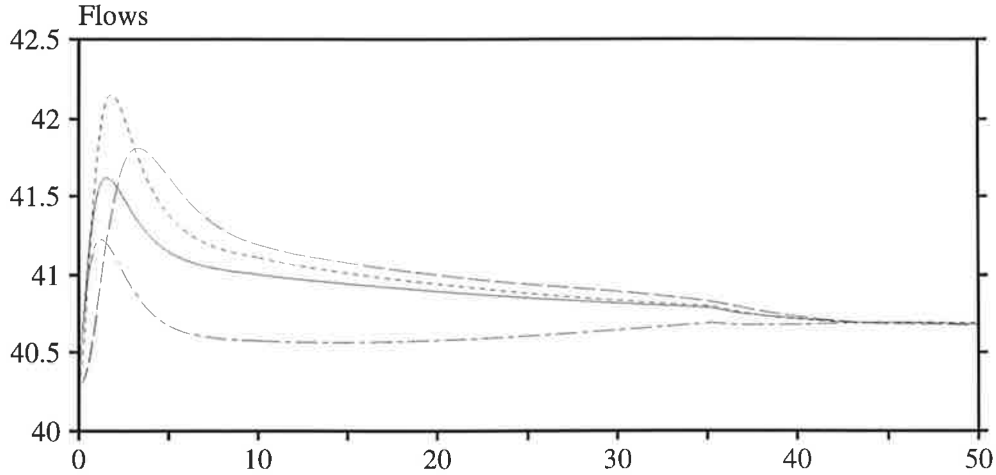

Figure 13. Flow changes when the pressure setpoint is decreased. (Solid line - steam, dashed - condensate, dotted - feedwater, dash-dotted - turbine flow.)

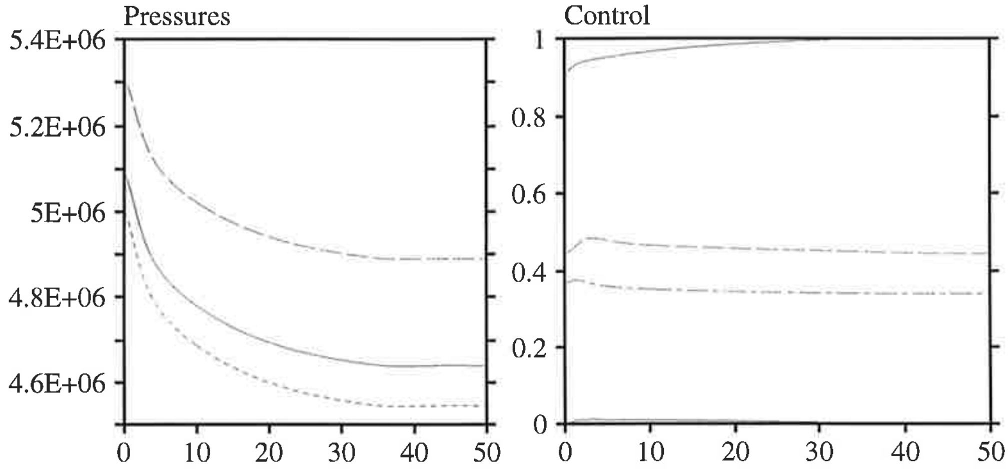

Figure 14. Pressures in the pan and the main control variables with decreasing pressure. (Solid lines - throttle and bypass valve, dashed - deaer.valve, dash-dotted - boiler valve.)

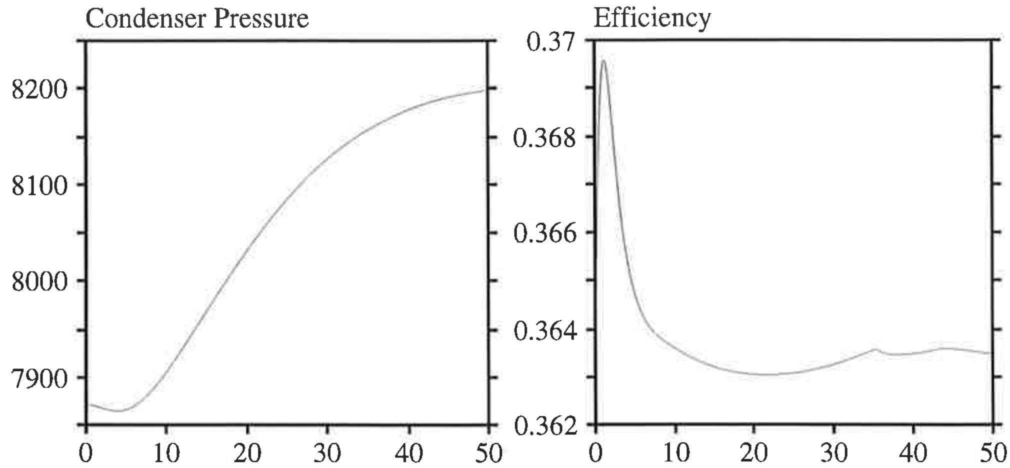

Figure 15. Condenser drum pressure and the total efficiency (P_{out}/P_{tot}) when the pressure setpoint is decreased.

Case 3:

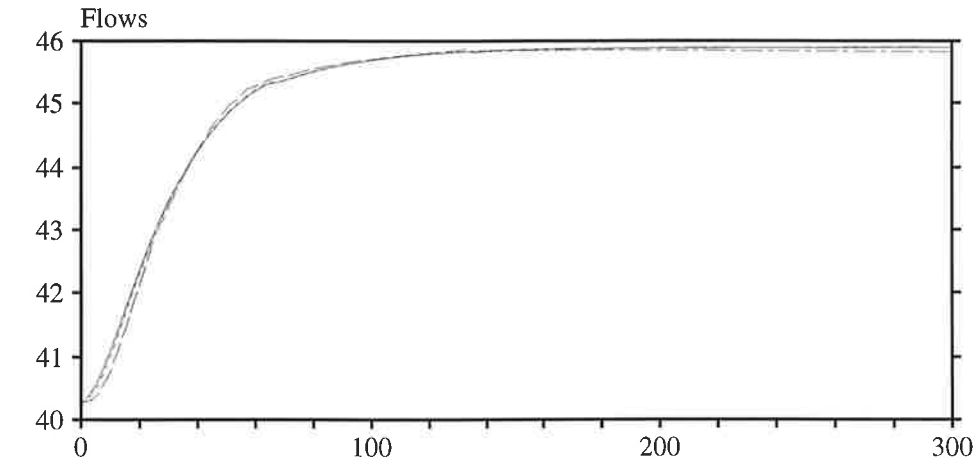

Figure 16. Flow changes when the flue-gas flow increases. (Solid line - steam, dashed - condensate, dotted - feedwater, dash-dotted - turbine flow.)

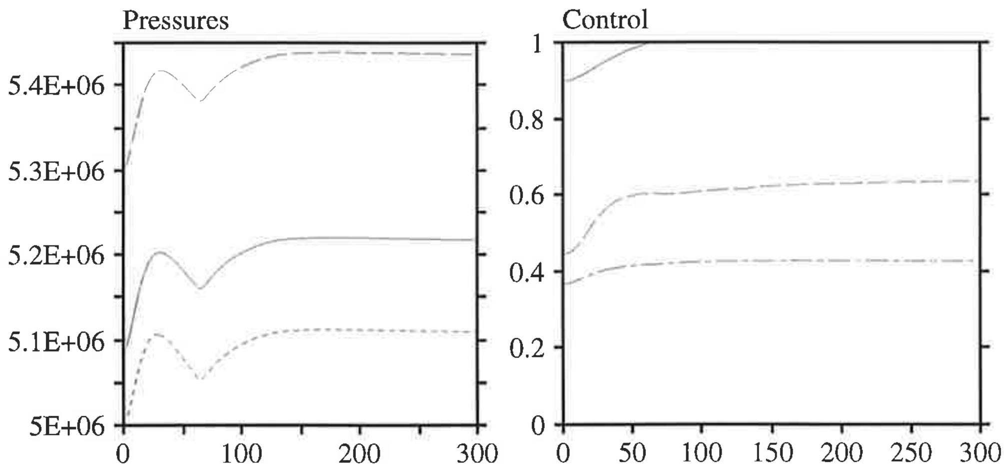

Figure 17. Pressures in the pan and the main control variables with increasing flue-gas flow. (Solid lines - throttle and bypass valves, dashed - deaer.valve, dash-dotted - boiler valve.)

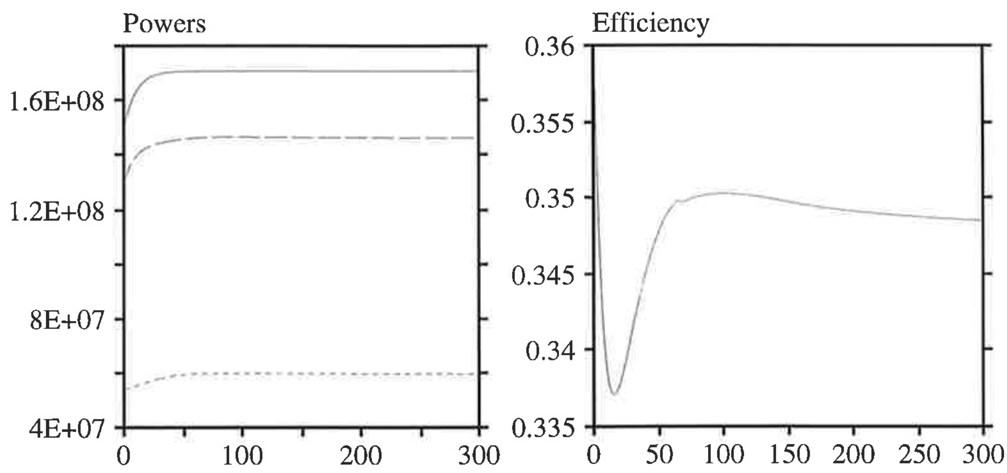

Figure 18. Power and efficiency (P_{out}/P_{tot}) with increasing flue-gas flow. From the top: total heat, transferred heat and electrical output.

Case 3: First a simulation where the flue-gas flow increased slowly (T =10 s) to 400 kg/s has been made. The results are shown in the Figures 16-18. The increased heat flow makes the circulation flow and drum pressure increase but the turbine controllers returns the pressure to the reference value after 2-300 seconds. The reason why the pressure at first is brought down and then starts increasing again after 64 s is that the throttle valve saturates at this time. Then the bypass controller starts opening the bypass valve at t =133 s and the pressure is brought to the bypass controllers setpoint, which is 51 bars. The control signal of the bypass controller can not be seen in the plot since it is only 0.1%, but this is sufficient to keep the pressure at the desired level. The increased heat flow makes the output power go up from 54 to 60 MW but the total efficiency drops due to increasing pressure in the condenser. The pressure in the condenser drum increases from 8 to 10.5 kPa which corresponds to a temperature increase from 41.6 to 47 °C.

Case 4: When the flue-gas flow is decreased to 300 kg/s the results look like in the Figures 19-21. The pressures and flows start to decrease immediately but the turbine controller catches up quickly and stabilizes the pressure at the setpoint after 200 seconds. The flow decrease makes the output power drop from 54 to 48 MW but in spite of this the efficiency goes up a little because the decrease in total heat flow is even larger. Just like in the previous simulation the drum pressure in the condenser is affected by the changes in flow rate. In this case the pressure goes down from 8 to 6 kPa, which corresponds to a temperature drop to 36 °C. These two simulations both require approximately 220 seconds of CPU-time to complete.

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Case 4:

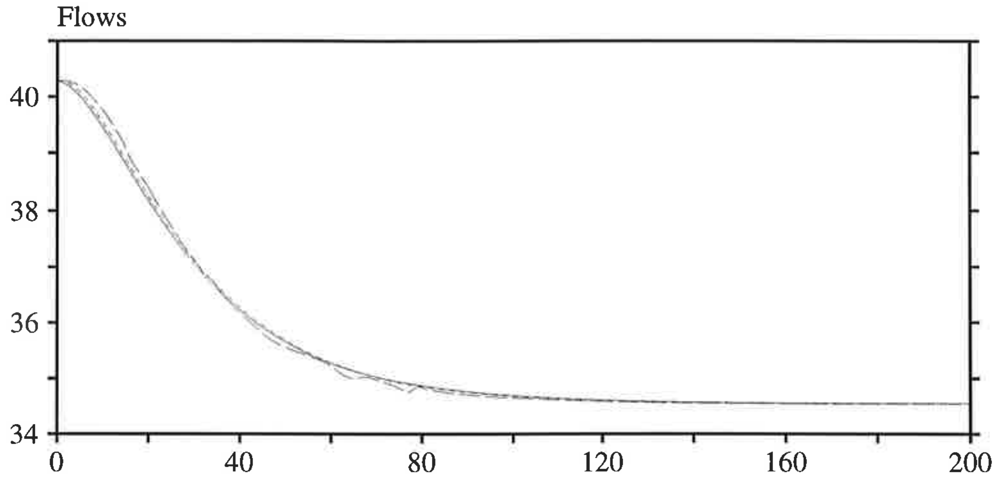

Figure 19. Flow changes when the flue-gas flow decreases. (Solid line - steam, dashed - condensate, dotted - feedwater, dash-dotted - turbine flow.)

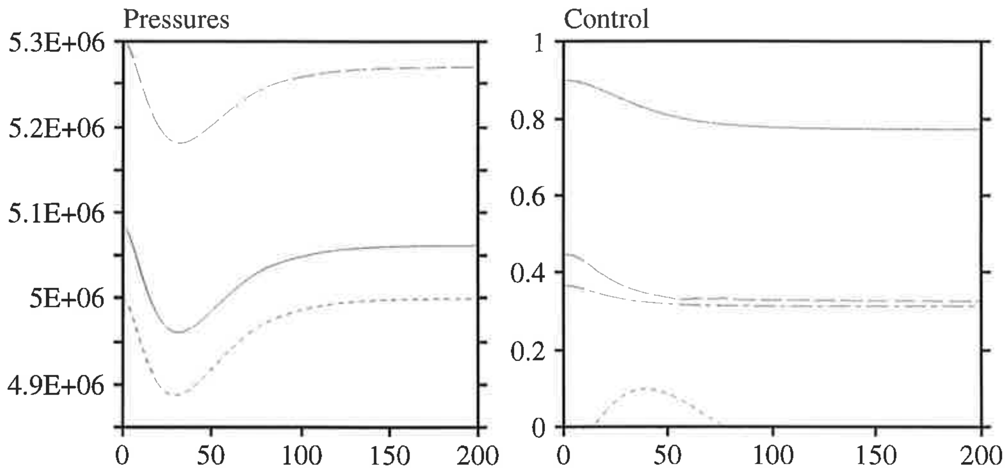

Figure 20. Pressures in the pan and the main control variables with decreasing flue-gas flow. (Solid line - throttle valve, dashed - deaer.valve, dash-dotted - boiler valve, dotted - steam injection valve.)

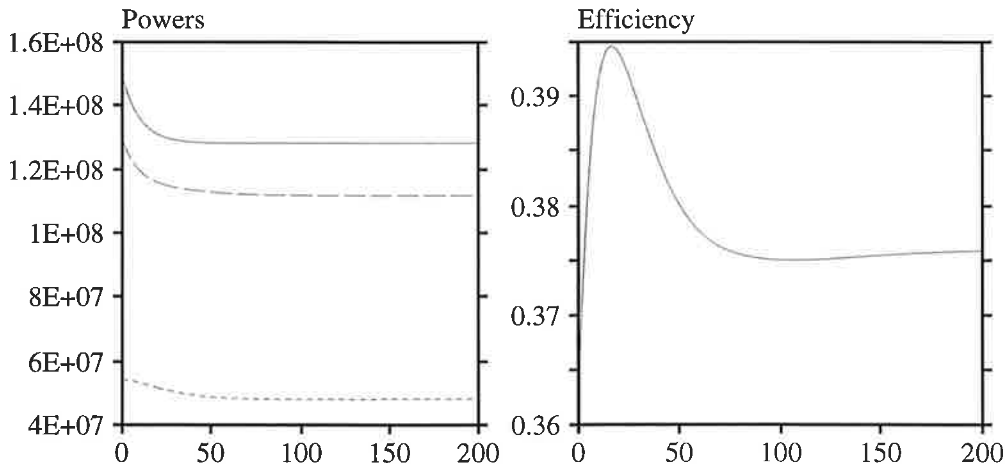

Figure 21. Power and efficiency (P_{out}/P_{tot}) with decreasing flue-gas flow. From the top: total heat, transferred heat and electrical output.

Appendix A. Initial values

```
% Parameter values
  m.wgas := 350.0;
  m.hgas := 627000.0;
  m.V := 1.0;
  m.DH := 1.0;
  m.diameter := 0.1;
  m.zeta := 2.0;
  m.delta := 0.0004;
  m.T := 1.0;
  m.BoilPower := 10000.0;
  m.CondPower := 11000.0;
  m.levRef := 0.54;
  m.Tref := 480.0;
  m.pRef := 5.1e+06;
  m.wRef := 5e+06;
  m.DealRef := 0.5;
  m.DeapRef := 120000.0;
  m.PumpFF := 570000.0;
  m.Gin.T := 10.0;
  m.Pan.Cold.length := 500.0;
  m.Pan.Boil.length := 1000.0;
  m.Pan.Boil.Control.PID_Module.K := 25.0;
  m.Pan.Boil.Control.PID_Module.Ti := 50.0;
  m.Pan.Boil.Control.PID_Module.Td := 100.0;
  m.Pan.Boil.Control.PID_Module.b := 1.0;
  m.Pan.Boil.Control.PID_Module.tr := 100.0;
  m.Pan.Boil.Control.PID_Module.Ion := 1.0;
  m.Pan.Boil.Control.Limiter.Umin := 0.01;
  m.Pan.Hot.Heat1.length := 120.0;
  m.Pan.Hot.Heat2.length := 120.0;
  m.Pan.Hot.PID.PID_Module.K := 0.05;
  m.Pan.Hot.PID.PID_Module.Ti := 0.5;
  m.Pan.Hot.PID.PID_Module.Td := 1.0;
  m.Pan.Hot.PID.PID_Module.b := 1.0;
  m.Pan.Hot.PID.PID_Module.tr := 1.0;
  m.Pan.Hot.PID.PID_Module.Ion := 1.0;
  m.Pan.Hot.PID.PID_Module.uReverse := 1.0;
  m.Eco2.length := 65.0;
  m.Deaerator.levelPID.PID_Module.K := 20.0;
  m.Deaerator.levelPID.PID_Module.Ti := 50.0;
  m.Deaerator.levelPID.PID_Module.Td := 100.0;
  m.Deaerator.levelPID.PID_Module.b := 1.0;
  m.Deaerator.levelPID.PID_Module.tr := 100.0;
  m.Deaerator.levelPID.PID_Module.Ion := 1.0;
  m.Deaerator.presPID.PID_Module.K := 0.00001;
  m.Deaerator.presPID.PID_Module.Ti := 20.0;
  m.Deaerator.presPID.PID_Module.Td := 100.0;
  m.Deaerator.presPID.PID_Module.b := 1.0;
  m.Deaerator.presPID.PID_Module.tr := 40.0;
  m.Deaerator.presPID.PID_Module.Ion := 1.0;
```

```
  m.Deaerator.CritValve.Cd := 1.0;
  m.Deaerator.CritValve.krit := 1;
  m.TurbS.length := 1.0;
  m.TurbS.Turbine.etat := 0.5;
  m.TurbS.Turbine.etam := 0.9;
  m.TurbS.Turbine.Flow.Cd := 1.0;
  m.TurbS.Turbine.Flow.krit := 1;
  m.TurbS.BypassV.Cd := 1.0;
  m.TurbS.BypassV.krit := 1;
  m.TurbS.pControl.PID_Module.K := 4e-08;
  m.TurbS.pControl.PID_Module.Ti := 50.0;
  m.TurbS.pControl.PID_Module.Td := 10.0;
  m.TurbS.pControl.PID_Module.b := 1.0;
  m.TurbS.pControl.PID_Module.tr := 70.0;
  m.TurbS.pControl.PID_Module.Ion := 1.0;
  m.TurbS.pControl.PID_Module.uReverse := 1.0;
  m.TurbS.wControl.PID_Module.K := 1e-07;
  m.TurbS.wControl.PID_Module.Ti := 5.0;
  m.TurbS.wControl.PID_Module.Td := 10.0;
  m.TurbS.wControl.PID_Module.b := 1.0;
  m.TurbS.wControl.PID_Module.tr := 10.0;
  m.TurbS.wControl.PID_Module.Ion := 1.0;
  m.TurbS.wControl.PID_Module.uReverse := 1.0;
  m.CondS.length := 3000.0;
  m.CondS.wCold := 400.0;
  m.CondS.hCold := 30000.0;
  m.CondS.pCold := 648000.0;
  m.CondS.Lowlev1 := 0.175;
  m.CondS.Hilev1 := 0.325;
  m.CondS.Lowlev2 := 0.225;
  m.CondS.Hilev2 := 0.3;
  m.CondS.PresRef := 200000.0;
  m.CondS.TankRef := 1.0;
  m.CondS.Tv := 1.0;
  m.CondS.Valvediam := 0.02;

% Continuous State Variables:
  m.Gin.w := 350.0;
  m.Pan.Cold.GasComp.p := 690276.0;
  m.Pan.Cold.GasComp.h := 288300.0;
  m.Pan.Cold.WaterComp.h := 1.13479e+06;
  m.Pan.Boil.DrumComp.p := 5.08468e+06;
  m.Pan.Boil.DrumComp.h := 1.20477e+06;
  m.Pan.Boil.Valve.Fin.p := 5.27596e+06;
  m.Pan.Boil.Control.SetPoint := 0.54;
  m.Pan.Boil.Control.PID_Module.i := 0.365522;
  m.Pan.Boil.Hex.GasComp.p := 903615.0;
  m.Pan.Boil.Hex.GasComp.h := 366640.0;
  m.Pan.Boil.Hex.WaterComp.h := 1.92448e+06;
  m.Pan.Boil.Hex.WaterFlow.Fin.p := 5.20491e+06;
  m.Pan.Hot.Heat1.GasComp.p := 1.12861e+06;
  m.Pan.Hot.Heat1.GasComp.h := 554808.0;
```

```
m.Pan.Hot.Heat1.SteamComp.p := 5.06488e+06;
m.Pan.Hot.Heat1.SteamComp.h := 3.2428e+06;
m.Pan.Hot.Heat2.GasComp.p := 1.33146e+06;
m.Pan.Hot.Heat2.GasComp.h := 605777.0;
m.Pan.Hot.Heat2.SteamComp.p := 5.03469e+06;
m.Pan.Hot.Heat2.SteamComp.h := 3.38696e+06;
m.Pan.Hot.Temp.out := 480.0;
m.Pan.Hot.Valve.Fin.p := 5.30152e+06;
m.Pan.Hot.PID.SetPoint := 480.0;
m.Pan.Hot.PID.PID_Module.i := -0.00225728;
m.Eco2.GasComp.p := 448919.0;
m.Eco2.GasComp.h := 257036.0;
m.Eco2.WaterComp.h := 444216.0;
m.Eco2.WaterFlow.Fout.p := 256933.0;
m.Deaerator.Comp.p := 124861.0;
m.Deaerator.Comp.h := 445922.0;
m.Deaerator.levelPID.SetPoint := 0.5;
m.Deaerator.levelPID.PID_Module.i := 0.446319;
m.Deaerator.presPID.SetPoint := 120000.0;
m.Deaerator.presPID.PID_Module.i := 0;
m.TurbS.Turbine.Comp.p := 5e+06;
m.TurbS.Turbine.Comp.h := 3.38696e+06;
m.TurbS.Turbine.Flow.Fout.p := 14447.8;
m.TurbS.pControl.SetPoint := 5.1e+06;
m.TurbS.pControl.PID_Module.i := 0.00157515;
m.TurbS.wControl.SetPoint := 5e+06;
m.TurbS.wControl.PID_Module.i := -0.898486;
m.CondS.Hex.InC.w := 400.0;
m.CondS.Hex.HotC.h := 172579.0;
m.CondS.Hex.ColdC.h := 203148.0;
m.CondS.Hex.ColdF.DeltaP := 648456.0;
m.CondS.Drum.p := 7870.91;
m.CondS.Drum.h := 173004.0;
m.CondS.ValveLCP.y := 0;
m.CondS.Tank.V := 5.0;
m.CondS.Tank.h := 132290.0;
m.CondS.Pump.Pe := 11000.0;
m.CondS.ValveLCA.Fin.p := 283241.0;
m.CondS.ValveLCA.y := 0;
```