Dynamic modelling of power cycles for small modular reactors

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Nomenclature

Roman Letters

A	Area	$[m^2]$
d	Pipe diameter	$[m]$
e	Specific total energy	$[kJ/kg]$
E	Total energy	$[kJ]$
$\dot{E}$	Total energy rate	$[kW]$
f	Darcy friction factor	$[]$
g	Gravitational acceleration	$[m/s^2]$
h	Heat transfer convection coefficient	$[W/m^2K]$
h	Specific enthalpy	$[kJ/kg]$
H	Heat flow	$[kW]$
h_0	Specific total enthalpy	$[kJ/kg]$
h_{frict}	Frictional pressure loss	$[kPa]$
k	Thermal conductivity	$[W/mK]$
ke	Specific kinetic energy	$[kJ/kg]$
KE	Total kinetic energy	$[kJ]$
l	Length	$[m]$
L	Specific latent heat	$[kJ/kg]$
M	Mass	$[kg]$

$\dot{m}$	Mass flow rate	$[kg/s]$
P	Pressure	$[kPa]$
pe	Specific potential energy	$[kJ/kg]$
PE	Total potential energy	$[kJ]$
q	Heat transfer per unit mass	$[kJ/kg]$
Q	Total heat transfer	$[kJ]$
q''	Heat flux	$[W/m^2]$
$\dot{Q}$	Heat transfer rate	$[kW]$
Re	Reynolds number	[]
t	time	$[s]$
T	Temperature	$[K]$
u	Specific internal energy	$[kJ/kg]$
U	Total internal energy	$[kJ]$
v	Specific volume	$[m^3/kg]$
V	Velocity	$[m/s]$
w	Work per unit mass	$[kJ/kg]$
W	Total work	$[kJ]$
$\dot{W}$	Power	$[kW]$
x	Horizontal direction in the plane	$[m]$
z	Elevation	$[m]$

Greek Letters

ϵ	Roughness	[mm]
η	Efficiency	[]

θ	Specific total energy of a flowing fluid	$[kJ/kg]$
ρ	Density	$[kg/m^3]$
μ	Dynamic viscosity	$[Ns/m^2]$
ν	Kinematic viscosity	$[m^2/s]$
ϕ	Energy flow rate	$[kW]$
ϕ	Stodola's Ellipse	$[kW]$

Abbreviations

CMSR	Compact Molten Salt Reactors
PVT	Pressure-Volume-Temperature
SMR	Small Modular Reactors

Subscripts

a	Real
A	Turbine inlet in Stodola's Ellipse
B	Turbine outlet in Stodola's Ellipse
g	Gas
in	Inlet
l	Liquid
lg	Liquid-Gas
out	Outlet
P	Pump
s	Isentropic
sl	solid-liquid
T	Turbine

Abstract

Small Modular Reactors (SMRs) present a transformative approach to nuclear energy, offering enhanced cost-effectiveness and ease of implementation compared to traditional large-scale reactors. This study investigates the dynamic behavior of the steam cycle within SMRs using Simscape MATLAB for simulation. The research focuses on understanding the thermodynamic principles and fluid dynamics that govern the steam cycle in these reactors. By modeling the interaction between the turbine, condenser, and pump, the study aims to evaluate the performance and safety of SMRs.

The simulation model was developed by initially creating individual component models to understand their behavior. These models were then integrated into a complete system, simulating various operational scenarios. Special attention was given to the initialization of variables to ensure convergence, which is crucial for accurate simulations. Subsequently, a second boiler was added in parallel to study the scenario of two SMRs operating simultaneously and connected to a single turbine. Using this model, pressure drops were simulated with granular intervals to study their effects on system stability and performance. The impact of varying heat flow in one of the boilers, representing increased heat generation by the SMR, and the variation of mass flow imposed on the turbine were also analyzed.

Findings reveal significant instability with the addition of a second boiler, primarily due to complexities in mass flow distribution and mass balance equations. These instabilities are further exacerbated by abrupt changes in mass flow, emphasizing the need for careful flow rate management. Additionally, increasing the heat flow leads to higher values across the system, including pressures, temperatures, and internal energy. On the other hand, optimizing mass flow significantly enhances system efficiency, as demonstrated by notable improvements in mechanical power generation when the mass flow is reduced.

Keywords: Small Modular Reactors, steam cycle, Simscape, dynamic behavior, two-boilers, mass flow distribution, pressure drop, system efficiency

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Chapter 1

Introduction

Sustainable energy sources have become increasingly imperative in the face of the escalating climate crisis, prompting a global drive to explore cleaner alternatives. Notably, nuclear energy offers the advantage of emitting zero CO2 emissions during electricity generation, positioning it as a critical component in the transition to a low-carbon future. In this context, nuclear energy stands out, particularly with the emergence of Small Modular Reactors (SMRs) as a key innovation in this field. SMRs represent a transformative approach due to their smaller, modular design, which not only enhances cost-effectiveness but also facilitates easier implementation compared to traditional large-scale reactors.

The integration of SMRs with renewable energy sources presents a holistic approach towards achieving sustainable development objectives, particularly in regions where renewables may be less efficient due to climatic factors. Within this framework, this study focuses on examining the dynamic behavior of the steam cycle within SMRs, highlighting its critical role in converting the heat generated by nuclear fission into mechanical energy. Understanding the dynamic operation of the steam cycle is essential for ensuring the efficiency and safety of SMRs.

1.1 Background

In the realm of nuclear energy innovation, Seaborg Technologies specializes in the development of Compact Molten Salt Reactors (CMSRs), a type of small modular reactor poised to revolutionize the industry. Despite the promise of SMRs, their widespread adoption has been hindered by concerns regarding safety and feasibility, which remain key obstacles preventing their entry into the market. Addressing these concerns is crucial for advancing nuclear energy's role in the transition to a low-carbon future.

Seaborg Technologies aims to explore the safety and viability of nuclear power plants featuring CMSRs, recognizing this as a pivotal step towards commercialization. A significant aspect of their research involves investigating the possibility of integrating multiple nuclear reactors into a single turbine system, which could enhance efficiency and scalability. Central to this endeavor is the examination of dynamic behavior in response to system instabilities, which is crucial for ensuring operational safety.

One essential aspect of this investigation is the study of the steam cycle, also known as the Rankine cycle, within CMSRs. By simulating various operational scenarios and analyzing the response of the steam cycle, researchers can gain valuable insights into its behavior under different conditions. This comprehensive analysis not only contributes to enhancing the performance of CMSRs but also facilitates their integration into innovative nuclear power plant designs.

Moreover, this research will utilize Simscape MATLAB as the primary simulation tool. Simscape MATLAB offers a robust platform for modeling and analyzing complex systems, providing researchers with the necessary tools to conduct in-depth analysis and optimization of steam cycles.

1.2 Motivation

This study is driven by two primary motivations. Firstly, it aims to pave the way for the widespread adoption of Small Modular Reactors (SMRs) by addressing potential operational risks associated with their implementation. Additionally, it explores the possibility of integrating multiple reactors into a single turbine system, aiming to provide valuable insights that contribute to advancing the viability of SMRs as a sustainable energy option. Secondly, this research is motivated by the exploration of Simscape MATLAB as a simulation tool for analyzing complex nuclear reactor systems. By leveraging Simscape MATLAB in this study, we aim to demonstrate its effectiveness and suitability for studying the dynamic behavior of nuclear reactor systems, particularly focusing on the steam cycle within Small Modular reactors (SMRs).

1.3 Prior studies and research

Previous studies and research efforts have significantly contributed to our understanding of Small Modular Reactors (SMRs) and the challenges associated with their development and deployment. However, due to the limited production and the potential risks involved in experimental studies, there remains a critical need to explore alternative approaches, such as advanced simulation methods, to further advance our understanding of SMRs and their associated systems.

This thesis focuses on leveraging prior knowledge in thermodynamics and fluid mechanics, particularly emphasizing the steam cycle within SMRs. Understanding this cycle's intricacies is crucial, as it's the primary method for converting heat generated by the SMR into mechanical energy. Moreover, familiarity with MATLAB scripting and functions is essential for understanding and customizing simulation models. Experience with Simulink is also recommended since Simscape operates within the Simulink environment.

Additionally, it's noteworthy that Simscape provides an example model of the Rankine cycle [1], accessible to all users, which will be considered in this thesis. Even some elements from this model will be proposed for integration into the system under study. However, it's important to note that this model includes numerous elements deemed unnecessary for the scope of this thesis. Furthermore, the system is primarily designed for use with a boiler, and the objective is to simulate two boilers operating in parallel. It is noteworthy that no studies or simulations have been found that involve two boilers connected to a turbine.

1.4 Objectives

The main objective of this project is to simulate the steam cycle and study its dynamic behavior within the context of Small Modular Reactors (SMRs), as outlined in the preceding sections. This involves conducting detailed studies of each cycle component, such as the turbine, condenser, and pump, to enhance our understanding of their interactions within the SMR framework. Additionally, the aim is to model the connection of two reactors to a turbine and analyze the associated risks.

To achieve these objectives, the project will utilize the Simscape MATLAB tool for simulation. This software provides a powerful platform for modeling and analyzing complex, dynamic systems. However, as Simscape is a relatively new tool, there is also a need to expand knowledge about its capabilities and define its limitations during the development of the system and simulation. This represents both an objective and a challenge, as it requires mastering the software while simultaneously advancing understanding of its potential applications and constraints in nuclear engineering.

1.5 Research methodology

This project begins by studying Simscape and its various components within the Simulink MATLAB environment. The initial stage involves analyzing existing components in Simscape's two-phase fluid library to understand their functionalities and applications.

The project will first study which components from the Simscape library can best represent the elements of the system, comprising the reactor, turbine, condenser, and pump. Once the most suitable components are identified, the basic model of the rankine cycle will be established using these components. Potential enhancements will then be explored by integrating alternative or more complex components available in the library.

If necessary, custom components will be developed using MATLAB coding to meet specific simulation requirements.

After establishing a stable system, the model will be expanded to simulate the integration of two SMRs with a single turbine. Fluctuations will be introduced within the subsystem formed by the two boilers through pressure drops and increased heat flow, and externally through the control of mass flow with the turbine. These changes will test the system's resilience and ability to maintain safety and efficiency under stress. The response to these dynamic fluctuations will provide vital insights into the behavior and risk mitigation strategies of integrated SMRs.

This detailed approach aims to provide a thorough understanding of the steam cycles within SMRs, optimizing performance and safety under variable operational conditions.

1.6 Limitations

The primary limitations of this study arise from the use of the Simscape simulator within Simulink, MATLAB. A notable challenge is the limited expertise available and a lack of detailed information on utilizing Simscape for advanced simulation techniques. Ensuring the accuracy of simulations is also critical, as it depends on the initial data closely aligning with expected outcomes, requiring variables to converge appropriately to prevent modeling errors and ensure reliability.

Additionally, there is a limitation in the model where the mass flow provided by the turbine is constant and not controlled based on pressure, as would be the case with a centrifugal pump. This constraint further impacts the realism and fidelity of the simulation results. Moreover, the absence of external comparative results specifically related to simulations of SMRs and steam cycles limits the ability to validate our findings externally. This lack of comparative benchmarks restricts the capacity to confirm the accuracy and practical applicability of the simulated outcomes.

Chapter 2

Theoretical Background

2.1 Principles of thermodynamics

The first law of thermodynamics, also known as the principle of conservation of energy, states that ”Energy cannot be created or destroyed; it can only be transformed from one form to another” [2]. This implies that in any given process, the difference between the total energy entering a system and the total energy leaving it must equal the change in the total energy within the system as in Eq. 2.1. This law is always applied to a control volume, which can refer to a specific item within a system, such as a turbine, or to the entire system generating electrical energy through the Rankine cycle.

$$E_{\text{in}} - E_{\text{out}} = \Delta E_{\text{system}} \quad (\text{kJ}) \quad \dot{E}_{\text{in}} - \dot{E}_{\text{out}} = \frac{dE_{\text{system}}}{dt} \quad (\text{kW}) \tag{2.1}$$

The increase in a system’s energy is determined by comparing the initial and final states of the process. If the internal process within the system does not involve electrical or magnetic effects, and surface tension is not considered, the change in total energy is equal to the sum of the changes in internal energy, kinetic energy, and potential energy [3].

$$\Delta E_{\text{system}} = \Delta U + \Delta KE + \Delta PE = \Delta U + \frac{1}{2} m \Delta V^2 + mg\Delta z \tag{2.2}$$

Regarding the energy entering or leaving the system, there are three main mechanisms of energy transfer: heat transfer (Q), work transfer (W), and mass flow transfer (θ) [4] . In closed systems, such as the combined elements of the Rankine cycle, there is no mass flow transfer. However, when analyzing the energy balance of each component within the system, mass flow transfer must be considered due to the mass entering and exiting the segment.

$$\left(\dot{Q}_{\text{in}} + \dot{W}_{\text{in}} + \sum_{\text{in}} \dot{m}\theta\right) - \left(\dot{Q}_{\text{out}} + \dot{W}_{\text{out}} + \sum_{\text{out}} \dot{m}\theta\right) = (\dot{m}_2 e_2 - \dot{m}_1 e_1)_{\text{system}} \quad [\text{kW}] \quad (2.3)$$

The energy balance of uniform flow can be expressed as in Eq.2.3, where $\theta = h + ke + pe$ represents the flow energy and $e = u + ke + pe$ is the specific energy of the fluid within the control volume.

For compressible fluids, the differential work performed due to expansion or compression is defined as: $\delta w = Pdv + vdP$. Under the assumptions of an isobaric process ($dP = 0$) and steady state ($ke = pe = 0$), the energy balance simplifies as in Eq. 2.4 [5]. This simplification led to the concept of enthalpy (h) to define the overall amount of energy in a system, which becomes total enthalpy ($h_0 = h + ke$) when kinetic energy is also considered.

$$\delta q = du + \delta w = du + Pdv = d(u + Pv) = dh \quad [\text{kJ/kg}] \qquad (2.4)$$

This measure allows the characterization of the working point of a substance through its registration in a property table. Consequently, this simplification facilitates the calculation of energy transfer, both in the form of heat and work, enabling straightforward operations.

2.2 The Rankine Cycle

In the industry, two primary thermodynamic cycles are predominantly used for electricity generation: the Rankine cycle and the Brayton cycle. In both cycles, a working fluid absorbs heat energy, which is then transformed into mechanical energy through the expansion of the fluid within a turbine. This mechanical energy is subsequently converted into electrical energy by a generator, enabling efficient power generation.

The main differences between these cycles lie in the type of fluid and the energy source. The Brayton cycle uses a gas as the working fluid, while the Rankine cycle employs a two-phase fluid. In the Brayton cycle, the gas absorbs significant heat energy through the combustion of a fuel in contact with the gas. In contrast, the Rankine cycle does not require combustion. Instead, it involves the absorption of sufficient energy from an external heat source to induce a phase change in the working fluid [2] .

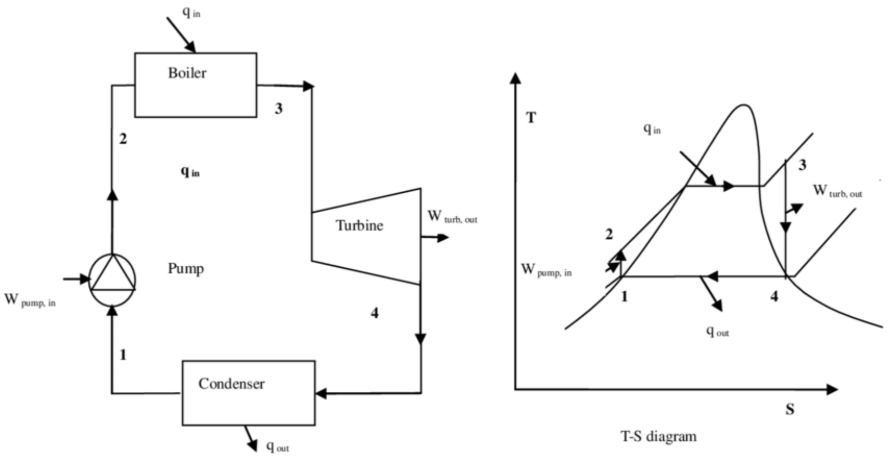
Nuclear reactors generate a substantial amount of heat energy through fission reactions within the reactor. Therefore, the steam cycle in a nuclear power plant can be described using the Rankine cycle, with the nuclear reactor serving as the external heat source. The complete cycle consists of four stages [4]:

- **Compression of the Fluid:** An isentropic process where the fluid in a liquid state enters a pump that compresses the fluid, increasing its pressure.
- **Heat Absorption:** An isobaric process where the fluid enters a heat exchanger and absorbs heat from an external source, increasing its internal energy and changing its phase to a gaseous state.
- **Expansion of the Fluid:** Ideally an isentropic process where the fluid enters the turbine and expands, generating kinetic energy that is converted into mechanical energy. Both the pressure and temperature of the fluid decrease during this process.
- **Condensation of the Fluid:** An isobaric process where the fluid enters a heat exchanger known as a condenser. Here, it releases heat from the system, condensing back into a saturated liquid state.

2.2.1 Thermodynamic Analysis

Ideal Rankine Cycle

The ideal Rankine cycle consists of four main components: a pump, a heat source (usually a boiler), a turbine, and a condenser. These elements are connected as shown in Figure 2.1, forming a closed system and executing a four-phase cycle [3]. Since it is a cyclic process, the initial and final states of the system must be identical, meaning $\Delta E_{\text{system}} = 0$ and $E_{\text{in}} = E_{\text{out}}$.



T-S diagram

Figure 2.1: Ideal Rankine cycle [4]

The cycle is considered ideal when it is composed of two isobaric processes and two isentropic processes, defined by the following elements [4]:

- Pump ($q = 0$): $w_{\text{pump}} = (h_2 - h_1)$

- Boiler ($w = 0$): $q_{\text{boiler}} = (h_3 - h_2)$
- Turbine ($q = 0$): $w_{\text{turbine}} = (h_3 - h_4)$
- Condenser ($w = 0$): $q_{\text{condenser}} = (h_4 - h_1)$

Thus, the energy balance for a steady-state case is given by:

$$\left(\dot{Q}_{\text{boiler}} + \dot{W}_{\text{pump}}\right) - \left(\dot{Q}_{\text{condenser}} + \dot{W}_{\text{turbine}}\right) = 0 \quad [\text{kW}] \tag{2.5}$$

Where the thermal efficiency is calculated as:

$$\eta_{\text{t}} = 1 - \frac{\dot{Q}_{\text{out}}}{\dot{Q}_{\text{in}}} \tag{2.6}$$

Real Rankine Cycle

The ideal Rankine cycle provides a foundational understanding of the processes involved. However, in practical applications, several inefficiencies and real-world constraints result in deviations from this ideal model. The various components that make up this system, along with the necessary connections between them, introduce a series of irreversible processes that affect both its behavior and efficiency.

These irreversible processes present several challenges. One of them is the pressure drops, which occur due to fluid friction within the pipelines and valves that connect the components. This issue is further compounded inside the boiler, leading to a pressure decrease between the inlet and outlet, and from the boiler outlet to the turbine inlet. Furthermore, heat losses are inevitable throughout the system as the working fluid comes into contact with various materials at different operational points and moves through the system [2].

The irreversibilities that most significantly impact system efficiency are those generated in the turbine and the pump. Therefore, thermodynamic analyses of steam power cycles often consider the isentropic efficiency of both them, as shown in Eq. 2.7 [4]. Where the subscript s refers to the isentropic case and the subscript a refers to the real case, as illustrated in 2.2.

$$\eta_P = \frac{w_s}{w_a} = \frac{h_{2s} - h_1}{h_{2a} - h_1} \quad \eta_T = \frac{w_a}{w_s} = \frac{h_3 - h_{4a}}{h_3 - h_{4s}} \tag{2.7}$$

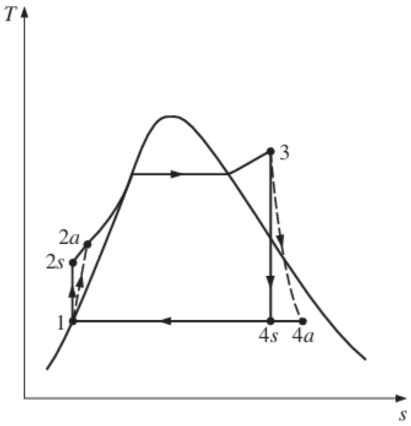


Figure 2.2: Real Rankine cycle [4]

2.3 Heat Transfer Mechanisms

The transfer of energy through heat occurs due to temperature differences in space. This temperature gradient can manifest in several ways: along a solid medium or stationary liquid medium (conduction); between a surface and a moving fluid (convection); or through the emission of electromagnetic waves from all matter or finite surfaces (radiation) [6]. In this study, the last mechanism will not be considered, as it is assumed to have a negligible impact on the system's operation.

Conduction

Conduction occurs within a stationary solid or liquid medium due to molecular activity (diffusion) within the material. This activity generates constant interactions between particles, causing the more energetic particles to transfer energy to the less energetic ones. As a result, energy always seeks to equalize, moving from the more energetic or hotter point to the cooler or lower-energy point.

Unidirectional heat transfer by conduction can be quantified using Fourier's law (Eq. 2.8) [7]. The heat flux (q''_x) per unit area, perpendicular to this transmission, is considered to be in a single direction. This flux is proportional to the material's thermal conductivity ($k\,[W/mK]$) and the temperature gradient in that direction.

$$q''_x = -k\frac{dT}{dx} \quad [W/m^2] \tag{2.8}$$

Convection

In addition to molecular movement in a fluid, the fluid itself can move, displacing its mass through space. This displacement is known as advection and also contributes to energy transfer. Therefore, when discussing energy transfer due to particle interaction (conduction) and the fluid's own movement (advection) together, it is referred to as convection [7].

The heat flux in convection can be calculated using Newton's law of cooling (Eq. 2.9) [6]. This equation considers the heat transfer convection coefficient ($h[W/m^2K]$), which depends not only on the fluid but also on conditions such as whether it is in a gaseous or liquid state, and whether the convection is natural or forced.

$$q'' = h(T_{surface} - T_{fluid}) \quad [W/m^2] \tag{2.9}$$

2.4 Phase change

In a heat transfer process, not only can a change in temperature occur, but a phase change of the substance can also take place. The two processes explained so far describe sensible heat, which is the amount of energy required to change the temperature of a substance. However, when a substance changes phase, the temperature remains constant and it involves latent heat transfer, which is the energy necessary to modify intermolecular forces and achieve the phase change [7].

Both types of heat transfer are reflected in the internal energy (u). If the temperature increases, the internal energy will increase, while a decrease in temperature will result in a decrease in internal energy. On the other hand, if the phase change is to a more disordered state of matter (melting, boiling), the latent energy increases. Conversely, if the phase change is to a more ordered state of matter (condensation, solidification), the latent energy decreases.

$$Q = ML \quad [kJ] \tag{2.10}$$

The energy required per unit mass for the phase change is represented by the specific latent heat, denoted as $L[kJ/kg]$. The value is the same for energy absorbed during evaporation as it is for energy released during condensation, but the latent heat for evaporation (L_{lg}) differs from the latent heat for fusion (L_{sl}). The latent heat of evaporation is shown in property tables as the difference in enthalpy between the saturated liquid and saturated vapor states at a specific pressure and temperature:

$$L_l g = h_g - h_l \tag{2.11}$$

where h_g is the enthalpy of the saturated vapor and h_l is the enthalpy of the saturated liquid at a specific pressure and temperature. This relationship highlights the significant amount of energy involved in phase changes compared to sensible heating or cooling.

For example, the specific latent heat of vaporization for water at its boiling point is approximately 2257 kJ/kg, whereas the specific latent heat of fusion is about 333.6 kJ/kg [6]. These values, measured at 1 atm, illustrate how much more energy is required to vaporize water than to melt ice, reflecting the strength of the intermolecular forces that need to be overcome in each process.

2.4.1 Relationship between water properties

The relationship between the pressure, volume, and temperature of water can be visualized using a PVT (pressure-volume-temperature) diagram [4]. This three-dimensional representation helps to understand the phase behavior of water under various conditions.

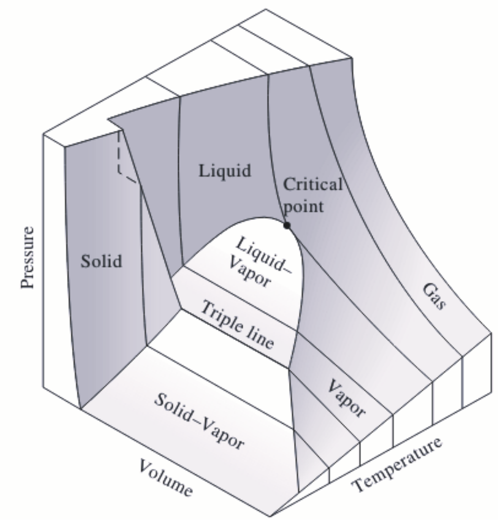


Figure 2.3: PVT Diagram: This diagram shows the relationships between pressure, volume, and temperature for water, highlighting the regions of different phases and the phase change boundaries. [4]

In the PVT diagram, the regions where phase changes occur are clearly delineated. The lines on the diagram represent the phase boundaries, where two phases coexist in equilibrium. For example, the line separating the liquid and vapor regions is the vaporization/condensation line. The diagram illustrates how pressure, volume, and temperature are interrelated and how changes in one property affect the others during a phase change.

The problem arises when the gas increases significantly in pressure and temperature. At constant temperature, if the pressure increases, the specific volume decreases. Conversely, at constant pressure, if the temperature increases, the specific volume increases. This information is crucial because in the steam cycle, these three variables change consecutively. Depending on whether the temperature increases more than the pressure or vice versa, the specific volume is affected, which in turn impacts the thermal masses.

2.5 Fluid Dynamics in Power Cycles

In the study of a steam cycle, the thermodynamic behavior of the fluid, as previously explained, is typically the primary focus. A more detailed analysis of the fluid's dynamic behavior is usually performed when examining specific system components, using computational fluid dynamics (CFD). Although this study does not emphasize these details extensively, the system will include a pump feeding two boilers, necessitating the use of pipes to direct the flow.

The main characteristic defining the flow distribution is the pressure loss 2.12. In this case, the pressure loss is attributed to two phenomena: the change in velocity itself and the friction of the fluid with the pipe walls [8]. The simulation does not take the height of each object into account, so the static pressure and its difference are equal to zero.

$$\Delta p = \frac{\rho \Delta V^2}{2} + \rho g \Delta z + h_{friction} \tag{2.12}$$

$$h_friction = f \frac{l}{d} \frac{\rho V^2}{2} \tag{2.13}$$

$$Re = \frac{Vd}{\nu} \tag{2.14}$$

Given the high temperatures and high pressures of the simulation, the flow will be turbulent, characterized by a Reynolds number greater than 4000 (Eq. 2.14). Therefore, the Darcy friction factor needs to be calculated using the Haaland equation [9]:

$$\frac{1}{f^{1/2}} \approx -1.8 \log \left[\frac{6.9}{\mathrm{Re}} + \left(\frac{\epsilon/d}{3.7} \right)^{1.11} \right] \tag{2.15}$$

Chapter 3

Simulating with Simscape

Simscape is a computational tool for designing physical models, which facilitates the programming and simulation of physical elements. As an extension of Simulink, it allows smooth integration of Simulink components and ensures connectivity with the MATLAB desktop environment.

One of the key advantages of Simscape over Simulink is its ability to create physical connections between blocks, rather than merely facilitating signal transmission or the solving of mathematical equations. This capability significantly simplifies the execution of complex, multi-domain models, making the modeling process more direct and intuitive. Additionally, Simscape supports the creation of customized blocks. By utilizing the Simscape Language, based on MATLAB's programming language, users can define physical connections, algebraic equations, and necessary parameters [10].

3.1 Domains in Simscape

Simscape is distinguished by its physical network architecture, whereby each node must belong to a specific physical domain. Nodes can only connect to other nodes within the same domain, but a block can have nodes from different domains, allowing for the construction of multi-domain models.

A domain is primarily defined by its variables, which are the data transmitted between nodes. These variables are specified in the domain through equations or parameters and are differentiated into two types [11]:

- **Across variables:** These variables measure the difference in a physical quantity across a component. For instance, pressure in hydraulic systems measures the difference across the terminals of an hydraulic component. Importantly, these variables must be consistent at the connection points between different components to ensure continuity and correct physical representation.
- **Through variables:** These variables represent the flow of quantities through a component. They enforce the conservation of fundamental quantities, such as

mass, energy, or charge, which is whay the sum of all values flowing into a branch point must equal the sum flowing out, maintaining the balance of the system.

Simscape offers the capability to create custom domains or utilize any of the predefined domains within the software. Each predefined domain in the software is represented by a unique color, making the library and the physical network between nodes visually distinctive. For this project, three existing domains from the Simscape libraries will be implemented: the Two-Phase Fluid Domain, the Thermal Domain, and the Mechanical Rotational Domain [11].

Two-Phase Fluid Domain

The steam cycle, as depicted by the Rankine cycle, involves a fluid transitioning between two states—specifically, water in this context. Throughout the cycle, the fluid alternates between subcooled liquid and superheated steam, also passing through saturated states. To accurately represent this dynamic, the Two-Phase Fluid Domain is utilized, which is represented by a light blue color in Simscape.

This domain is characterized by pressure (p, measured in MPa) and specific internal energy (u, measured in KJ/kg) as Across variables, alongside mass flow rate (mdot, measured in kg/s) and energy flow rate (Phi, measured in kW) as Through variables. The parameters for the Across variables are constrained, with pressure ranging from 1e-3 to 95 MPa and specific internal energy spanning from 0 to 4000 KJ/kg. Moreover, this domain is pre-configured with water as the default fluid and includes comprehensive property tables that are essential for developing precise simulations.

Thermal Domain

The phase transitions within the steam cycle are fundamentally driven by heat transfer, a process integral to the operation of the cycle. The Thermal Domain in Simscape is crucial for modeling the heat generated by the Small Modular Reactor (SMR) that transfers to the steam system and the heat extracted in the condenser, which enables fluid recirculation.

This domain supports the simulation of complex thermal interactions such as conduction, convection, and radiation within the system. This capability allows for a comprehensive analysis of thermal behavior across various components, significantly enhancing the understanding of system dynamics and thermal management.

It is characterized by temperature (T, measured in Kelvin) as the Across variable, and heat flow (H, measured in Joules per second or Watts) as the Through variable. This domain is represented by an orange color throughout its network connections.

Mechanical Rotational Domain

The third domain essential for this simulation is the Mechanical Rotational Domain. This domain is particularly relevant for components such as turbines and pumps, where the transmission of energy involves converting the kinetic or potential energy of the fluid into rotational mechanical energy, or vice versa. This domain facilitates the detailed analysis of rotational dynamics, allowing engineers to optimize the mechanical design for enhanced efficiency and reliability.

Within this domain, angular velocity (ω, measured in radians per second) is defined as the Across variable, and torque (τ, measured in Newton-meters) is the Through variable. Torque represents the twisting force that causes rotation, playing a crucial role in the mechanical performance of rotating components in the system. This domain is represented by a light green color.

3.2 Selected Components for Simulation

The Rankine cycle, fundamental to the operation of Small Modular Reactors (SMRs), is characterized primarily by four elements: a heat source (traditionally a boiler), a turbine, a condenser, and a pump. In this case, instead of a conventional boiler where heat is generated by combustion, an SMR serves as the heat source. The objective is to represent these components within Simscape to accurately simulate the steam cycle. This is accomplished by utilizing the extensive libraries available in Simscape [12], which are designed for each domain, or by creating custom components using the Simscape language. This approach allows for precise modeling of the physical processes and interactions within the system.

3.2.1 Representing the Small Modular Reactor

In a power generation system utilizing a Small Modular Reactor (SMR), the reactor is connected to the steam cycle through an internal system composed of heat exchangers. Given that this work focuses on the steam cycle and its dynamic behavior, the reactor will be represented simply as a heat source. Accurately simulating the cycle with heat generation from the reactor would require considering the physical and chemical reactions within the reactor—a theory beyond the scope of this introductory project in simulation with Simscape.

Consequently, a block is needed to represent steam generation, combining the Thermal Domain and the Two-Phase Fluid Domain. This block must include a heat source (SMR) and an element that allows for the representation of heat transfer and phase change of water. By exploring the libraries of these domains, the appropriate components have been identified, as shown in Figure 3.1.The heat generated by the SMR is represented by the *Heat Flow Rate Source* element, which allows the application of a constant or controlled heat value to the system. This source is then connected to the *Constant Volume Chamber (2P)* element.

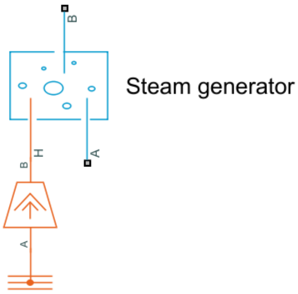


Figure 3.1: Steam generator for simulation

Constant Volume Chamber (2P)

This component represents a tank filled to a constant fixed volume, enabling the study of mass and energy conservation. The Constant Volume Chamber adds dynamic behavior to the system through the definition of volume and the mass balance equation represented by Equations 3.1 and 3.2. These equations take into account the variation of mass by density. Although liquid water is considered incompressible, steam is compressible, and during a phase change the density varies significantly with pressure and temperature, resulting in dynamic behavior within the tank.

$$\left[\left(\frac{\partial\rho}{\partial p}\right)_u \frac{dp}{dt} + \left(\frac{\partial\rho}{\partial u}\right)_p \frac{du}{dt}\right] V = \dot{m}_A + \dot{m}_B + \dot{m}_C + \dot{m}_D + \epsilon_M, \tag{3.1}$$

$$\frac{dM}{dt} = \dot{m}_A + \dot{m}_B + \dot{m}_C + \dot{m}_D \tag{3.2}$$

Additionally, the Constant Volume Chamber has assumptions and limitations that must be considered. Firstly, the flow resistance and thermal resistance between the ports and the interior are negligible, implying that the pressure must be equal at the different inlet or outlet ports of the tank. Furthermore, the kinetic energy within the chamber is not considered, simplifying the calculation of the total energy as shown in Equations 3.3 and 3.4.

$$E = Mu, \tag{3.3}$$

$$\dot{E} = \phi_A + \phi_B + \phi_C + \phi_D + Q_H, \tag{3.4}$$

3.2.2 Modelling the Condenser

The condenser is an essential component in the Rankine cycle, facilitating the cooling of the fluid in a closed loop. This component is connected to a secondary circulation system, which usually uses ambient temperature liquid to cool the primary system fluid and absorb the residual heat not utilized by the turbine. To simplify the system, only a constant temperature source will be referenced instead of the entire secondary cooling system.

As shown in Figure 3.2, the *Constant Volume Chamber (2P)* component is used again for the condenser, with its characteristics detailed in the previous subsection. This time, heat transfer is achieved using a *Temperature Source* set at a constant temperature, combined with a *Convective Heat Transfer* element in series para realizar correctamente la transmision de calor.

Defining the initial parameters of this block is crucial since, in the Rankine cycle, the fluid exits the condenser in a saturated liquid state. This operational point is particularly challenging for the simulation due to its relative instability, but it is necessary to ensure the pump operates under the appropriate conditions.

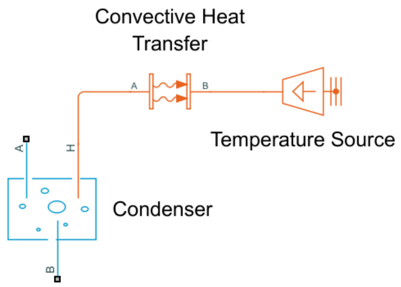


Figure 3.2: Condenser simulation

3.2.3 Modelling the Turbine

The turbine is a critical component in the Rankine cycle, responsible for converting thermal energy into mechanical energy. When selecting the turbine for the simulation, two options were available in Simscape: one from the Two-Phase Fluid Domain library [13] and another from the Simscape Rankine cycle simulation example [1].

The primary difference between these turbines lies in their performance correction methods. The turbine from the Two-Phase Fluid Domain uses the corrected mass flow approach, typically applied in gas turbines. In contrast, the turbine from the Rankine cycle example employs Stodola's ellipse, a well-established method for steam turbines that accurately characterizes the relationship between mass flow rate, pressure, and temperature.

Given that Stodola's ellipse is more suited for steam turbines, the turbine model from the Simscape Rankine cycle simulation example was selected for this project. This choice ensures accurate representation of the steam turbine's operational dynamics within the Rankine cycle.

Stodola's Law

Stodola's Law, also known as Stodola's Ellipse, is a key principle in thermodynamics and fluid mechanics, particularly relevant to steam turbine performance analysis. Developed by Aurel Stodola, this empirical law provides a relationship between the mass flow rate, pressure, and temperature of steam through a turbine. It is particularly useful for explaining off-design conditions in multi-stage turbines, where the performance deviates from the optimal design point.

The essence of Stodola's Law is that the mass flow rate through a turbine at a given pressure ratio is proportional to the square root of the enthalpy drop, adjusted for changes in steam conditions. Calculating the mass flow coefficient as in Eq.3.5 develops a proportionality that defines Stodola's Ellipse, shown in Eq. 3.6. This equation relates the mass flow coefficient to the pressure ratio. Additionally, the variable n represents the polytropic efficiency (typically equal to 1) [14].

$$\Phi = \frac{\dot{m}}{\sqrt{\frac{P_A}{v}}} \tag{3.5}$$

$$\Phi \propto \sqrt{1 - \left(\frac{P_B}{P_A}\right)^{\frac{n+1}{n}}} \tag{3.6}$$

This elliptical relationship allows for the calculation of a constant value for different operating points of the turbine, known as Stodola's Constant (Eq. 3.7). This law is instrumental in defining the performance curves of the turbine, enabling a more accurate simulation of its behavior under different conditions. By utilizing Stodola's Law, various off-design operating points can be calculated, as demonstrated in Eq. 3.8 [15].

$$\frac{\Phi}{\sqrt{1 - \left(\frac{P_B}{P_A}\right)^2}} = K(Stodola'sConstant) \tag{3.7}$$

$$\frac{\Phi_1}{\Phi_2} = \frac{\sqrt{1 - \left(\frac{P_{B1}}{P_{A1}}\right)^2}}{\sqrt{1 - \left(\frac{P_{B2}}{P_{A2}}\right)^2}} \tag{3.8}$$

Turbine design

The turbine designed for the Rankine cycle example is composed of two domains: the two-phase fluid domain and the mechanical rotational domain. This configuration allows for the accurate representation of energy transformation into mechanical work. To establish the operating conditions, the *Ideal Angular Velocity Source* element is added, which defines the rotational speed at 3000 rpm by using a constant signal from the *PS Constant* and the *Mechanical Rotational Reference*. Since no additional elements are introduced to modify the turbine's torque, varying the system speed is unnecessary; the torque will adjust to maintain consistent mechanical power output.

It is important to emphasize that the initial values set in this element determine the Stodola's constant, which remains fixed throughout the simulation. This value compels the system to adjust either the mass flow or the pressure differential across the turbine, making it a crucial factor for understanding the simulation results and the dynamic response of the system.

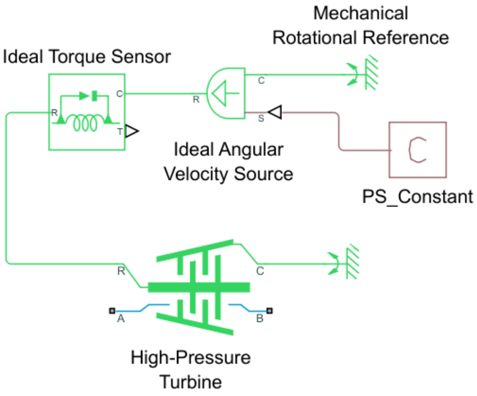


Figure 3.3: Turbine for simulation

3.2.4 Modelling the Pump

The Two-Phase Liquid Domain library in Simscape offers three options for modeling a pump: *Flow Rate Source (2P)*, *Centrifugal Pump (2P)*, and *Displacement Pump (2P)*.

Given the objective of simulating a pump in a steam circuit, the Displacement Pump option will not be considered. Displacement pumps typically operate with smaller capacities and can cause issues in systems with phase changes due to their mechanism.

The primary component used will be the *Flow Rate Source (2P)*, which allows for the definition of a constant mass flow at the inlet and outlet of the element. This component also provides the option to perform isentropic work, which is suitable for the Rankine cycle application and simplifies the process. Additionally, if necessary, it allows for the connection of a Simulink signal to control the mass flow. The ability to manipulate and set the mass flow variable in the system is highly beneficial for simplifying the system of equations required to solve the simulation.

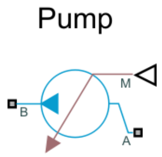


Figure 3.4: Flow Rate Source

3.3 Limitations

3.3.1 Initial variables priority

In Simscape, the initialization of variables is a crucial and limiting aspect of the simulation process. Proper initialization ensures that the simulation starts from a realistic and stable state, which is essential for obtaining accurate and reliable results. Variables in Simscape can have different priority levels assigned to them, ranging from high to low. This priority determines how closely the simulation system attempts to match these variables. For example, a high-priority variable will have the system make a more precise effort to achieve its initial value, while a low-priority variable allows for more flexibility. This feature allows for better control over the simulation's starting conditions, ensuring that critical variables are given the necessary emphasis.

Some blocks in Simscape allow users to set the priority of their initial variables. However, other blocks come with predefined priorities coded into them, which cannot be altered. These predefined settings can impose limitations on how the initialization can be configured and require careful consideration when setting up the model to avoid potential issues. For instance, the initial variables of the *Constant Volume Chamber* are set to high priority not only at the initial moment but throughout the entire simulation. This necessitates that the initial values be very close to the expected real outcome. Any significant deviation or instability in the system, particularly when testing transient states, can be adversely affected by these fixed high-priority settings. Consequently, the accuracy of these initial values becomes paramount to the overall performance and reliability of the simulation.

3.3.2 Initial convergence

The initialization of variables is one of the most important steps in setting up a simulation in Simscape because the software requires these initial values to converge to a solution. If any value is unbalanced, the simulation cannot initialize properly, leading to errors and potentially invalid results. This means that during the initialization phase, it is imperative to input values that are as accurate and precise as possible to the real-world conditions the model aims to replicate. Ensuring that all initial values are balanced and lead to a convergent solution is essential for the successful initialization and subsequent performance of the simulation.

However, a significant limitation arises because the purpose of many simulations is to investigate the effects of introducing new conditions, for which exact initial data might not be available. Often, researchers do not have precise initial values when they begin their simulations, making it difficult to ensure the necessary convergence. This lack of exact initial data poses a challenge in achieving a stable and reliable simulation start, potentially affecting the validity of the results obtained from testing new scenarios or conditions.

3.3.3 Limit values of the two-phase fluid domain

The Two-Phase Fluid Domain in Simscape has limit values for pressure and specific internal energy. The minimum pressure (pmin) is 1e-3 MPa, and the maximum pressure (pmax) is 95 MPa. For specific internal energy, the minimum (umin) is 0 kJ/kg, and the maximum (umax) is 4000 kJ/kg. These limits can cause problems when studying transient cases, where the system may become unstable due to simulation iterations, leading to errors without the ability to adjust values. This issue is especially significant when the boiler operates at very high temperatures, resulting in very high internal energy. Such conditions can push the system beyond the defined limits, causing simulation failures and making it hard to analyze transient phenomena accurately.

3.3.4 Limit visibility of source code

In Simscape, not all elements from the software libraries provide access to their underlying source code. This means that users cannot always see how the equations and variables are applied within these components. The lack of transparency complicates the understanding of certain elements, making it difficult to comprehend how they function and are executed within the simulation. This can be a significant limitation, as it may prevent the proper utilization of some elements or even lead to not using them at all due to a lack of understanding. Consequently, this limitation can affect the effective application of these elements in the simulation model, potentially impacting the accuracy and reliability of the results.

Chapter 4

Methodology

4.1 Study of individual elements

The initial phase of this project involves understanding the Simscape simulation software and the selected components from its libraries. Initially, the source code for most of the components to be used is available. However, since Simscape does not solve the system of equations in the order they are written in the code, it can sometimes be challenging to understand how all the equations are resolved and which variables have priority.

To better understand the components, individual systems were created for each component to study their responses. This was done with the help of the *Controlled Reservoir (2P)* element. This element represents an infinite source of fluid where the pressure and another property of the fluid, such as temperature or vapor quality, can be defined. The idea is to simulate an open circuit with a reservoir at each end instead of a closed circuit, where it is more complicated to determine which element causes each change.

When simulating the boiler and condenser, it is also necessary to add a flow rate source that functions as a valve (zero work) to set the mass flow rate and the direction of flow. This is necessary because the ports of the constant volume chamber element serve as both inlet and outlet, so the flow direction must be defined for proper operation. This approach helps to understand the dynamic behavior of these elements and observe the response of the mass flow rate at the boiler outlet as a function of the heat flow signal. Due to the conservation of energy and mass equations, if a step signal is added to the heat flow, it will instantly affect the mass flow rate, influencing the response of the entire system.

Using these simplified systems, it was verified that the pump and turbine do not show dynamic behavior on their own. However, because of the relationship between water properties, as shown in diagrams like the temperature-entropy diagram, any slow change from one operating point to another will involve some dynamic behavior. This happens because gradual changes in properties like temperature and pressure cause the system to respond differently, meaning that even components that seem static can show dynamic characteristics in certain situations.

As the next step in the project, multiple elements were combined without completing the closed cycle. Specifically, the pump, boiler, and turbine were integrated into a single system. This setup allowed for the observation of how the Stodola's ellipse, implemented in the turbine, affects the pressure difference. The Stodola's ellipse describes the relationship between the flow rate and the pressure drop across the turbine, which in turn influences the dynamic behavior of the boiler. As the pressure changes due to variations in the mass flow rate at the boiler outlet, more dynamic behavior was observed in the boiler. This integration provided valuable insights into the interactions between these components and how changes in one element can impact the overall system performance.

This initial phase is one of the most critical and time-consuming parts of the project. Each element has its code that needed to be studied and verified for proper functionality. By doing this, the equations involved in each process were obtained. However, each code has a system of equations that is not always compatible or determined. This means that the software often solves an indeterminate system without any warning to the user. Because there are not enough equations to fix a single response, the simulation can produce multiple solutions and provide an arbitrary one. This can lead to unexpected results, necessitating the addition of more elements to the model to stabilize the solution and achieve the desired outcomes.

4.2 Basic model of Rankine cycle

Once the individual elements were understood, they were combined to execute the ideal Rankine cycle. Additionally, a set of sensors was added between components, consisting of the *Vapor Quality Sensor (2P)*, *Thermodynamic Properties Sensor (2P)*, and *Pressure, Temperature, and Internal Energy Sensor (2P)*. These sensors are essential for understanding the system's dynamics and verifying its correct operation by providing real-time data on key variables.

Initially, the pump was modeled to operate with a constant mass flow rate to simplify the problem. This approach allows for a more straightforward analysis of the basic Rankine cycle. However, it also introduces some contradictions in the results because, in a real system, the pump's behavior would dynamically adjust to changes in the system, affecting pressure and flow rate. Consequently, these simplifications can lead to discrepancies when comparing the simulation results with expected real-world outcomes. Despite this, starting with a constant flow rate helps isolate other variables and understand their effects more clearly.

For the simulation to work, the initial values must converge. To ensure this, data from a steam cycle problem in the book by Cengel et al. (2020) [4, p. 560] were used. This guarantees that the expected values are known and that the simulation functions correctly. The main data used include a 4 MW energy source, with the system operating between 3 MPa and 75 kPa, and a thermal efficiency of 26%. By using these well-documented values, the model can be validated through comparison with theoretical expectations.The simulation is then executed with these initial values until it reaches a steady-state. Although the steady-state values obtained are very similar to those from the problem, they do not match exactly, highlighting minor discrepancies that may arise in the modeling process.

Through this example, it was revealed that the Phi variable in the two-phase fluid domain, which represents the energy flow rate, is actually the total enthalpy (h_0). Consequently, potential energy is never considered in the simulation, while kinetic energy is essential in power calculations. This means that the area of the inlet and outlet ports of the elements also plays an important role in the calculation of variables. Therefore, any modifications to them must be handled with care.

To further study the influence of variable initialization, the initial temperature of the boiler was modified. By changing this variable, the results at the boiler outlet were observed. For initial values of 350°C, 300°C, and 250°C, the steady-state temperature was very similar (333.243°C, 331.963°C, 330.578°C) despite different starting points. However, when initialized at 200°C, the system became completely unstable, as shown in Fig. 4.1. The pressure exceeded the maximum allowable in the two-phase fluid domain (95 MPa), causing the simulation to stop and display the error shown in Fig. 4.2. This highlights the critical nature of selecting appropriate initial conditions to prevent system instability.

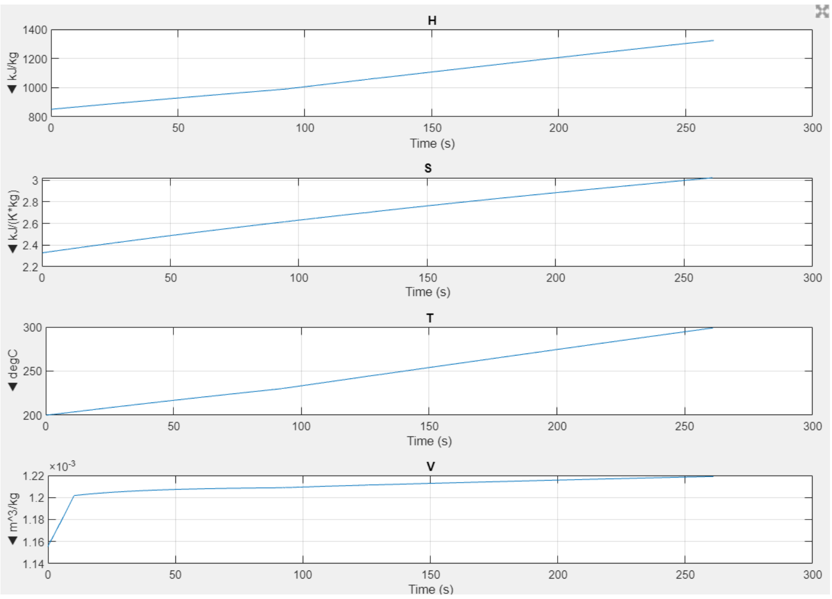
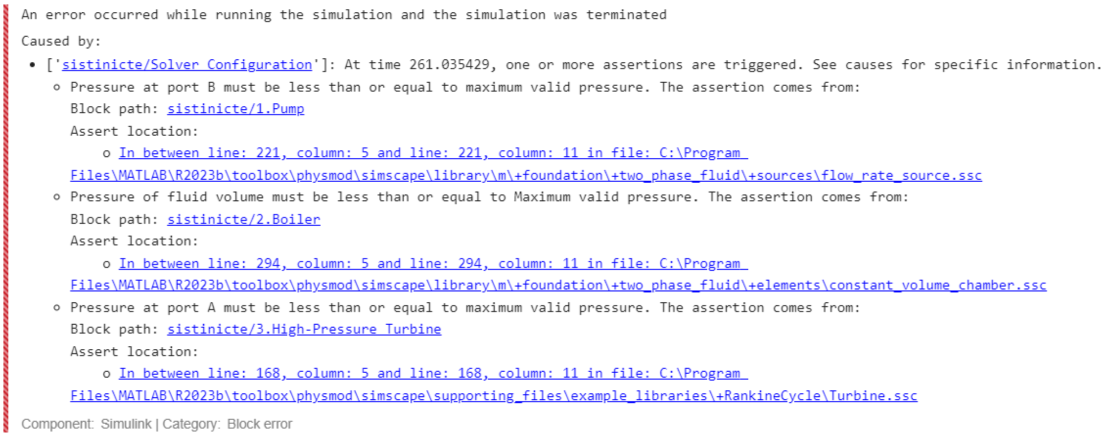


Figure 4.1: Sensor S3 in basic model: Thermodynamic Properties Sensor located after the boiler. The simulation starts at 200ºC, causing instability and eventual failure.



```
An error occurred while running the simulation and the simulation was terminated
Caused by:
 • ['sistinicte/Solver Configuration']: At time 261.035429, one or more assertions are triggered. See causes for specific information.
    o Pressure at port B must be less than or equal to maximum valid pressure. The assertion comes from:
      Block path: sistinicte/1.Pump
      Assert location:
          o In between line: 221, column: 5 and line: 221, column: 11 in file: C:\Program 
      Files\MATLAB\R2023b\toolbox\physmod\simscape\library\m\+foundation\+two_phase_fluid\+sources\flow_rate_source.ssc
    o Pressure of fluid volume must be less than or equal to Maximum valid pressure. The assertion comes from:
      Block path: sistinicte/2.Boiler
      Assert location:
          o In between line: 294, column: 5 and line: 294, column: 11 in file: C:\Program 
      Files\MATLAB\R2023b\toolbox\physmod\simscape\library\m\+foundation\+two_phase_fluid\+elements\constant_volume_chamber.ssc
    o Pressure at port A must be less than or equal to maximum valid pressure. The assertion comes from:
      Block path: sistinicte/3.High-Pressure Turbine
      Assert location:
          o In between line: 168, column: 5 and line: 168, column: 11 in file: C:\Program 
      Files\MATLAB\R2023b\toolbox\physmod\simscape\supporting_files\example_libraries\+RankineCycle\Turbine.ssc
Component: Simulink | Category: Block error
```

Figure 4.2: Error in basic model: Starting the simulation at 200ºC caused the values to become so unstable that the maximum pressure of 95 MPa in the domain was reached, resulting in simulation failure.

4.3 Dual SMR system

The original idea for this project, proposed by the company Seaborg, was to study the behavior of two nuclear reactors connected to a single turbine. This means that the closed steam cycle requires two separate and independent energy sources. Independence is necessary to study and manipulate the behavior of each reactor individually. To achieve this, the model implements two boilers in parallel. They are not placed in series because the power generated by the reactors is very high, which would cause the steam to become excessively superheated, reaching dangerously high pressures and temperatures.

The initial challenge when attempting to implement the two boilers in parallel is that the system lacks any physical basis or information to regulate the distribution of the pump flow. Consequently, the simulation distributes the flow between the two boilers randomly until it stabilizes. To improve this situation, pipes (Pipe(2P)) are included between the pump and the boilers. If the pipes are identical and the energy supply to each boiler is equal, the system stabilizes properly, with half of the flow being directed to one boiler and the other half to the other.

The pipes impact the simulation results in several ways. Firstly, they account for the accumulation of mass within them, which affects the mass balance by causing variations in the mass flow rate at the inlet and outlet. This dynamic behavior is crucial for accurately modeling the system. Secondly, they incorporate the typical pressure losses associated with pipes, as discussed in Section 2.4. These pressure losses depend on fluid conditions such as density and velocity, so variations in these properties will affect the losses and, consequently, the final system response.

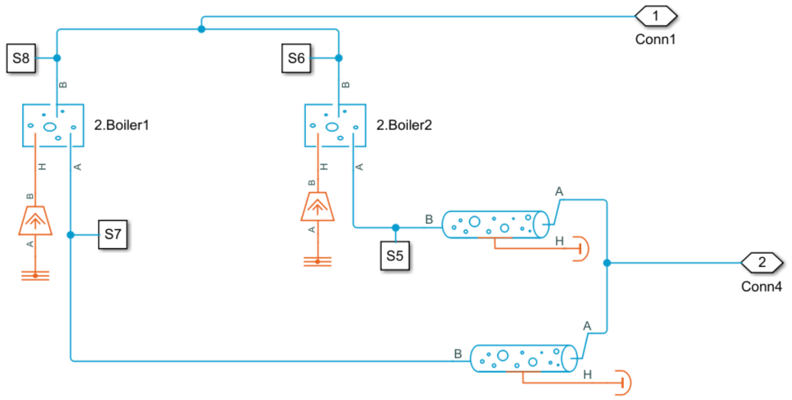


Figure 4.3: Subsystem with dual boilers and pipes: The flow splits before the pipes and merges after passing through the boilers, illustrating the division and recombination of the flow within the system.Sensors S5, S6, S7, and S8 are included to study the system's behavior.

4.3.1 Design scaling

Initially, indicative values were used to ensure the simulation functioned correctly. However, these are not the real values one would find in a thermal power plant. SMRs can produce up to 300 MWe [16], whereas the initial exercise values do not generate even 1 MW of mechanical energy. Therefore, it was decided to scale the elements to larger dimensions to achieve a mechanical energy output of at least 30 MW to 40 MW.

Based on the desired energy production, a turbine capable of generating this power was selected. The Siemens SST-300 model, which can generate up to 45 MWe, was chosen for this purpose. The characteristics of this turbine, along with the selected nominal operating values, are listed in the table below. In the model's turbine, only the nominal operating values can be specified, which the code uses to calculate Stodola's constant, as explained in Section 3.2. The simulation then adjusts the properties according to Stodola's law.

Property	**Limit value**	**Selected value**
Power output	45 MW	-
Speed	12000 rpm	3000 rpm
Efficiency	85%	85 %
Inlet temperature	540°C	475ºC
Inlet pressure	140 bar	120 bar
Outlet pressure	0.3 bar	0.15 bar

Table 4.1: Turbine characteristics:This table displays the operating limit values of SST-300 turbine [17] and the nominal values selected for Stodola's constant.

From these values, the initial parameters for other components can be completed. Additionally, the initial heat flow to be added to the boiler can be calculated. Assuming a target of generating 30 MWe with a mechanical and isentropic efficiency of 85% for the turbine, along with an overall system thermal efficiency of 30%, an initial heat flow of approximately 140 MW would be required in the boiler.

Furthermore, considering the enthalpy of vaporization in the boiler ($h_{lg}(120\text{bar}) = 1197.48$ kJ/kg) and in the condenser ($h_{lg}(0.15\text{bar}) = 2373.24$ kJ/kg) [4], along with the potential use of centrifugal pumps with the necessary head ($H = 1222$ m) [18], a mass flow rate of 50 kg/s was decided upon. Subsequently, the diameters of the ports for each component and the volume were adjusted to standard values.

4.4 System perturbations

Once a simulation model is established, it is essential to conduct various simulations to study the system's results and behavior under different conditions. By introducing perturbations, we can observe how the system responds to changes and identify potential areas for improvement. The first significant modification to the model that impacts the results is a pressure drop between the boilers and the turbine. This pressure drop can lead to changes in the performance of the entire system. Additionally, there are two main variables that can be easily adjusted in the simulation: the amount of heat flow and mass flow. By varying these inputs, we can analyze their effects on the system's thermal and dynamic behavior, providing deeper insights into the system's stability and operational limits.

4.4.1 Pressure drop

During the development of the system with two parallel boilers, it was observed that the pressure and internal energy, being across variables in the two-phase fluid domain, were identical for the outlet ports of the boilers and the inlet port of the turbine. To address this issue and enhance the independence in the response of each boiler, the idea of introducing a pressure drop after each boiler and before the two flows combined to enter the turbine was considered.

The element used to create this pressure drop is the Flow Resistance (2P), implemented twice, with one placed after each boiler. In this element, the nominal conditions for the pressure drop are specified. Based on these values, a pressure drop factor is calculated, allowing the solver to compute the pressure drop as a function of this parameter, the mass flow, and the specific volume.

However, when this change was applied, the result was significant instability in the system depending on the pressure drop. Consequently, this new variable was used for further study. Specifically, four simulations with different nominal pressure drops were compared: 0 kPa, 1 kPa, 10 kPa, and 100 kPa. These are nominal values, but as explained earlier, the actual values depend on other variables. Furthermore, a simulation with a 2 kPa pressure drop was conducted to reflect the system's instability.

Additionally, to study the true impact of the pressure drop on the simulation, a ramp signal was added to the heat flow source of one of the boilers. This approach allows for a comparison of the system with different pressure drops in the scenario where one boiler increases its heat flow from 70 MW to 71 MW. The change is executed with a ramp over 250 seconds, providing valuable data on the system's dynamic response to varying heat inputs.

4.4.2 Changes in heat flow and mass flow

Throughout the project, modifications have been made to the heat flow in the boilers and the mass flow in the pump. Both variables have significant impacts on the results and allow for the study of dynamic behavior. For this reason, once a model with two parallel boilers and a pressure drop of 100 kPa after each boiler is obtained, it was decided to repeat these simulations and make comparisons between them.

In the case of modifying the heat flow, a ramp function was employed to gradually increase the heat flow over 500 seconds to the desired limit. This approach ensures a smooth transition and helps in observing the system's gradual response to changes. Initially, each boiler receives a heat flow source of 70 MW. To investigate the impact of incremental increases in heat flow, three simulations were conducted where the heat flow in one of the boilers was increased to 70.5 MW, 71 MW, and 71.5 MW. These variations help in understanding how slight changes in heat input can affect the overall system performance.

For modifying the mass flow, while a step signal could have been used, a ramp function over 500 seconds was chosen to maintain consistency with the heat flow modification and to allow for a more gradual adjustment. The initial mass flow rate is set at 50 kg/s. This value was then reduced in the simulations to examine the effects of decreased flow rates. The rationale behind reducing the mass flow is based on the principle that a greater pressure difference in a centrifugal pump typically results in a lower mass flow rate. By decreasing the mass flow to 49 kg/s, 48 kg/s, and 47 kg/s, the simulations aimed to reveal how lower mass flow rates impact the system.

Chapter 5

Results

The following sections present the main results of the project. All simulations start from a steady state. In cases where simulations are compared between models or different pressure drops, the comparisons are made in the context of an increase in heat flow. This approach ensures consistency and allows for a clear understanding of the system's dynamic responses. Additionally, the results highlight the system's stability, performance, and efficiency under varying operational conditions.

5.1 Comparison between single and dual boiler models

Initially, to compare the response between the single boiler model and the dual boiler model with pressure drop (100 kPa), the system's reaction to a step signal applied to the heat flow source of one of the boilers was studied. Specifically, the step signal changes from 70 MW to 71 MW at 100 seconds into the simulation. Unfortunately, the simulation fails at 136.14 seconds, indicating that the internal energy of one of the boilers has exceeded the limit of the two-phase fluid domain, which is 4000 kJ/kg.

As shown in Figure 5.1, at the moment the step function is applied, the mass flow in the affected boiler exits through both ports instead of having a distinct inlet and outlet. Consequently, this response leads to an uncontrolled increase in internal energy. Moreover, Figure 5.2 illustrates the response in the mass of the boiler receiving the increased heat flow within 70 milliseconds after the step function is applied. The derivative clearly shows a significant variation in a short time in the mass balance of the system, which forces substantial changes in the mass flow. This drastic change highlights the instability and the challenges of maintaining a balanced flow when transitioning from a single to a dual boiler setup under sudden changes in heat input.

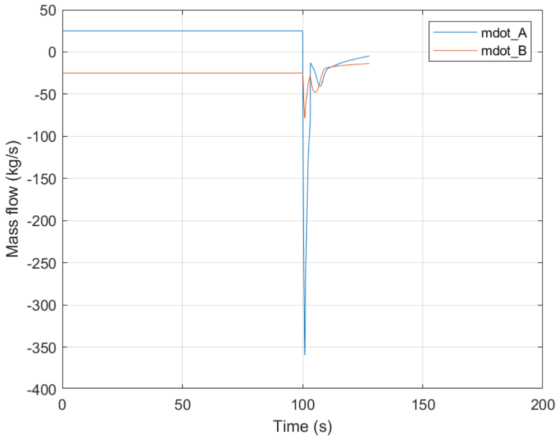
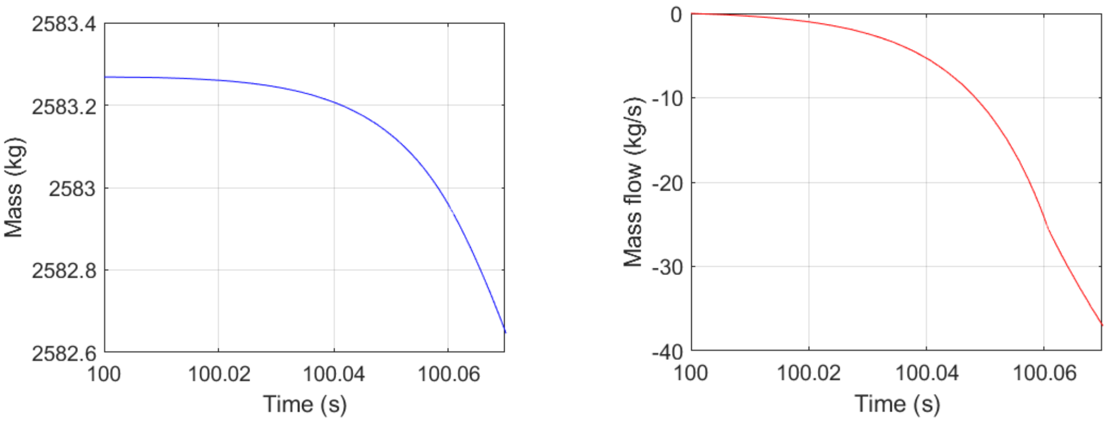


Figure 5.1: Mass flow error in two boilers model when step function is applied: The figure illustrates $\dot{m}_{\mathrm{A}}$ (mass flow at the port intended as the boiler inlet) and $\dot{m}_{\mathrm{B}}$ (mass flow at the port intended as the boiler outlet).



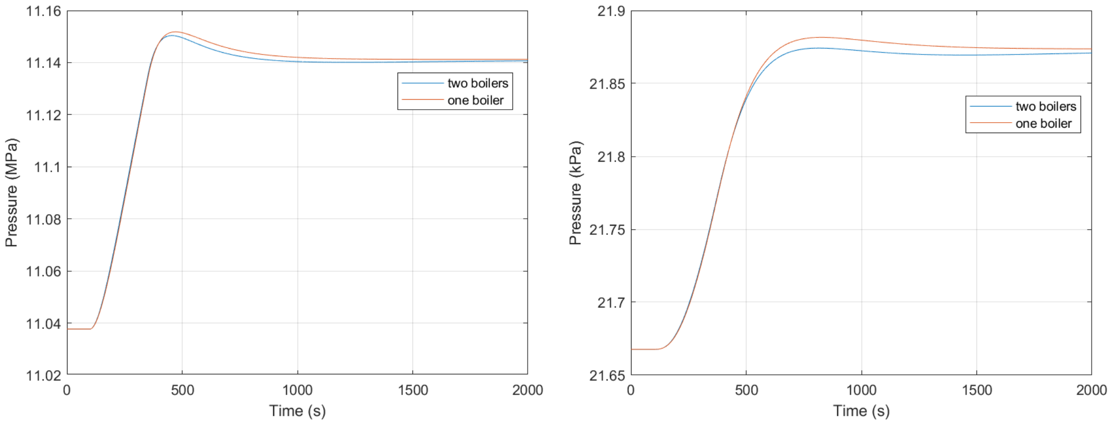
(a) Mass in the boiler receiving the step function

(b) Mass derivative

Figure 5.2: Mass and mass flow response of boiler receiving the step heat input in two boilers model: (a) Mass of the boiler as a function of time after receiving a step heat input, illustrating the system's dynamic response; (b) Derivative of the boiler mass representing the change in mass flow over time.

Next, a ramp signal was applied to compare the models more effectively. In the case of a single boiler, the ramp increases the heat flow from 140 MW to 141 MW, while in the case of two boilers, the ramp is only applied to one of them, modifying the heat flow from 70 MW to 71 MW. Both ramps have an ascent duration of 250 seconds and begin 100 seconds after the start of the simulation.

Figure 5.3 shows the main pressures in the system: the pressure before the turbine, which corresponds to the boiler pressure, and the pressure after the turbine, which corresponds to the condenser pressure. As can be seen in the figures, there is no significant difference in the responses, although it appears that the model with two boilers has a slightly slower response.



(a) High pressure steam cycle

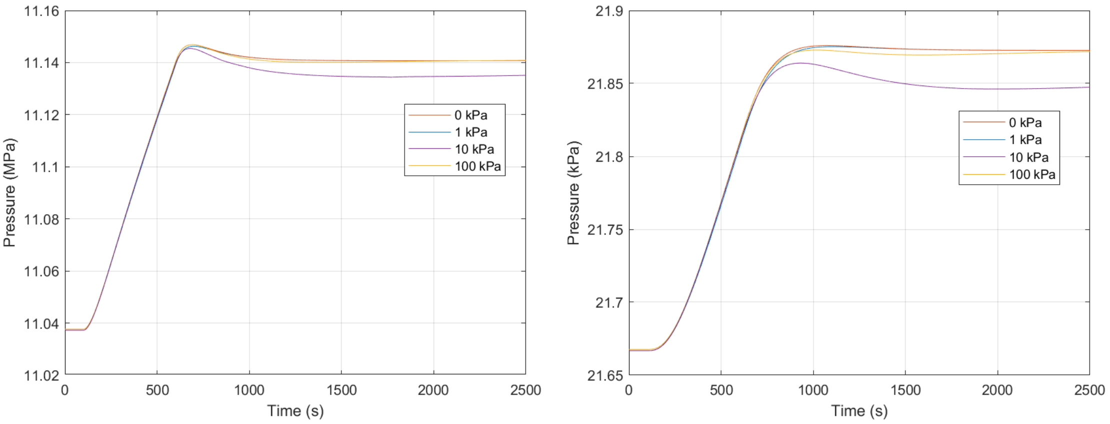
(b) Low pressure steam cycle

Figure 5.3: Pressure analysis in the steam cycle with single and dual boilers in response to a ramp heat flux signal:(a) High pressure within the boiler, (b) Low pressure within the condenser.

5.2 Impact of pressure drop

To investigate the effect of pressure drop on the system's performance, various simulations were conducted with different nominal pressure drops between the boilers and the turbine. The simulations compared four different nominal pressure drops: 0 kPa, 1 kPa, 10 kPa, and 100 kPa. Each simulation started from a steady-state condition. Afterward, a ramp signal was applied to the heat flow source of one boiler, increasing it from 70 MW to 71 MW over 500 seconds, beginning 100 seconds after the start of the simulation.

The initial results, as shown in Figure 5.4, display the main pressures of the system, both before and after the turbine. As seen in the images, there is barely any difference in response based on the pressure drop. The most notable difference is observed in the case of a nominal pressure drop of 10 kPa, where the values drop below the steady-state values. Although the figure only shows the first 2500 seconds of the simulation, it is worth noting that the simulations were run for a total of 5000 seconds. Over this extended period, the values eventually rise again, reaching the same results as in the other cases. This outcome will be explained with the following images.

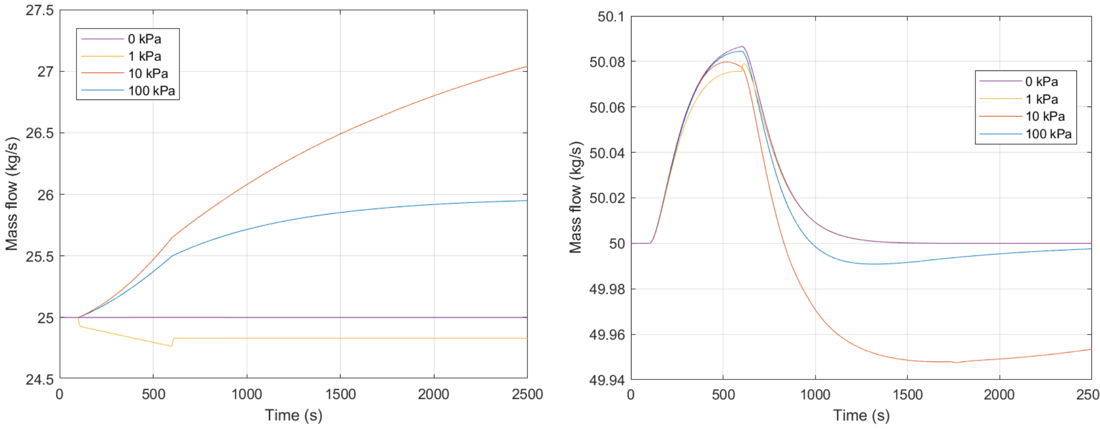


(a) High pressure before the turbine **(b)** Low pressure within the condenser

Figure 5.4: Pressure analysis with pressure drop between the boilers and the turbine

The results indicate that, in general, the overall system does not suffer a significant impact due to the pressure difference. Instead, the differences arise within the subsystem formed by the two boilers operating in parallel. Figure 5.5a shows the mass flow entering the boiler receiving the ramp signal, considering that the response in the other boiler is complementary since the mass flow set by the pump is 50 kg/s. It can be observed that the response varies for each pressure difference but does not have a direct relationship. Specifically, when a small pressure drop (1 kPa) is introduced, the mass flow entering this boiler decreases. If the pressure drop is increased slightly more (10 kPa), the maximum values are obtained, and with a 100 kPa drop, the mass flow increases but not as much as in the previous case. Therefore, the final response does not have a direct correlation between pressure difference and mass flow. Additionally, the response before reaching the steady-state value does not follow the same pattern.

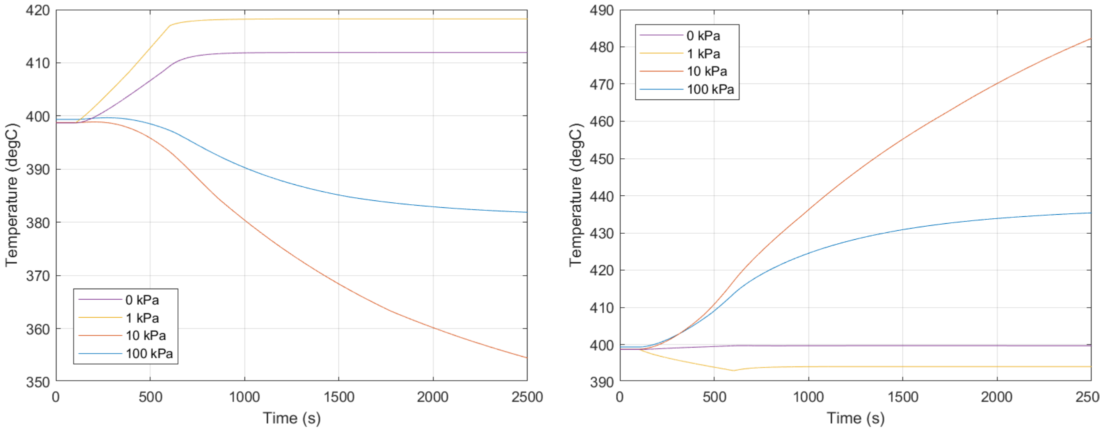
Despite the differences in the distribution of mass flow at the boiler inlets, the total steam generated by the two boilers is similar across the different cases. Figure 5.5b shows the steam entering the turbine, which is the combined steam generated by both boilers. It can be seen that as the heat flow increases, more steam is generated, but once the heat flow stabilizes, the mass flow must return to 50 kg/s, which is set by the pump. Furthermore, there is a tendency for the mass flow to decrease below the steady-state value before stabilizing when there is a higher pressure difference. In the 10 kPa case, it decreases much more, explaining why the pressure response in Figure 5.4 also dropped before stabilizing.



(a) Inlet mass flow in boiler with increased heat flow **(b)** Combined mass flow entering the turbine

Figure 5.5: Comparison of mass flow behavior with pressure drop simulations

In Figure 5.6, more results from these simulations are shown, this time graphing the temperatures inside the two boilers. In no case do the temperatures exceed the temperature limit imposed at the turbine inlet (540ºC). Additionally, it can be seen that the 10 kPa case has the widest temperature range, achieving both the highest and lowest temperatures among the different cases. The highest temperature is obtained in the boiler with constant heat flow, with values between 480 and 490ºC, while the lowest temperature is observed in the boiler with increased heat flow, reaching temperatures between 350 and 360ºC.



(a) Temperature in boiler with increased heat flow **(b)** Temperature in boiler with constant heat flow

Figure 5.6: Temperature comparison in boilers with pressure drop simulations

To better understand these results, Table 5.1 shows the response of certain properties in the two boilers under different pressure drop scenarios.

- **No Pressure Drop (0 kPa):** The mass flow remains constant, but the pressure increases due to the increased heat flow in one boiler. This pressure increase impacts the second boiler, which, while maintaining constant mass flow, compresses the fluid as the specific volume decreases, resulting in increased temperature and internal energy.

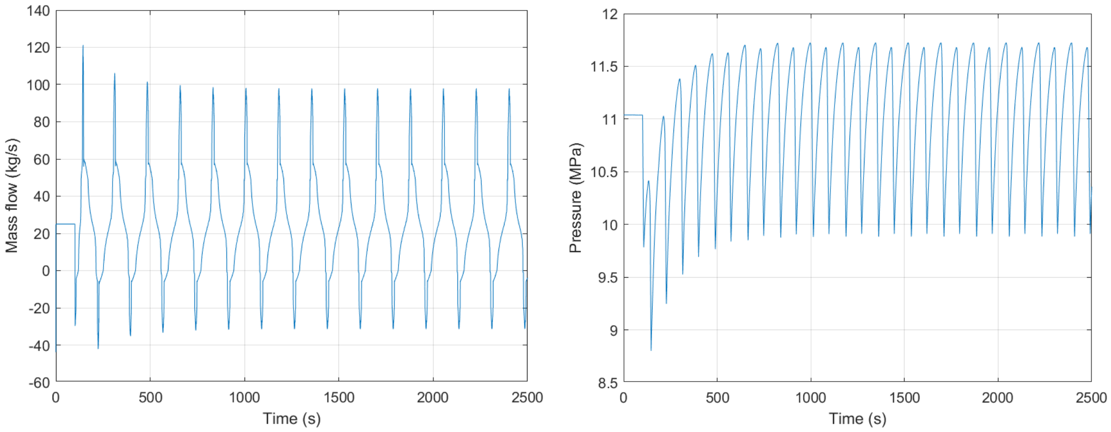
- **Small Pressure Drop (1 kPa):** The system responds by increasing the mass flow in the boiler with increased heat flow, consequently decreasing the mass flow in the other boiler. The relationship between heat flow and mass flow means that with constant heat flow and increased mass flow, the energy transferred per unit mass decreases, reducing all properties. Conversely, if the heat flow increases and the mass flow decreases, the properties increase even more.
- **Moderate Pressure Drop (10 kPa):** The system shows the opposite response in mass flow distribution and properties compared to the 1 kPa case. The mass flow in the boiler with increased heat flow rises significantly, reducing the other properties, while in the other boiler, the mass flow decreases, leading to an increase in its properties.
- **High Pressure Drop (100 kPa):** The mass flow increases in the boiler with increased heat flow, but not as much as in the previous case, leading to different changes in properties.

These results demonstrate that there is more than one way to balance the subsystem formed by the two boilers to achieve the same response at the turbine inlet.

Table 5.1: Modifications of properties in each boiler in response to a pressure drop: The table displays changes in pressure (p), inlet mass flow($\dot{m}$), specific volume (v), internal energy (u), and temperature (T) indicated by + (increase), - (decrease), and = (no change).

	Boiler 1 (Q ↑)					**Boiler 2 (Q = cte)**				
	p	$\dot{m}$	**v**	**u**	**T**	**p**	$\dot{m}$	**v**	**u**	**T**
Δp = 0 kPa	+	=	+	+	+	+	=	-	+	+
Δp = 1 kPa	+	-	+	+	+	+	+	-	-	-
Δp = 10 kPa	+	++	- -	- -	- -	+	- -	++	++	++
Δp = 100 kPa	+	+	-	-	-	+	-	+	+	+

Additionally, another simulation was conducted to study the difference in responses between simulations with a nominal pressure drop of 1 kPa and 10 kPa. The simulation conditions remained the same, except the nominal pressure drop was set to 2 kPa. As shown in Figure 5.7, the response is completely oscillatory and does not correlate with the previous simulations. In the left figure, the mass flow at the port acting as the inlet to the boiler receiving more heat flow is represented. It can be seen that this port oscillates between behaving as an inlet with positive values and as an outlet with negative values. In the right figure, the pressure before the turbine is shown. Unlike the previous simulations, this time it is affected by the oscillatory response in the mass flow distribution, reaching values both lower and higher than those in the other simulations, approximately between 9 MPa and 11.5 MPa.



(a) Mass flow at boiler inlet with increased heat flow

(b) Pressure at turbine inlet

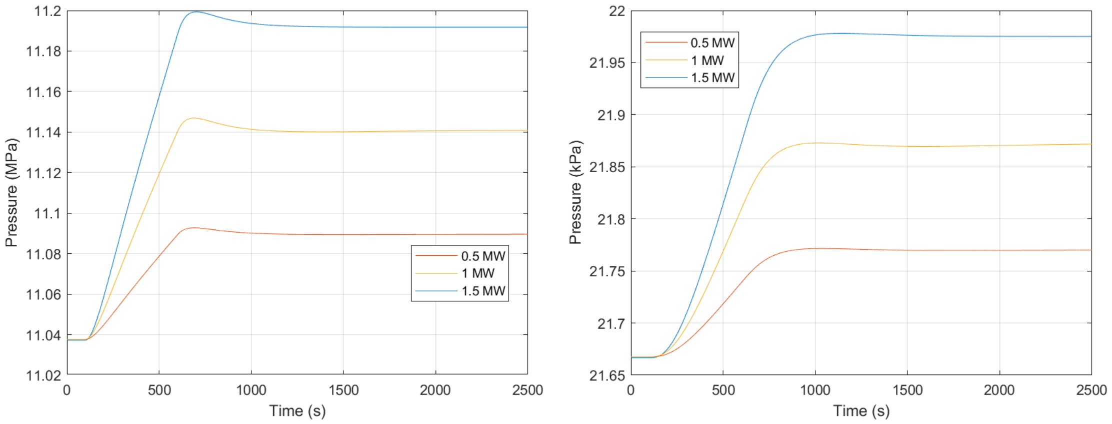
Figure 5.7: Simulation results with a nominal pressure drop of 2kPa

5.3 Effects of heat flow and mass flow variations

It was considered convenient to conduct simulations with varying heat flow and mass flow inputs to better understand the dynamic behavior of the system. These variations allow for an assessment of how changes in these key parameters impact the overall performance and stability of the system.

In the case of heat flow, three simulations were conducted starting with 70 MW in each boiler and increasing to 70.5 MW, 71 MW, and 71.5 MW in one of the boilers. As observed in other results, applying a step function to the heat flow tends to cause errors in the simulation. Therefore, the increase in heat flow needs to be gradual, achieved using a ramp. This ramp lasts 500 seconds in all cases to allow for comparison of the results, considering that the slope can also affect the outcomes.

The results of the simulations as a function of increased heat flow are shown in Figure 5.8. As expected, the pressure increases both before and after the turbine since there is more energy per unit mass. It is also observed that in the case of a 1.5 MW increase, the overshoot before reaching steady state is more pronounced in the pressure before the turbine.



(a) Pressure before the turbine

(b) Pressure after the turbine

Figure 5.8: Simulation results with increased heat flow

Additionally, examining the mass flow distribution in these simulations (Figure 5.9), it can be seen that when the heat flow increment is greater, the mass flow distribution is reversed. In the first two cases, the mass flow in the boiler receiving the increased heat flow rises, while in the last case with a 1.5 MW rise, the mass flow decreases in this boiler and increases in the boiler with constant heat flow. This again shows the peculiar behavior of mass flow distribution previously observed in the pressure drop cases.

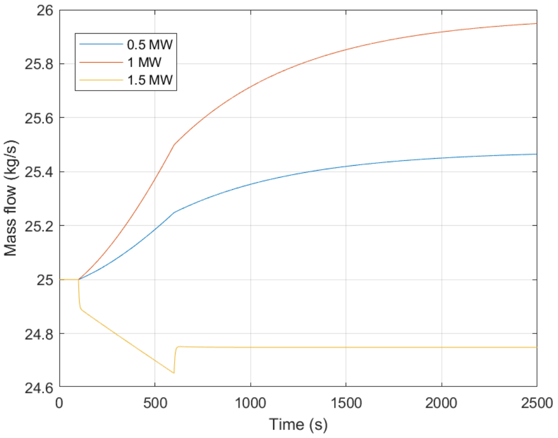
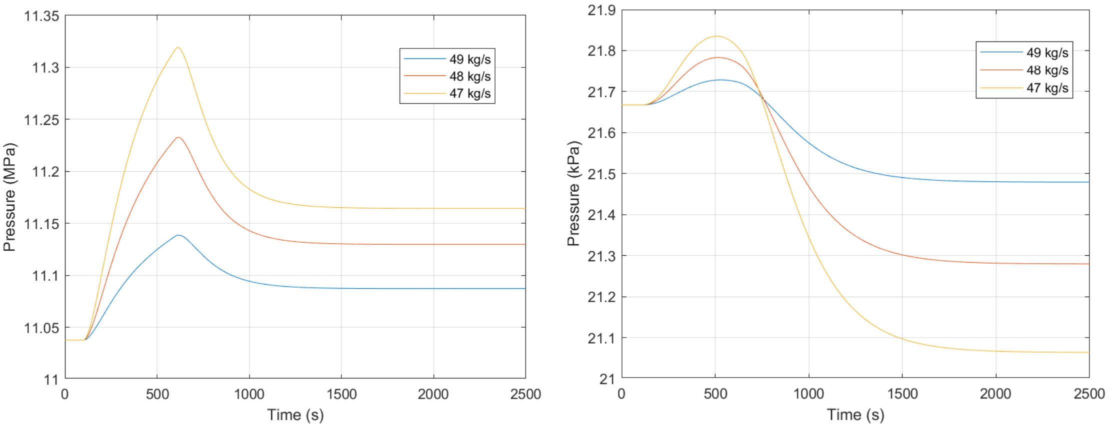


Figure 5.9: Mass flow at the boiler inlet with increased heat flow for various heat flow increments.

Given the significant impact on mass flow in the different simulations, a comparison using mass flow as the variable was performed. Three simulations were conducted, changing the mass flow from an initial value of 50 kg/s, with a 500-second ramp to lower the value to 49 kg/s, 48 kg/s, or 47 kg/s. The ramp is the same as in the heat flow increase cases to allow for subsequent comparison. All cases were conducted with a constant heat flow of 70 MW for each boiler.

In Figure 5.10, the response of the main system pressures in these cases is shown. The pressure before the turbine increases primarily while the ramp function is active, but when the mass flow value stabilizes, this pressure decreases until reaching a steady state, which has a higher value when the mass flow is lower. There is a significant impact on the pressure overshoot before stabilizing, which is even more pronounced as the mass flow is reduced. In contrast, the response of the pressure after the turbine first increases and then decreases to a greater extent, reaching values lower than the initial state. The range of values is larger when the mass flow is diminished, so the 47 kg/s case has the highest and lowest pressure values in the condenser.



(a) Pressure before the turbine

(b) Pressure after the turbine

Figure 5.10: Pressure analysis with pressure drop between the boilers and the turbine

Finally, Table 5.2 presents the results of the mechanical power generated in the different simulations based on heat flow and mass flow. Initially, with 70 MW in each boiler and a mass flow of 50 kg/s, 32.51 MW of mechanical power is generated, corresponding to a system efficiency of 23.22%. As expected, the mechanical power increases when the heat flow is elevated or when the mass flow is lessened. The most surprising result is that the gain in mechanical power is double when the mass flow is reduced by 3 kg/s (47 kg/s) compared to increasing the heat flow by 1.5 MW (71.5 MW and 70 MW). This result highlights the importance of studying mass flow in this system and the potential to reach a more efficient optimal point.

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Table 5.2: Mechanical Power and Gain for different heat flux and mass flow.

		Mechanical Power (MW)	**Gain (MW)**
Initial values	70 MW and 50 kg/s	32.51	
Heat flow	70.5 MW	32.72	0.21
	71 MW	32.93	0.42
	71.5 MW	33.14	0.63
Mass flow	49 kg/s	32.90	0.39
	48 kg/s	33.31	0.81
	47 kg/s	33.76	1.25

Chapter 6

Discussion

6.1 Scope of results

This study aimed to explore the dynamic behavior of a steam cycle system with varying configurations and input conditions. By conducting simulations with different setups, including single and dual boiler models, and varying heat flow and mass flow inputs, we sought to understand the key factors influencing system stability and performance. The following conclusions summarize the primary findings and their implications for the design and operation of such systems.

One of the key findings is that the model becomes unstable when an additional boiler is added in parallel. This instability is particularly evident when step functions are applied, leading to significant fluctuations in internal energy and mass flow, which ultimately cause simulation failures. The introduction of a second boiler complicates the system's response, as the mass flow distribution between the boilers becomes unpredictable and highly sensitive to changes in heat flow and pressure drops.

Another crucial aspect highlighted by the results is the impact of mass balance within the boilers and the condenser on the simulation's stability. The equation governing the mass balance equates the derivative of the mass inside the tank to the mass flow at the inlet and outlet. This relationship generates complexities when step functions are applied, as abrupt changes in mass flow lead to transient imbalances that the system struggles to stabilize. This issue underscores the importance of carefully managing mass flow rates to maintain system stability, especially when dealing with dynamic inputs.

The role of mass flow has been shown to be pivotal in all simulations conducted. Variations in mass flow not only affect the distribution of energy within the system but also have a profound impact on pressure and temperature profiles. Although the difference in mass flow distribution with two boilers does not exceed 10%, as seen in the scenario with a pressure drop of 10 kPa, where one boiler has 27 kg/s and the other 23 kg/s, the impact on the properties inside the boilers is greater than expected, potentially creating critical situations. Additionally, the simulations revealed that reducing the mass flow leads to a substantial increase in mechanical power generation, significantly enhancing system efficiency.

It is also important to consider the limitations inherent in the simplified model used for simulation. The model, while effective for illustrating general trends and behaviors, does not capture all the complexities of a real-world system. Factors such as detailed fluid dynamics, precise heat transfer mechanisms, and potential nonlinearities in the system's response are not fully accounted for in the simplified approach. Furthermore, it has been observed that adding conditions such as pressure drop leads to system instability and unpredictable responses. These responses can be due to physical, numerical, or simulation reasons, highlighting the need for a more thorough study of the system. This would help determine whether the random response of the system corresponds to reality or if it can be better adjusted by adding more equations or descriptive variables.

In conclusion, the study has demonstrated that adding a second boiler introduces significant instability, primarily due to complexities in mass flow distribution. This instability is influenced by the mass balance equations, which are crucial in system dynamics, and abrupt changes in mass flow can exacerbate this issue. Moreover, the simulations showed that the distribution of mass flow between the two boilers is one of the main variables affected in the system, and optimizing mass flow significantly enhances efficiency. However, the simplified model used in this study does not capture all real-world complexities, such as detailed fluid dynamics and precise heat transfer mechanisms. Therefore, future work should incorporate detailed simulations and experimental validations to improve the accuracy and applicability of these findings.

6.2 Simulator selection

The selection of the simulation tool was a crucial decision for this project. Initially, there was a lack of familiarity with the chosen tool, which introduced several limitations and challenges that impacted the project's timeline and the accuracy of the solutions obtained. Throughout the process, it became evident that certain characteristics of the simulation tool posed significant obstacles, which are discussed in detail below.

One of the most critical limitations was the initialization of variables. If the initial values do not converge, the simulation fails to start, making it impractical for studying scenarios without real data, as is the case here. This issue resulted in errors due to inaccurate initial variables, which slowed the project's progress and affected the solution.

Another significant challenge was dealing with variables such as specific volume and void fraction, which are crucial to the simulation. These variables are on the order of $10^{-}3$, meaning they are very small. The system struggled to simulate with a relative and absolute error that includes these values because there are many variables to consider. The accuracy required for these small values increased the complexity of achieving reliable results.

Lastly, the model demonstrated a high sensitivity to small variations, indicating that even minor changes could significantly impact the results. This sensitivity suggests that it might be necessary to consider a different simulation platform that is more robust and better suited to handle such conditions. A more comprehensive and adaptable simulation tool could potentially provide more reliable outcomes and improve the overall efficiency of the project.

6.3 Future work

The current study has highlighted several areas that require deeper investigation and improvement to address the limitations and challenges encountered. Expanding the scope of research to include more detailed analyses and experiments will help refine the model and achieve more reliable results. The following suggestions were initially considered during the project, but their implementation required more time than was available, so they should be prioritized in future work.

One promising area for future research is to investigate how the system's response varies with smaller intervals of pressure drop. As observed in the results, the system exhibits unpredictable behavior when subjected to a series of nominal pressure drops. By using more granular pressure drop values, it would be possible to gain a clearer understanding of the system's sensitivity and stability. Furthermore, examining the impact of initial values on the system's performance could offer valuable insights for optimizing the initialization process, thereby avoiding errors and ensuring smooth simulations. This could involve testing various initial conditions and assessing their effects on the overall system performance.

Additionally, it may be necessary to consider the option of creating custom components instead of using those provided in the software libraries. By developing custom components, it would be possible to define specific equations or simulation conditions more accurately. For instance, setting initial values for variables to be used only at the initial instant and not as a reference throughout the simulation could lead to more precise results. Custom components could also allow for more flexibility in modeling complex interactions and behaviors that are not well represented by standard library elements.

Incorporating a centrifugal pump into the model would also make the simulation more realistic. This approach would allow the study of the impact of mass flow that depends on pressure, providing a more accurate representation of real-world conditions. Understanding how a centrifugal pump influences the system could reveal important insights into the dynamic behavior and efficiency of the cycle. This addition would help in examining scenarios that closely mimic actual operational conditions.

Furthermore, exploring the use of different simulation software could be beneficial, although it would first require learning how to use the new software effectively. Adopting a new platform might offer advanced features and greater flexibility, but it comes with the challenge of a learning curve and the need to adapt existing models to new environments.

Overall, these areas represent promising directions for future research to improve the simulation model's accuracy, reliability, and applicability. Addressing these aspects will contribute to a better understanding of the system and support the development of more effective and efficient solutions for real-world applications.

Bibliography

[1] The MathWorks, Inc., *Simscape user's guide*, R2024a, The MathWorks, Inc., 2024. [Online]. Available: https://www.mathworks.com.

[2] H. N. Michael J.Moran, *Fundamentos de termodinámica técnica*. Reverte, 2004.

[3] B. S. Ansermet JP, *Principles of Thermodynamics*. Cambridge University Press, 2019.

[4] Y. Çengel, M. Boles and M. Kanoglu, *Thermodynamics: an engineering approach*, 9th ed. McGraw-Hill Higher Education, 2020.

[5] M. Kaufman, *Principles of Thermodynamics*. Marcel Dekker,Inc., 2002.

[6] S.P.Venkateshan, *Heat Transfer*, 3rd ed. Springer Cham, 2021, ISBN: 9783030583385.

[7] T. Bergman, A. Lavine, F. Incropera and D. DeWitt, *Fundamentals of Heat and Mass Transfer*, 8th ed. Wiley, 2020, ISBN: 9781119722489. [Online]. Available: https://books.google.se/books?id=6piuzQEACAAJ.

[8] G. Visconti and P. Ruggieri, *Fluid Dynamics: Fundamentals and Applications*. Springer International Publishing, 2020, ISBN: 9783030495626.

[9] F. White, *Fluid Mechanics*, 7th ed. McGraw-Hill Education, 2011.

[10] The MathWorks, Inc., *Simscape getting started guide*, R2024a, The MathWorks, Inc., 2024. [Online]. Available: https://www.mathworks.com.

[11] The MathWorks, Inc., *Simscape language guide*, R2024a, The MathWorks, Inc., 2024. [Online]. Available: https://www.mathworks.com.

[12] The MathWorks, Inc., *Simscape reference*, R2024a, The MathWorks, Inc., 2024. [Online]. Available: https://www.mathworks.com.

[13] The MathWorks, Inc., *Simscape fluids reference*, R2023b, The MathWorks, Inc., 2024. [Online]. Available: https://www.mathworks.com.

[14] S. Dixon, *Fluid Mechanics and Thermodynamics of Turbomachinery*, 4th ed. Butterworth-Heinemann, 1998.

[15] D. Cooke, "Modeling of off-design multistage turbine pressures by stodola's ellipse," *Journal of Engineering for Gas Turbines and Power*, vol. 107, pp. 596–606, 1985.

[16] SMR Regulators' Forum, "Pilot project report: Considering the application of a graded approach, defence-in-depth and emergency planning zone size for small modular reactors," International Atomic Energy Agency, Tech. Rep., 2018. [Online]. Available: https://www.iaea.org/sites/default/files/18/01/smr-rf-report-29012018.pdf.

[17] Siemens Energy. "Industrial steam turbines." (2024), [Online]. Available: https://www.siemens-energy.com/global/en/home/products-services/product/industrial-steam-turbines.html#Description-tab-4.

[18] SHINKO IND.LTD. "Standard centrifugal pumps." (2024), [Online]. Available: https://www.shinkohir.co.jp/pdf/catalog/Centrifugal_Pumps_CL-100D.pdf.