

THESIS WORK FOR DUAL MASTER'S DEGREE

ITBA Mag. in Energy and Environment

KIT M.Sc. in Mechanical Engineering

DESIGN OF A MONIKA-ORC-TURBINE MODEL IN SIMULINK AND COMPARISON WITH EXPERIMENTAL RESULTS

Julia Filipe

Materials Engineer

Universidad Nacional de La Plata

Tutor

Prof. Dr.-Ing Thomas Schulenberg

Co-Tutor

Dipl.-Ing Hans-Joachim Wiemer

Examiners

Dr.-Ing Thomas Schulenberg

Prof. Dr.-Ing. Andreas Class

Declaration by the author

I declare that I have written this Master Thesis independently and that the bibliography and work of others is completely and clearly referenced in the text. All the words taken from others, unchanged or with modifications, are accurately cited. This Master Thesis was written as a closing final work for the corresponding KIT degree, and was not used in the same or in a similar version to achieve other academic grading nor to be published elsewhere.

Karlsruhe, May 2022

Julia Filipe

Acknowledgement

In these few lines, I would like to express my gratitude to the people that helped me along the way to achieve this objective. First of all, I am sincerely grateful for the opportunity of doing my master thesis under the direction of Thomas Schulenberg and Hans-Joachim Wiemer. Working with them was a truly enriching experience for me.

I also want to say a huge thank you to Cecilia Smoglie and to Ferdinand Schmidt, who are key parts in making this amazing opportunity to become real.

Following, I want to express my complete gratitude to Joaquin Mardon Pérez, it was a great experience to work alongside with him; and to Juan Ignacio Giménez. Their support and encouragement made me go way further than I had ever imagined at the beginning of this journey. Also were very important to me Juan F. Gutierrez Guerra, Federico Wagner, Macarena Alvarez and Eugenio Torres de Ritter.

Finally, I want to thank my family and my friends, who have always been by my side.

Abstract

This work consists in the development of a computational model for the steam turbine currently operational in MoNiKa test facility plant, located in KIT-Campus Nord, Germany. Given that this corresponds to the first attempt to model the mentioned turbine, the selected approach was to elaborate a highly simplified model that considers the system as a whole, unique element, and therefore calculates in terms of the turbine's inlet and outlet parameters.

The development was made in Simulink, using a basic configuration of blocks and features, and also some specific parts were coded in MATLAB. The building process resulted firstly in a simplified version of the model that supports constant inputs and outputs and consequently is independent of time; and a final version that supports time-dependent inputs and outputs, and can be employed to simulate transient operation conditions.

The validation was made using real data provided by the plant, with a selection of several cases that reflected different operation conditions. Final results showed that the model is successful in predicting stationary operation cases, and also achieved good results with some transient operation conditions that presented progressive variations. However, the model is not suitable for simulation of fast-varying conditions.

Table of contents

Declaration by the author.....	I
Acknowledgement.....	II
Abstract.....	III
Table of contents.....	IV
List of abbreviations and symbols.....	VI
1. Introduction.....	1
2. Technical background.....	3
2.1 Geothermal energy.....	3
2.1.1 Binary Organic Rankine Cycles.....	3
2.1.2 Supercritical cycles.....	4
2.2 MoNiKa description.....	5
2.2.1 Steam turbine.....	6
2.2.2 Valves and instrumentation.....	8
2.3 Previous work.....	10
2.3.1 GESI.....	10
2.4 Governing equations of the steam turbine.....	11
2.4.1 Energy balance.....	11
2.4.2 Stodola's law.....	14
2.4.3 Heat loss.....	15
3. Model development.....	18
3.1 Initial considerations.....	18
3.2 Model building chronology.....	18
3.3 Model architecture.....	20
3.3.1 Input source.....	23
3.3.2 LookUp tables.....	25
3.3.3 Heat loss calculation.....	26
3.3.4 Stodola equation.....	29
3.3.5 Energy balance.....	30

3.3.6 Post-processing	32
4. Stationary validation & results.....	33
4.1 Stationary model parameters and constraints	33
4.2 Averaged Inputs	34
4.3 Stationary Results.....	35
5. Transient validation & results	38
5.1 Parameters definition and model constraints	38
5.2 Time-dependant inputs	39
5.3 GESI inputs & results.....	40
5.4 Transient Results	43
5.4.1 Steady state operation	43
5.4.2 Transient periods	47
5.4.3 Warm-up effect	52
6. Conclusions	54
7. References	56
8. Annex.....	57
8.1 Table Generator – MATLAB code	57
8.2 Stodola’s law – MATLAB function block code.....	59
8.3 Heat Loss subsystem – Simulink model	60
8.4 Energy Balance subsystem – Simulink model	61
8.5 Stationary Results – Turbine Power	62
8.6 Stationary Results – Turbine inlet pressure	64
8.7 Stationary Results – Turbine inlet Temperature	66
8.8 Time-dependent Results	68
8.8.1 Stationary operation – D1R1 data set	68
8.8.2 Transient periods – D1R7 data set.....	69
8.8.3 Transient periods – D2R11 data set.....	70
8.8.4 Shut-down	72

List of abbreviations and symbols

CP	Critical Point	
CV	Control Valve	
MoNiKa	Modularer Niedertemperaturkreislauf Karlsruhe	
ORC	Organic Rankine Cycle	
REFPROP	Reference Fluid Properties	
A	Area	[m ²]
c	Stodola's correction factor	-
c'	Stodola's correction factor	[kg/s]
c _p	Specific heat	[kJ/(kg·K)]
E	Energy	[kJ]
e	Specific energy	[kJ/kg]
e _k	Kinetic energy	[kJ/kg]
e _p	Potential energy	[kJ/kg]
F	Stodola's design factor	[K·(kg/(s·MPa)) ²]
h	Specific enthalpy	[kJ/kg]
m	Mass	[kg]
\dot{m}	Mass flow	[kg/s]
\dot{Q}	Heat flux	[kW]
\dot{W}	Work rate	[kW]
p	Pressure	[MPa]
P _e	Turbine electric power	[kW]
P _t	Turbine shaft power	[kW]
T	Temperature	[K]
u	Internal energy	[kJ/kg]
v	Specific volume	[m ³ /kg]
w _t	Specific turbine work	[kJ/kg]
α	Global heat transfer coefficient	[kW/(K·m ²)]
η _t	Turbine efficiency	-
λ	Thermal conductivity	[kW/(K·m)]
τ	Time constant	[s]

Subscripts

in	Inlet
out	Outlet
s	Steel
t	Turbine
v	Control Valve
n	n-time step
0	Design Point

1. INTRODUCTION

The worldwide energetic and environmental situation has grown more complex and delicate in the last decades. In the energetic sector, the demand of energy consumption is ever rising, while policies against CO₂ emissions and other substances that promote global warming are getting increasingly restrictive. These facts originate the efforts to optimise existing productive processes and develop new alternatives to environmentally damaging practices.

This search for novel solutions brings the possibility of making use of low temperature (T) heat sources in focus. This gave rise to the development of Organic Rankine Cycles (ORCs) from the classic Rankine cycle, designed to convert this low T heat into electricity. Geothermal energy is one of the main fields of application for these particular cycles, although they can also be considered as an option for generating power from industrial heat waste, and other processes that produce low T heat as a side product.

This master thesis is based on the project called MoNiKa (Modular Low Temperature Cycle Karlsruhe), which is a test facility plant installed by the Institute of Thermal Energy Technology and Safety (ITES) part of the Karlsruhe Institute of Technology (KIT). The facility is located at the KIT's Campus Nord in Eggenstein-Leopoldshafen, Germany. The main objective of MoNiKa is the optimization of low temperature geothermal cycles and thus the increase in efficiency of power generation.

The cycle corresponding to MoNiKa is a supercritical binary ORC that uses propane as its working fluid. The elements that compose the plant are modular and interchangeable, being the central basic components the feed pump and the auxiliary pump, the boiler, the turbine and the condenser. Since MoNiKa is a test facility and not a real geothermal power plant, currently its heat source is warm water that emulates a thermal source. This flux does not proceed from a thermal well, but instead the water is heated in a boiler up to temperatures that recreate water extracted from a thermal source.

This thesis is centred in the study of the steam turbine, which is one of the central components in MoNiKa Power plant, and is responsible for the power generation in the cycle. After heating and evaporating in the boiler, propane expands in the turbine, converting the enthalpy change in kinetic energy. This energy is further transformed into electrical energy in the generator and injected to the local grid.

Technical challenge

There exist several working fluids available to operate an ORC, thus the particular characteristics of the cycle need to be considered for the selection of the substance. This fact,

and the modularity and interchangeability of the components, provide a broad number of possible configurations to define the boundary conditions of the cycle. Consequently, the implementation of each cycle is unique and needs to be studied in particular. After taking general laws and correlations as a starting point, every component of the power plant should be analysed individually.

Taking this into account, the primary aim of this study is to develop a thermodynamic model in Matlab – Simulink that describes the thermodynamic behaviour of the steam turbine used in MoNiKa. This model is to be validated using different load points provided by real run data of the plant, corresponding to the test runs performed in November 2021 and further analysed in Joaquín Mardon Pérez's Master thesis [1], being the value of turbine power the most significant indicator. One of the main objectives is to create a model that is consistent in its outputs, and to obtain results that reflect the real measurements over a wide operating range.

The study of unknown characteristics and the behaviour of the turbine motivate this work. In line with this, another objective is to analyse the turbine efficiency and its dependence with the inputs to the model. Finally, the model is intended to describe and aid the understanding of the phenomena related to the supercritical operation, and to allow the definition of the fluid state at the inlet of the turbine.

The thesis starts with the definition of the fundamental concepts in Chapter 2 that define the problem and give context to the simulating work. Afterwards, the detailed explanation of the procedure followed to create the numeric model is portrayed in Chapter 3. The validation of the model and the consequent results are exposed in Chapter 4 and Chapter 5. Finally, Chapter 6 contains the conclusions to this thesis work and intends to answer the questions formulated above.

2. TECHNICAL BACKGROUND

In this chapter, the origin and fundamentals of the study are portrayed, in order to give an integral frame to the subsequent model. The project and the technical challenge are described from a technological perspective, and the mathematical outline is defined.

2.1 Geothermal energy

Geothermal energy originates within the inner part of the earth, and is the heat generated by radioactive decay since the formation of the planet. The core of the planet is at around 6000°C , which causes heat to flow continuously towards the surface. In the external layer of the earth, called crust, temperature increases from the outer surface deep into the earth at a rate of approximately $30^{\circ}\text{C}/\text{km}$ [2]. This is the area suitable to be geothermically exploited.

Geothermal energy is growing as an alternative to conventional energy sources. The increasing participation of fluctuating renewable sources in the electric grid, especially solar and wind, create the growing need of base-load power plants that compensate the instability and provide reliable energy. Geothermal energy is not subject to fluctuations and therefore can potentially replace conventional base power sources like nuclear power plants and thermal cycles [3]. The development of this technology allows for the exploitation of resources that can be found extensively in broad regions on Earth.

2.1.1 Binary Organic Rankine Cycles

Organic Rankine Cycles (ORC) are particularly suitable to make use of low temperature geothermal reservoirs as a heat source for power generation. ORCs are designed after traditional Rankine steam cycles, though they use hydrocarbons with low boiling temperature at high pressure as working substance. The ground principle of this kind of cycles is that the substance can reach the vapor state at relatively low temperatures in comparison with traditional steam cycles that employ pressurized water as working fluid. This characteristic enables the heat retrieval from warm sources ($100 - 280^{\circ}\text{C}$ [4]) that present small temperature differences with the ambient, which is a distinctive feature of geothermal sources.

In a binary ORC, the cycle is formed by two systems that exchange exclusively heat between them. As seen in Figure 2.1, thermal water flows from the production well through the open system, rejecting heat to the working substance in the boiler (evaporator), and is returned in the reinjection reservoir. Meanwhile, the working substance circulates through a closed loop, absorbing the heat and expanding in the turbine. This configuration increases the service life of the main components since it prevents scaling due to geothermal water chemistry.

Furthermore, it reduces environmental risks given that the working substance is contained completely within the closed scheme [5].

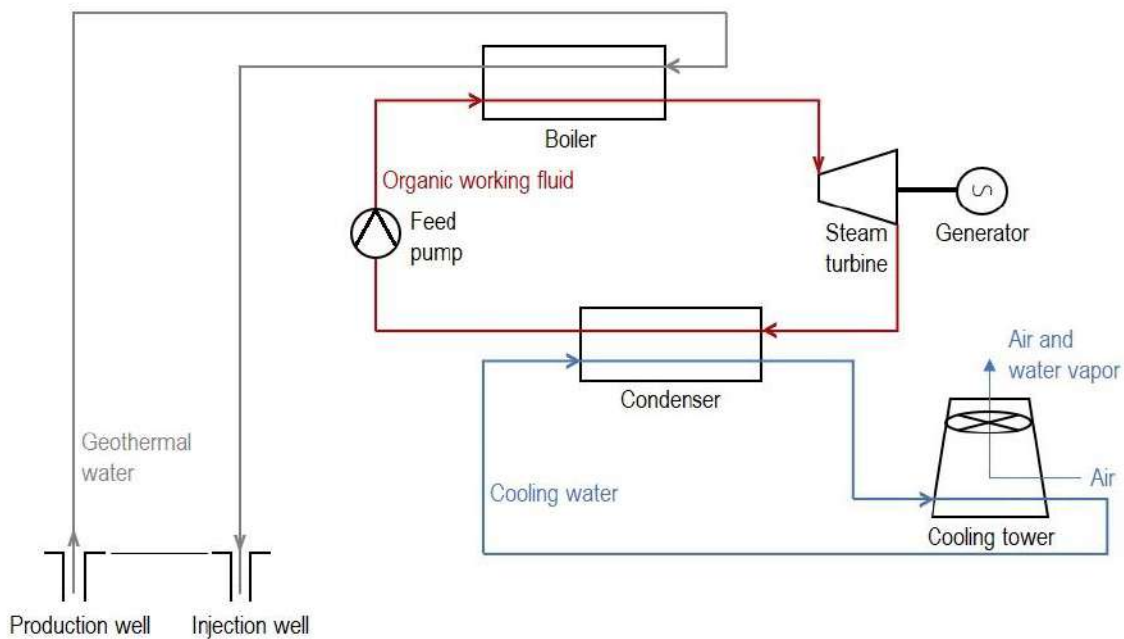


Figure 2.1 Simplified layout of a binary ORC.

In addition to geothermal energy applications, ORCs are also suitable to generate electricity from low temperature sources such as industrial waste heat. This heat is usually available in many industrial processes as a side product, and the coupling with an ORC can be an interesting opportunity for increasing the efficiency of the overall process.

2.1.2 Supercritical cycles

In a supercritical ORC, as seen in Figure 2.2, working fluid is compressed in the feed pump from 1 to 2 and then heated in the boiler up to a temperature and pressure located above the critical point (CP) of the substance, in 3. Therefore, the fluid reaches a state of superheated vapour right before expanding and delivering work in the turbine until 4. The cycle finishes with the removal of heat in the condenser from 4 to 1.

In the supercritical region, the substance does not show a limited phase change from liquid to vapour, thus cannot be defined strictly as liquid nor gas [6]. The main difference with a classic Rankine cycle lies in the process followed by the fluid to reach the superheated vapour state, since in Rankine cycles this is achieved by entering the two-phase region and thus evaporating at a fixed temperature.

The working fluids suitable to be employed in the closed system of a supercritical cycle are hydrocarbons that present a critical point substantially below the one corresponding to water. The main advantage of supercritical cycles is that in the heat exchange process, the thermal

water's cooling curve interacts better with the supercritical heating curve of the organic fluid, compared to the case in which an organic fluid that presents a phase change is used. This leads to a decrease in thermodynamic losses in the heat exchanger [5].

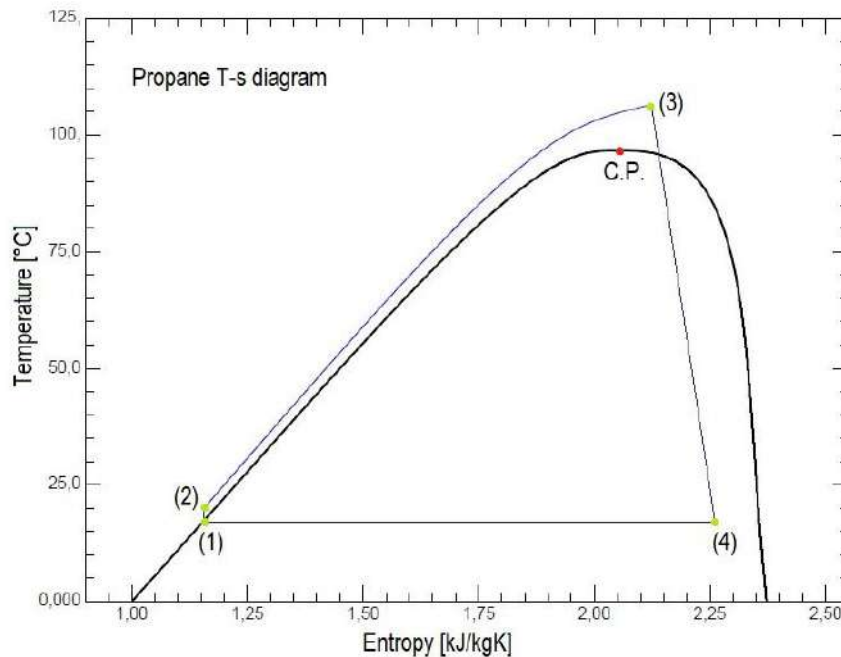


Figure 2.2 Temperature vs. Entropy diagram of a Propane supercritical ORC.

2.2 MoNiKa description

MoNiKa is a scaled pilot plant with a thermal capacity of 1000 kW. The power output is one of the main optimization objectives of the plant, and in current investigations it reaches approx. 100 kW when running at full load. The working fluid used is propane ($\text{CH}_3\text{CH}_2\text{CH}_3$), which shows high thermodynamic performance with very low global warming effects [4].

The propane circulates in a closed piping system, as shown in the scheme of Figure 2.3. Starting the analysis with the cold liquid propane, firstly there is the main piston pump that compresses the fluid and increases its pressure, and is supported by an auxiliary centrifugal pump that also increases the pressure and prevents cavitation issues. The fluid exits the pumping system with a relative design pressure of approx. 5,5 MPa and enters the evaporator. The evaporator consists of a plate heat exchanger in which propane increases its temperature by absorbing the heat provided by the synthetic thermal water. The working fluid exits the evaporator ideally above propane's critical point ($T_{\text{CP}} = 369,89 \text{ K}$; $p_{\text{CP}} = 4,251 \text{ MPa}$ [7]).

The supercritical fluid enters the turbine and undergoes a staged expansion process, thus causing the rotation of the blades and generating kinetical energy. This rotation is transformed to electricity in the generator, which outputs a three-phase current of 400V and is connected to the grid.

At the exit of the turbine, the propane needs to be liquefied in the condenser before restarting the cycle. The condenser installed in MoNiKa uses ambient air as the cooling medium, and is composed of three sets of fans and heat exchangers where the propane circulates. Propane exits the condenser at approx. 20°C (depending on ambient conditions) and flows towards the feed pump so that the cycle starts again.

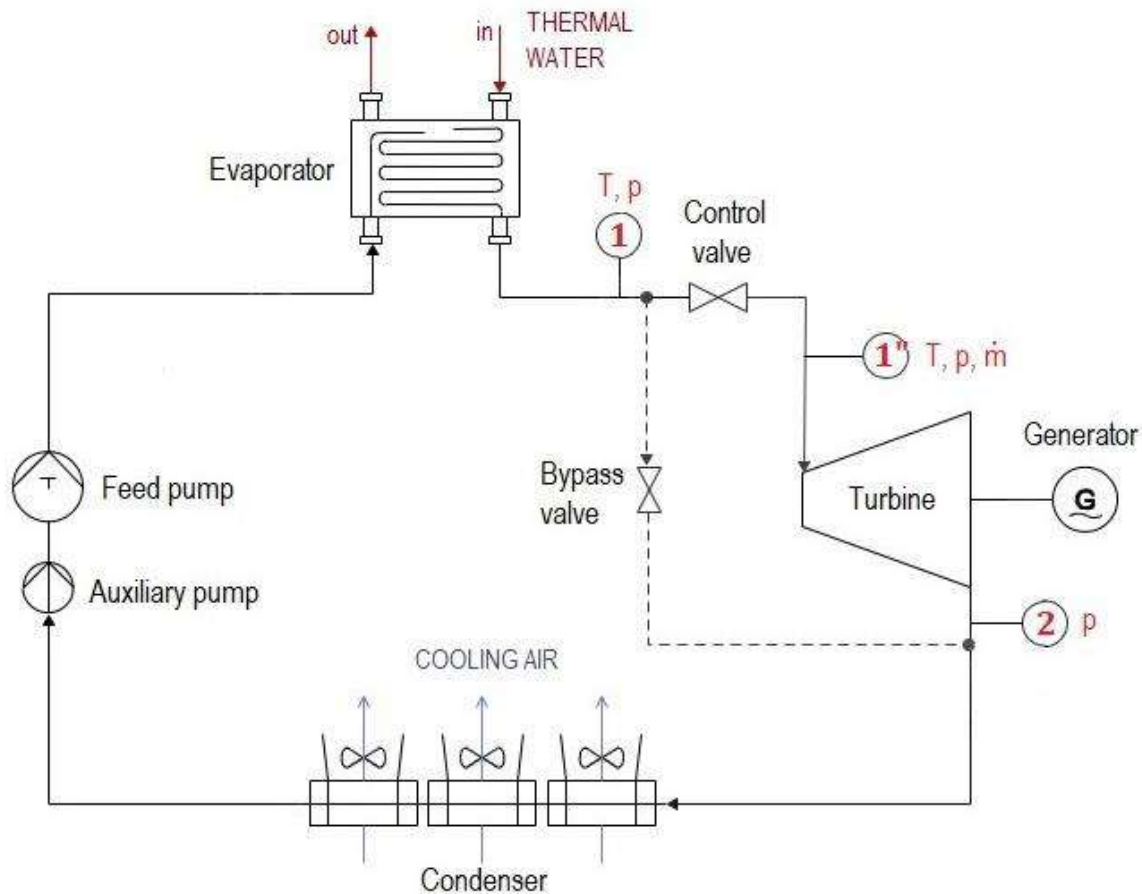


Figure 2.3 Simplified schematic of MoNiKa facility.

2.2.1 Steam turbine

The turbine is the central component studied in this master thesis. It consists of a four-stage steam turbine of constant pressure, specially designed for an ORC with propane as a working substance. Together with the synchronous generator, they conform the electromechanical unit that outputs electrical power, as shown in the scheme of Figure 2.4. The turbine and the generator are connected by the gearbox, which couples the different rotation velocities between them.

The turbine is a model GT 120 – 4 manufactured by M+M Turbinen-Technik GmbH. It is made of welded construction out of several stainless-steel alloys. The most relevant design parameters can be found in Table 2.1. These values correspond to the target projected parameters intended to be achieved during the design stages of the plant. However, in current test runs the turbine parameters actually achieved may differ from these values.

Steam turbine design parameters	
Steam mass flow	2,9 kg/s
Rotor speed	9960 rpm
Turbine inlet pressure of steam (abs.)	5,5 MPa
Turbine outlet pressure of steam (abs.)	1,1 MPa
Turbine inlet temperature	117 °C (390 K)
Power	139 kW

Table 2.1 Design parameters of the turbine as projected in MoNiKa design.

The turbine is basically conformed by a static housing that contains the four stages of guide vanes, and a solid, one-piece rotor composed by the shaft and the corresponding four stages of blades, as seen in Figure 2.5. The blades and vanes form a nozzle configuration through which propane flows. The flow is deflected by the blades, generating a circumferential force that causes the rotation of the shaft, transforming the fluid's enthalpy (associated to the pressure and heat) into kinetic energy.

For the operation of the steam turbine, the addition of nitrogen (N_2) is necessary to serve as a sealing gas. This is supplied to seal the carbon seals and to prevent propane leakage through the case at the turbine bearings on the outlet side. The result is a propane-0,2% N_2 mixture at the outlet of the turbine that must be considered when making calculations that include the composition and properties of the fluid.

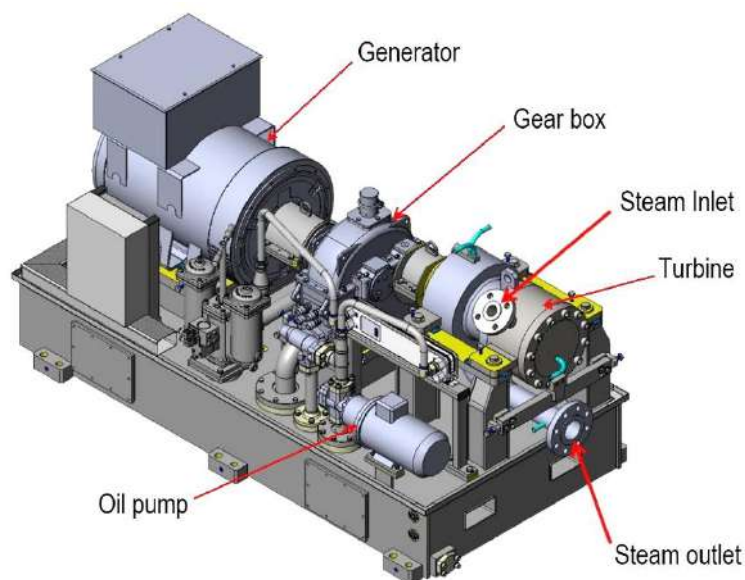


Figure 2.4 Turbine – generator unit [8].

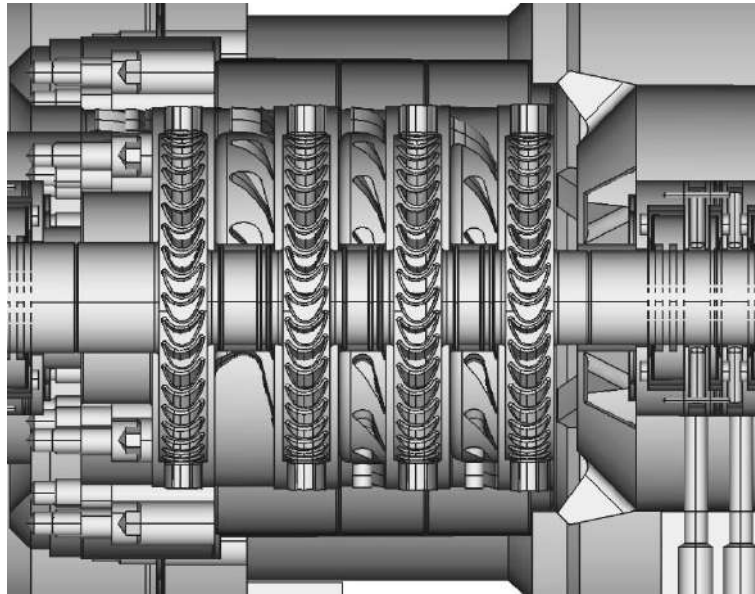


Figure 2.5 Cross-section showing the inside part of the turbine. Rows of blades and vanes are clearly seen [8].

2.2.2 Valves and instrumentation

The facility is equipped with a number of sensors that measure temperature, pressure and mass flow in several parts of the closed propane system. These sensors transmit continuous signals to the control system of the plant, and are fundamental elements when providing the information required for the research purposes of the project. As a counterpart, several valves of different kinds and functions serve as actuators that close the control loop.

The most relevant valves for the study of the turbine are the control valve (CV) and the bypass valve, as found in Figure 2.6. Each valve is paired with a safety valve installed right before, that can be activated during an emergency. The control valve is situated upstream of the turbine inlet and can be assumed to be isenthalpic. The function of the control valve is to regulate the pressure of steam that enters the turbine, while the mass flow is defined by the feed pump.

The bypass valve connects the inlet and the outlet of the turbine, and its function is to redirect the flow and prevent its entrance to the turbine. The bypass valve has a throttling effect, which generates a pressure and enthalpy loss in the fluid. This valve is opened mainly during the warm up of the facility, when propane is still cold and the turbine is not running yet. Besides, due to its throttling effect, this valve offers the possibility to study the cycle without operation of the turbine, since it can simulate the expansion suffered by the fluid through the turbine.

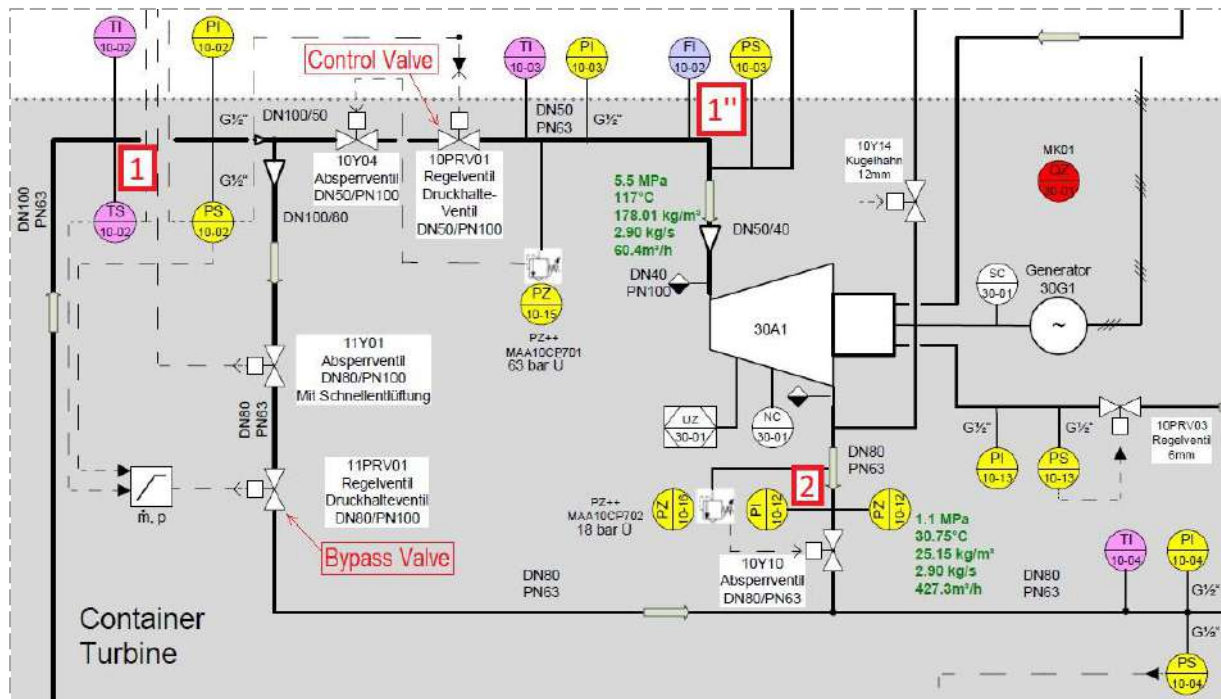


Figure 2.6 Detailed layout showing the relevant sensors numbered as 1, 1" and 2, the control valve and the bypass valve.

As mentioned previously, the instrumentation of the plant is composed of temperature, pressure and mass flow sensors. Because of the research objectives of MoNiKa, there are a relatively high number of sensors compared to an operative power plant. The relevant sensors for this study are shown in Figure 2.6 and numbered as 1, 1'' and 2. Number 1 refers to temperature and pressure sensors situated before the control valve. The sensors numbered as 1'' correspond to a pressure sensor and a mass flow sensor that also measures temperature, both of them installed at the entrance of the turbine. Finally, the sensor number 2 measures pressure at the outlet of the turbine.

From all the sensors shown in the scheme, the signals to be employed as inputs to the model are the temperature and pressure measured in 1 and the outlet pressure obtained by 2. Ideally, the mass flow signal used should be the one measured in 1". However, due to a malfunction of that sensor, the measurement actually used is the corresponding to the sensor located at the feed pump (not shown in the Figure). All other parameters relative to the turbine are modelled and further compared with the real measurements.

Apart from the instrumentation surrounding the turbine, other sensors must be considered. A resistance temperature sensor measures the air temperature outside the facility and provides this input to the model. Another important signal is the electric power measured in the control system of the turbine-generator unit, which is the primary source of information for the validation of the model.

2.3 Previous work

The planning of MoNiKa facility is well described in C. Vetter's doctoral thesis [9], in which the initial design and the dimensioning of the components was made and the operation points were analysed. The facility was built under consideration of these preliminary studies, and afterwards the optimization process began.

During the operative phase of the project, several studies have been carried out so far in order to describe the different components of the plant. Up to date, optimization and modelling studies about the condenser and the evaporator have been performed, but no analysis has been made regarding the turbine. The cycle was primarily studied in bypass operation in order to simplify the overall behaviour of the plant and to reduce the complexity of effects between components by cancelling the influence of the turbine. The modelling of the condenser in bypass operation, developed by M.J. Fossati [10], serves as a central reference work for the guidance of this thesis.

The operation at different load points with the turbine in service was analysed by J. Mardon Pérez [1]. In his thesis, he describes and processes the thermodynamic results obtained for different load points, focused on the turbine behaviour. The development of a Simulink model in this work aims to create a first model of MoNiKa's turbine, that is able to obtain results close to the ones portrayed in his thesis. Therefore, the model developed in this thesis employs these results as a primary source of validation.

2.3.1 GESI

GESI stands for Geothermal Simulation [9], and consist of a MATLAB-based program that has been developed at the Institute for Thermal Energy Technology and Safety (ITES - KIT) for the study and optimization of MoNiKa's ORC thermodynamic process. The program calculus is supported by the REFPROP fluid database, which is a program developed by the National Institute of Standards and Technology (USA). REFPROP calculates the thermodynamic and transport properties of industrially important fluids and their mixtures, and afterwards it displays these properties in Tables and Plots [7].

The GESI software can simulate an ORC Power Plant in stationary regime, with the option of selecting several different working substances. It works with constant inputs and outputs. The primary inputs are the thermal water parameters, the definition of the plant's operational point, the ambient characteristic and the equipment characteristics. After running the program, the outputs that can be obtained are the definition of the thermodynamic states of the ORC distinctive points, and the information related to the power output. In addition, GESI generates several plots that show the cycle.

In this thesis, GESI is used as a comparison tool to contrast against the complete, transient version of the model developed. From the different versions and modules of GESI that have been developed, for this purpose it is used GESI-Rankine Drossel, version 2.3.6, which was programmed considering a throttling valve upstream the turbine that can simulate the conditions caused by the control valve of the turbine.

2.4 Governing equations of the steam turbine

The study of the turbine is based on a thermodynamic approach that considers an energy balance according to the first law of thermodynamics and the relation of the fluid inlet and outlet made by the Stodola's law. In addition, heat transfer equations are needed at the entrance of the turbine.

The defined control volume in which the equations are applied includes the turbine as a whole unit where only the inlet and the outlet have significance. The description of the internal behaviour requires a different approach and the analysis of the phenomena occurring inside the turbine is out of the scope of this thesis.

2.4.1 Energy balance

The general form of the First Law of Thermodynamics states that the change in energy of a flowing system over time is equal to the difference in heat and work exchanged with the surroundings and the change of specific energy of the flowing mass. To analyse an open system a control volume is defined as shown in Figure 2.7. In the case of the system studied, the specified inlet and outlet areas are considered equal to the points 1'' and 2 where the instrumentation is located (Figure 2.6).

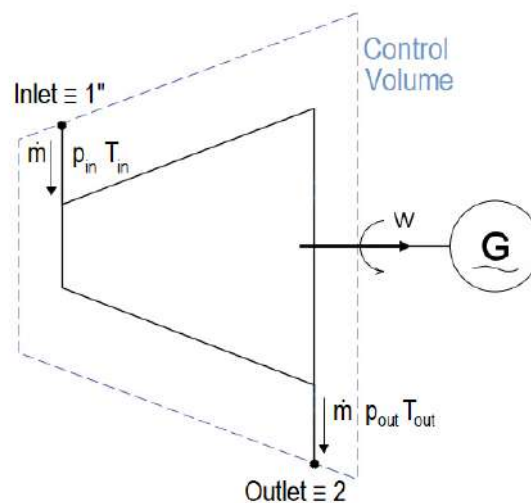


Figure 2.7 Control Volume defined in order to study the turbine.

As a simplifying assumption for this thesis, a quasi-steady-state approach is taken such that the working fluid is considered as incompressible. Consequently, fast pressure waves running

through the turbine will be ignored and only slow changes of temperature, pressure and quality will be modelled, like during warm-up or cool-down processes. Due to mass conservation, the mass flow (\dot{m}) is equal then at the inlet and outlet of the turbine; while pressure, temperature, density and quality of the fluid change from inlet to outlet.

The first law can be expressed as total energy E of the system changing with time according to:

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \dot{m}(e + pv)_{in} - \dot{m}(e + pv)_{out} \quad (2.1)$$

Where \dot{Q} and \dot{W} are heat and work exchanged with the surroundings per unit of time, e is the specific energy, p is the fluid's pressure and v is the specific volume. The product $p v$ is the flow work. Specific energy e can be decomposed in internal energy u , kinetic energy e_k and potential energy e_p , as follows:

$$e = u + e_k + e_p \quad (2.2)$$

Considering also that the enthalpy h is defined as:

$$h = u + p v \quad (2.3)$$

The first consideration made in this analysis is that the process is stationary over time, therefore Eq. (2.1) is equal to zero. Also, if Eq. (2.2) is replaced in (2.1), enthalpy appears explicitly in the energy balance:

$$\frac{dE}{dt} = \dot{Q} - \dot{W} + \dot{m}(h + e_k + e_p)_{in} - \dot{m}(h + e_k + e_p)_{out} = 0 \quad (2.4)$$

The expansion of fluid through a turbine can be assumed to be adiabatic, thus there is no heat exchanged with the ambient, only work provided to the turbine's shaft that causes it to rotate. To further simplify the balance to the particular case of the steam turbine studied, the change of kinetic energy related to the variation in velocity, and in potential energy related to a height difference are insignificant in comparison with the enthalpy change between inlet and outlet of the turbine. Further dividing by the mass flow allows to express the equation in terms of energy per unit of mass. Finally, the balance obtained states that the generated work (w_t) delivered by the turbine is produced by an enthalpy variation between the inlet and the outlet of the control volume.

$$w_t = h_{t,in} - h_{t,out} \quad (2.5)$$

The Eq. (2.5) explains a real expansion through a turbine, in which the inlet and outlet state of the substance must be known in order to calculate the generated work. Another approach can be made to calculate w_t , by considering the ideal isentropic expansion in which no losses occur. Ideal and real processes are related by the isentropic turbine efficiency η_t as follows:

$$w_t = \eta_t (h_{t,in} - h_{t,out,s}) \quad (2.6)$$

Then,

$$\eta_t = \frac{h_{t,in} - h_{t,out}}{h_{t,in} - h_{t,out,s}} \quad (2.7)$$

The turbine work is modelled using Eq. (2.6) by calculating the enthalpy associated to an ideal isentropic expansion. Thereafter the real outlet enthalpy is estimated. Finally, by obtaining the turbine work, the turbine's shaft power (P_t) can be calculated as follows:

$$P_t = \dot{m} \cdot w_t \quad (2.8)$$

The shaft power and the measured electric power (P_e) are related by the gearbox efficiency (η_{gb}) and the generator efficiency (η_{gen}), given by:

$$P_e = \eta_{gb} \cdot \eta_{gen} \cdot P_t \quad (2.9)$$

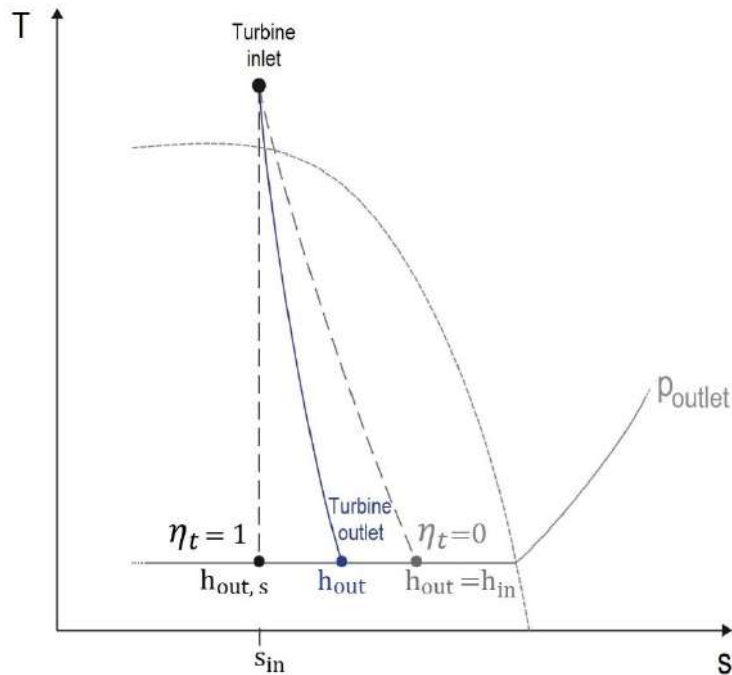


Figure 2.8 T-s diagram showing ideal isentropic expansion, real expansion and isenthalpic expansion.

In Figure 2.8, a graphic explanation of the difference between ideal and real expansion can be observed. An ideal process has no losses, therefore there is no entropy generation, and the efficiency is equal to 1. However, in reality there exist losses through the turbine, and the relation to an ideal case is given by the value of the isentropic efficiency, as stated in Eq.(2.7). On the other extreme, it is shown an isenthalpic expansion in which no work is generated and efficiency is null.

2.4.2 Stodola's law

The Elliptic Law of the turbine, developed by Stodola, is an empirical law that defines the turbine's working line in terms of the mass flow and the inlet and outlet pressures. It can be expressed as follows [11]:

$$\frac{\dot{m}^2}{\dot{m}_0^2} = \frac{(p_{in}^2 - p_{out}^2)}{(p_{in,0}^2 - p_{out,0}^2)} \frac{T_{in,0}}{T_{in}} \quad (2.10)$$

The indices *in* and *out* denote inlet and outlet of the turbine, and *0* stands for Design Point. This equation fixes the relationship between the mass flow circulating through the turbine and the pressure ratio between inlet and outlet. The design point of the turbine is a set of parameters in which the turbine works at its optimal capability.

Stodola's law is a simple equation that describes the turbine as a whole, unique element, in which only inlet and outlet conditions matter for calculus. In this thesis, Stodola is applied as a modelling equation in order to simulate the inlet pressure of the turbine. Even though the equation can be solved to find the outlet pressure, the result in this case is prone to diverge given that p_{out} is dependent on the relation between squared p_{in} and \dot{m} , which show a considerable difference in the order of magnitude ($p_{out}^2 \ll p_{in}^2$).

The design point parameters can be grouped together under a constant factor denoted as *F* that allows the simplification of the Stodola's equation:

$$F = \frac{\dot{m}_0^2 \cdot T_{in,0}}{(p_{in,0}^2 - p_{out,0}^2)} \quad (2.11)$$

Therefore, Eq. (2.10) is reorganized to find the inlet turbine pressure as follows:

$$p_{in} = \sqrt{p_{out}^2 + \frac{\dot{m}^2 T_{in}}{F}} \quad (2.12)$$

Since the Elliptic Law has an empirical origin, it makes sense to correct it by considering the particular behaviour of MoNiKa turbine. The correction of the equation was made by J. Mardon Pérez [1] after studying the results obtained from the running of the plant. The Eq. (2.12) is modified by the addition of two constant factors *c* and *c'*, arriving to the following expression:

$$p_{in} = \sqrt{p_{out}^2 + \frac{T_{in}(\dot{m} - c')^2}{c^2 F}} \quad (2.13)$$

The Eq. (2.13) is the expression employed in the Simulink model of the turbine.

2.4.3 Heat loss

The description of the turbine inlet conditions by the performed measurements prove to be inconsistent with the real behaviour of the fluid, as stated in J. Mardon Pérez thesis [1]. This is originated by the uncertain results obtained when the conditions are in proximity to the critical point of the substance. When this is the case, the enthalpy calculated from the temperature and pressure measured at the turbine inlet (sensors at 1", Figure 2.6) is prone to present high error due to error propagation originated in a small error in T measurement. In consequence, the enthalpy at the turbine inlet, which is a key parameter to model the turbine power, cannot be calculated directly from these measurements at the turbine inlet.

The alternative path followed is to first calculate the enthalpy at the control valve inlet ($h_{v,in}$), where the state of the fluid is known from measurements of T and p , and then estimate the enthalpy at the turbine inlet by assuming that the difference between them is only the heat loss between the points 1 and 1". This calculus is defined by:

$$h_{t,in} = h_{v,in} - \frac{\dot{Q}_{loss}}{\dot{m}} \quad (2.14)$$

Applying the energy balance from Eq. (2.4), the enthalpy loss between the control valve and the turbine inlet can be modelled as the heat lost by conduction to the pipe that connects both spots, and the heat lost to the ambient. Therefore, the overall steady-state heat losses can be expressed as:

$$\dot{Q}_{loss} = \alpha \cdot A \cdot \Delta T \quad (2.15)$$

Where A is the reference surface through which the heat transfer occurs, ΔT is the overall temperature difference (in this case will be the difference between the propane temperature and the ambient temperature) and α is the global heat transfer coefficient, which has the following form:

$$\alpha = \frac{1}{A \cdot \sum_1^j R_j} \quad (2.16)$$

Where R_j denotes the thermal resistance of the medium and adopts different forms depending on the geometry and the heat transfer mechanism. In the case discussed, the heat is convected from the fluid towards the pipe (q_{ci}), conducted through the thickness of the pipe (q_k

- considering only the insulation of the pipe as a thermal resistance) and convected at the outer surface to the ambient (q_{co}). This is shown graphically in Figure 2.9. If the proper form of the heat transfer coefficient for each heat transfer mechanism is replaced in Eq.(2.15), one can arrive to the formula that describes the global heat transfer that represents the heat lost in the pipe:

$$\dot{Q}_{loss} = \frac{\Delta T}{\frac{1}{A_i \bar{\alpha}_i} + \frac{\ln(r_o/r_i)}{2\pi L \lambda} + \frac{1}{A_o \bar{\alpha}_o}} \quad (2.17)$$

Where the indices i and o denote inside and outside of the pipe, respectively. Also, L is the length of the pipe and λ is the thermal conductivity of the insulation. In this case, α corresponds to the convection coefficient.

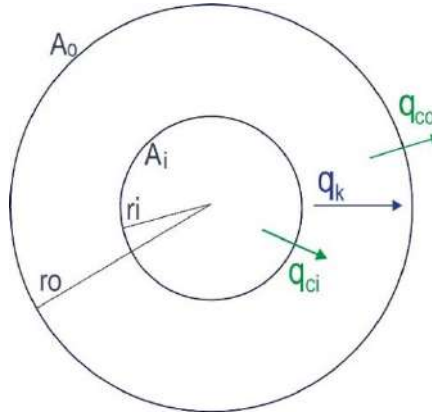


Figure 2.9 Cross-section of the pipe showing the geometric parameters and the differentiation in transferred heat.

In this analysis, a differentiation is made between steady state conditions and transient conditions. The total heat loss is modelled approximately as the sum of two asymptotic cases: a long-term stationary heat flux and a short-term, time-dependant heat flux. Then:

$$\dot{Q}_{loss} = \dot{Q}_{loss\ st} + \dot{Q}_{loss\ tr} \quad (2.18)$$

In the stationary state, only heat propagated by conduction through the insulation is considered. The description of the conducted heat is ruled by Fourier's law, which in a one-dimensional analysis is expressed as [12]:

$$\dot{Q}_k = -\lambda \cdot A \cdot \frac{dT}{dx} \quad (2.19)$$

Where \dot{Q}_k is conducted heat per unit of time and dT/dx is the ratio of the temperature change in the direction of x . Going back to the overall heat transferred in Eq. (2.17), the heat resistance by convection is neglected at both surfaces of the pipe and thus the expression obtained is the Fourier's law applied to the geometry of a pipe:

$$\dot{Q}_{loss\ st} \cong \dot{Q}_k = \frac{2\pi L\lambda}{\ln(r_o/r_i)}(T - T_{air}) \quad (2.20)$$

Where T is the propane temperature and T_{air} is the ambient temperature. The other part of the total heat loss is the transient heat loss, that only considers the flux towards the steel, caused by the temperature difference between the cold steel and the flow of hot propane. From Eq.(2.15), the transient heat loss is:

$$\dot{Q}_{loss\ tr} = \alpha_i \cdot A_i \cdot (T - T_s) \quad (2.21)$$

Where T_s is the temperature of the steel. The above equation can be compared with the heat absorbed by the steel, which can be expressed as:

$$\dot{Q}_{steel} = m_s \cdot c_{p_s} \cdot \frac{dT_s}{dt} \quad (2.22)$$

Where m_s is the mass of the pipe considered and c_{p_s} is the specific heat of the steel. Under the short-term transient conditions, the heat lost to the ambient is neglected, thus the heat lost by the fluid must be equal to the heat absorbed by the material (Eq.(2.21), which must be equal to Eq.(2.22)). This equality gives the following expression:

$$T - T_s = \frac{m_s c_{p_s}}{\underbrace{\alpha_i A_i}_{\tau}} \frac{dT_s}{dt} \quad (2.23)$$

The properties of this transient heat transfer problem are grouped under the time constant τ . Afterwards, by combining both equations, a differential equation is outlined from which T_s can be obtained:

$$\tau \frac{dT_s}{dt} + T_s = T \quad (2.24)$$

The time constant τ is obtained from the graphical analysis of the measured temperature of the fluid at the valve inlet and at the turbine inlet, in a time range right after the sudden opening of the valve. In this way, there is no need to calculate the heat transfer coefficient α_i at the inside of the pipe.

After the detailed analysis portrayed in this Chapter, the fundamentals of the study are defined. In the following Chapter, the creation of the model based in these fundamentals is described.

3. MODEL DEVELOPMENT

In this chapter, the building process of the turbine model is described, from the code beginning until the definition of the final version. Furthermore, the components and features of the program are explained in detail.

3.1 Initial considerations

The turbine model is developed in Simulink, which is a MATLAB-based graphical programming environment used to model, simulate and analyse multidomain dynamical systems. Its primary interface is a graphical block diagramming tool, and the creation of the model is made by a set of block libraries. It is characterised by its tight integration with the rest of the MATLAB environment.

The model developed is one-dimensional and performs a thermodynamic simulation of the working substance between the turbine's control valve inlet and the turbine outlet. The model is capable of defining the thermodynamic state of the substance at the inlet and outlet of the steam turbine, by implementing blocks to build the model based in the energy balance and Stodola's law explained in Chapter 2. Based on this data, the model can calculate the power of the turbine. The turbine model can be assumed to be time independent in terms of thermal variations, since the changes in temperature of the flow are absorbed by the turbine steel in a matter of milliseconds. The only transient effects in the model are related to the warm up of the pipe upstream the turbine.

The analysis of the fluid inside the turbine needs a more complex approach that can be done with the Mean-Line analysis, which considers the loss correlations through the turbine and the transformation of energy conducted on the blades and vanes. Given that this thesis work constitutes the first effort in building a model to represent this particular turbine, the amount of work needed regarding the Mean Line analysis must be set outside of the scope of this thesis.

3.2 Model building chronology

The original idea was to develop a model of the turbine that could be coupled with the condenser model created by M.J. Fossati in his master thesis [10]. This is one of the reasons why the condenser model was studied in detail and served as a guide to set a methodology for building the turbine model. Apart from that, the manipulation of that model was crucial to get the feeling of working with Simulink and learning the basics of the program, since I had no previous experience with the software. The learning process was also aid mostly with MATLAB-Simulink documentation and tutorials.

The first task was to model the Stodola's law as a block that could calculate the turbine inlet pressure ($p_{t, in}$). Therefore, the work started with the creation of a very simple blocks layout that recreated the operations in Stodola's equation. In this initial stage, the inputs were defined as averaged, constant values that had no variation with time. In fact, this methodology using simplified constant input parameters was maintained until the whole model was defined, leading to the simplified version of the model called stationary model. Only then, the inputs were modified to allow the parameter's variation over time.

Afterwards, the Stodola block modelled was coupled to the condenser model, by performing the modifications needed in the inputs and outputs of the blocks. Once this was completed, the energy balance modelling began. At this point, the model gained complexity because of the need for data acquisition provided by the REFPROP database, used to retrieve the intermediate values of enthalpy and entropy that allow the calculus of the turbine outlet enthalpy. Therefore, the indirect connection of REFPROP with Simulink through LookUp tables was implemented, following the methodology described by M.J. Fossati in his thesis.

What came next was the modification of the Stodola equation block, developing the iterative model that iterates the turbine inlet temperature ($T_{t, in}$). This was needed because the inputs to Stodola in the model are the enthalpy at the inlet of the turbine, and the turbine outlet pressure ($p_{t, out}$). Since Stodola was arranged to find $p_{t, in}$ as a function of $p_{t, out}$ and $T_{t, in}$ (remember Eq.(2.12)), the problem with such inputs became implicit regarding $T_{t, in}$.

At some point in the development of the turbine model, the idea of coupling the turbine with the condenser model had to be abandoned. Several reasons led to this decision, being the most critical that both models require the turbine outlet pressure as an input (which is equal to the condenser inlet pressure, if the pressure loss in the pipe that connects both is neglected). This results in an inconsistency in the coherence of simulation flow, since it fails to comply with the output of the turbine model acting as input to the condenser model. What was actually happening instead was that the turbine outlet pressure was used as an input for both models, creating a sort of splitting between them.

Another reason to abandon the idea of coupled models was that the validation would be far more complicated than expected. The condenser model was developed and validated using the data analysed by L. Gardella in his master thesis [13], corresponding to runs performed during 2019 with the plant running in bypass operation. The data processed in that thesis work is oriented to provide the condenser model with the necessary inputs and validation data, therefore there are several variables and parameters analysed which are particular of the condenser operation. When trying to validate the turbine model with that set of data, it was impossible since the operation was in bypass. At the same time, it is also difficult to validate

the condenser model with the data used in this work, provided by J. Mardon Pérez [1], since the particular condenser variables were not processed in this opportunity.

After separation of turbine and condenser model, the work with the turbine model greatly simplified and became more fluid. The final stages in the model building were the development of the heat loss equation to be inserted upstream the turbine model, and finally the modification of the source block to allow the running with time-dependent inputs. With that, the final Transient model was completed.

3.3 Model architecture

The structure of the final model is basically composed of three main parts, as seen in Figure 3.1: The Heat loss block, the Stodola's law function and the Energy balance block. Moreover, there is a source block for the inputs that is not shown in the image. The Heat loss and the Energy blocks are subsystems that contain block structures inside, while the Stodola's law part is actually a MATLAB function block, which is a special Simulink feature that allows the insertion of MATLAB code into the model.

The inputs to the model are mass flow (\dot{m}), turbine outlet pressure ($p_{t, out}$) and the parameters needed to calculate the turbine inlet enthalpy, which are the control valve inlet temperature and pressure ($T_{v, in}$ and $p_{v, in}$ respectively) and the ambient temperature (T_{AirIn}). There are other inputs named as “measured” that are not real inputs to the model, and actually they are the measured data that corresponds to the outputs, which are needed to validate the model.

The most relevant outputs to the model are the turbine outlet enthalpy and therefore the turbine power, and the conditions of the fluid at the inlet of the turbine, that is the pressure and temperature ($p_{t, in}$ and $T_{t, in}$). The efficiency of the turbine is also portrayed as an output, since its value depends on the calculated pressure $p_{t, in}$. All of the output signals lead to a Scope block, that can be used to analyse the results.

The flow chart of the model can be seen in the Figure 3.2. The program works solving in time steps, therefore the whole model is calculated before progressing to the next time step. This is different in the case of the Stationary model, which uses averaged constant inputs, since Simulink solves the whole model only once. The calculations in the model progress in a straight forward way, except for the Stodola function. In this block, the temperature is an implicit variable in the equation, and this is why the iterative loop needs to be applied.

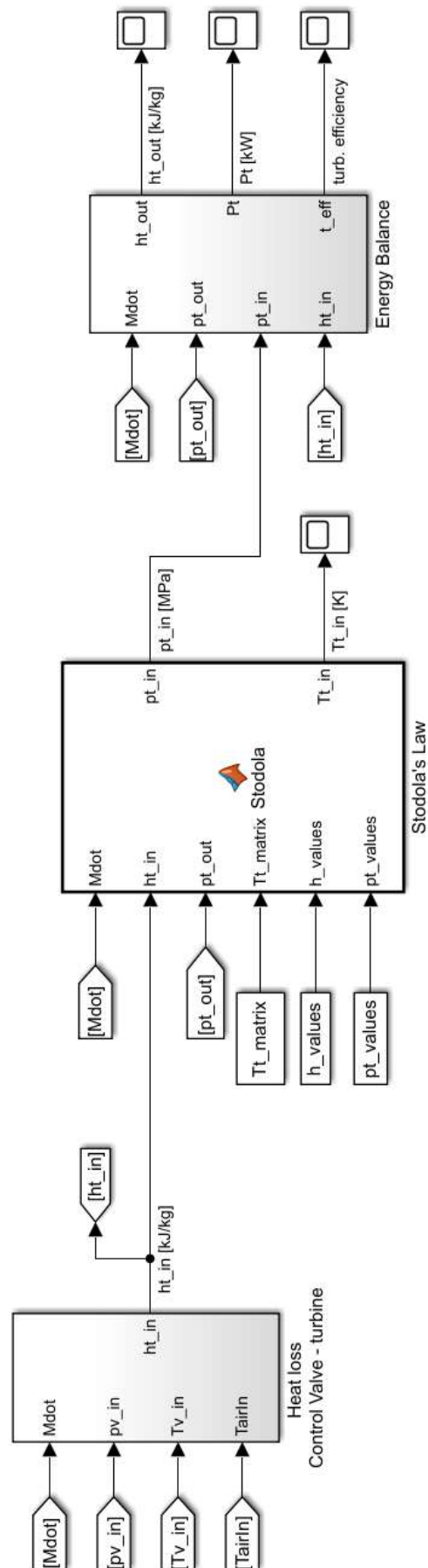


Figure 3.1 Main view of the turbine model (sources block is not shown).

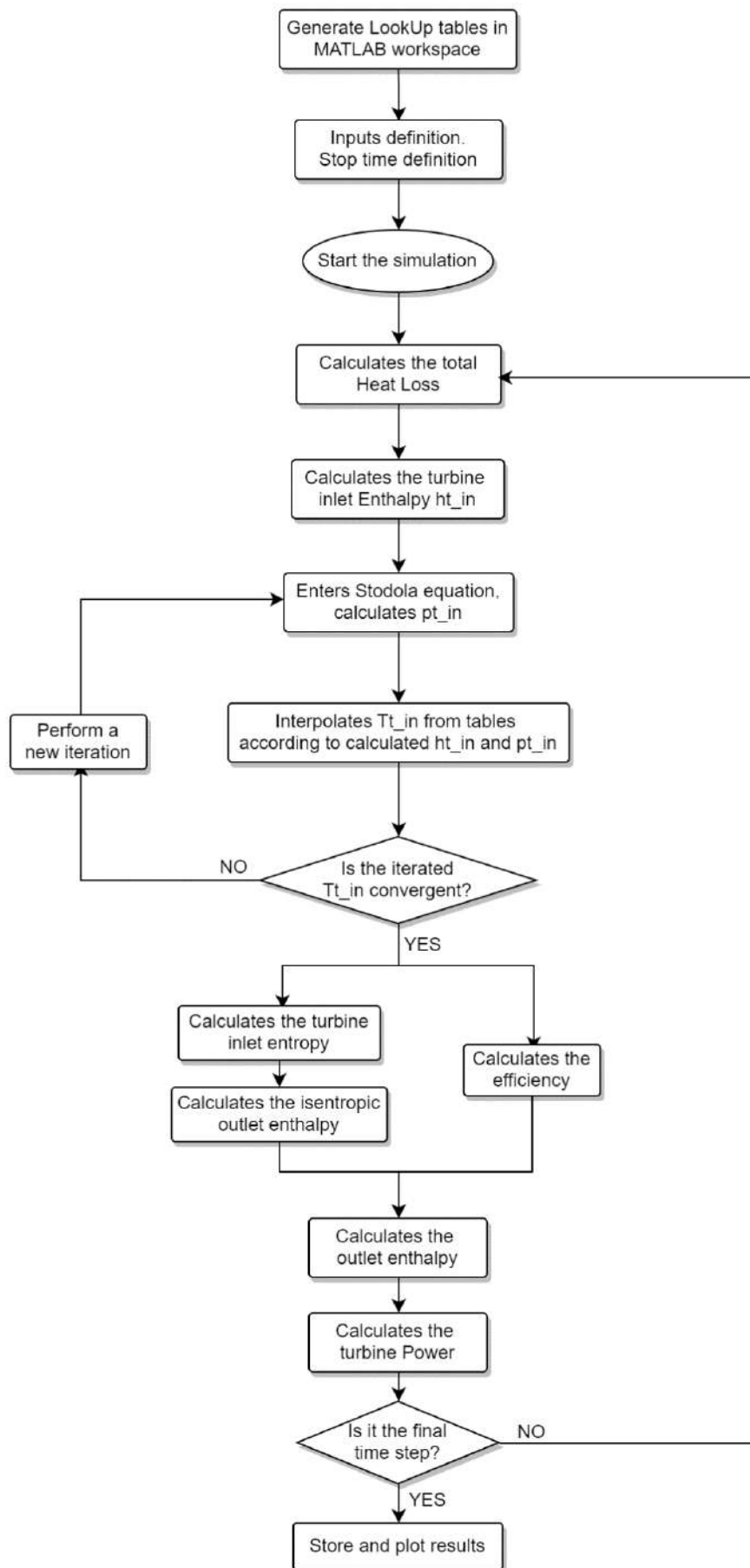


Figure 3.2 Flow chart of the turbine transient model.

3.3.1 Input source

As mentioned previously, a considerable part of the development process was done working with the stationary model, which uses averaged constant inputs. These inputs were defined by selecting steady state periods during the running of the plant and calculating the average value over time of each variable. This simplified source of data enables the program to run fast and prevents issues that add complexity to the program, related to the time variation in the model. Being the sources constant, the simulation runs as with one unique time step.

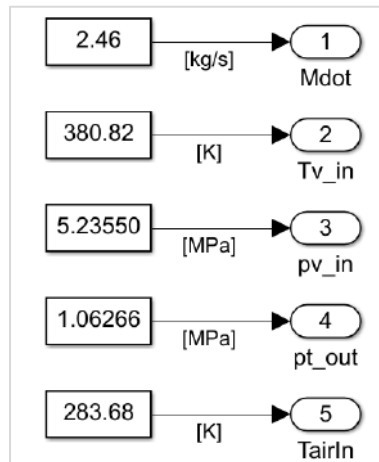


Figure 3.3 Constant input block used in the Stationary model.

In Figure 3.3, the constant source block can be observed. The signal is defined by the name that appears below the signal number, and its value is the constant number defined in the blocks. The simulations performed using this source present the same working principles as the simulation with GESI, since both models have constant inputs and therefore constant outputs.

The transient version of the turbine model supports time-dependant inputs, in order to analyse the development over time of the outputs and intermediate variables, and to study the occurrence of transient effects. This is achieved by using the Simulink block called “From Spreadsheet”, which reads the data from an Excel sheet and outputs the data as a signal. This block can be seen in Figure 3.4, in which the Excel sheet called “InputData.xlsx” corresponds to the file that contains the input data sheets, and “D2R2b” is the name of the sheet where the data corresponding to a particular running is stored.

This block allows the selection of the sample time used in the simulation. This sample time can be different to the time step in which the data is stored in the spreadsheet. When this is the case, the block performs an interpolation between data points to retrieve the values corresponding to the intermediate steps. In the particular case of this model, the data is arranged in Excel with a time step of 1 s, derived from the sample time of the sensors during the running. When the data inputs the model, the block defines a time step of 0,1 s.

The stop time of the simulation is another temporal parameter that must be defined in Simulink before running the program. This stop time must be coherent with the total time reached by the data stored in the spreadsheet.

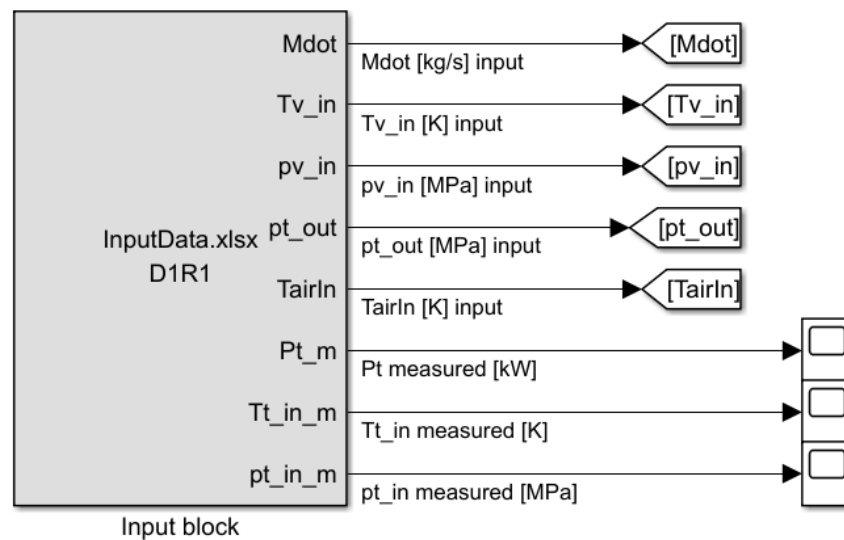


Figure 3.4 Time-dependant input source corresponding to the final model.

In Figure 3.4, the previously mentioned inputs to the model can be observed. The first five signals, from the upper part down, are the inputs itself. They are distributed in the model with the “Go to” and “From” features. Apart from that, the four last signals correspond to the measured data needed to compare with the simulated variables. These only enter the simulation in order to generate interpolated signals with the same time step as the modelled parameters, therefore they are outputted from the source block and immediately end in a Scope block used to analyse results.

S time	Mdot	Tv_in	pv_in	pt_out	TairIn	Pt_m	Tt_in_m	pt_in_m	Real t
1	2,30	378,03	4,93	1,12	284,05	101,25	374,00	4,61	15:45:13
2	2,37	378,03	4,93	1,12	284,05	101,25	374,00	4,61	15:45:14
3	2,40	378,03	4,93	1,12	284,05	101,25	374,00	4,61	15:45:15
4	2,40	378,03	4,93	1,12	284,05	101,25	374,00	4,61	15:45:16
5	2,43	378,03	4,93	1,12	284,05	101,25	374,00	4,61	15:45:17

Figure 3.5 Inputs sheet layout.

The data must be previously arranged in the Excel sheet in a specific way that defines the order in which it is outputted. In Figure 3.5 can be seen that the signals are arranged in columns, and the heading of each of them defines the name of the signal that the block outputs in Simulink. Furthermore, the first column represents “Simulink time” and it corresponds to the time step that Simulink reads from the sheet. It can be noted that the increasing “S time” is consistent with the time measured in the last column, therefore S time is an increasing progression in seconds.

3.3.2 LookUp tables

The enthalpy and entropy associated to a thermodynamic state of a substance can be obtained from tabulated values, which are usually defined as a function of temperature and pressure. The model also needs the obtention of entropy values as a function of enthalpy and pressure, and the other way around as well. All of this can be solved by using the REFPROP database and the implementation of LookUp tables.

The REFPROP database cannot be accessed directly from Simulink. This is why, in order to calculate the thermodynamic variables needed through the model, REFPROP data is previously arranged in matrixes stored in MATLAB's Workspace, and afterwards accessed by Simulink using the LookUp tables, as can be seen in the Figure 3.6. These consist of a Simulink block that outputs a value by looking up or interpolating a table of values defined in the block parameters.

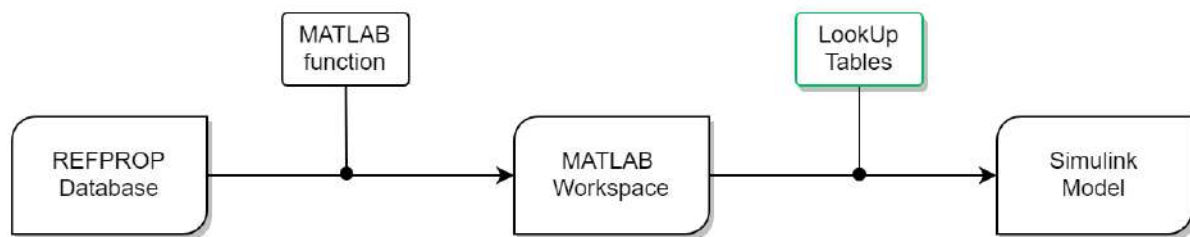


Figure 3.6 Flowchart showing the process for thermodynamic data retrieval, from REFPROP to Simulink.

The creation of the different matrixes needed is done by a MATLAB code called “TableGenerator”, that must be run prior to the simulation. The complete code can be found in the Annex, 8.1. The retrieval of data from REFPROP inside this code is done by a MATLAB function called “Refpropm”. The code works with “for” loops that enter the database multiple times and retrieve each value needed to build each matrix. The code can be tailored to define the seed vectors needed, the ranges of the tables generated and its accuracy. When the running of the code is complete, the matrixes are stored in the Workspace.

Afterwards, each LookUp table is loaded with the corresponding matrix and the vectors that define the dependant variables related to the input signals. Therefore, the information can be directly called when running the simulation. In the Figure 3.7 can be observed a LookUp table built to obtain the value of enthalpy associated to a fluid state defined by temperature and pressure. The input signals are contrasted with the T and p vectors loaded in the block, and then it either looks up the enthalpy value, or is obtained by interpolation.

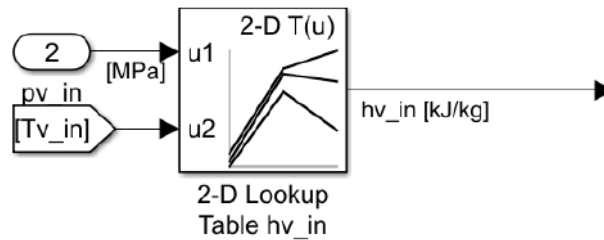


Figure 3.7 Example of a LookUp table used to calculate enthalpy.

It should be noticed that it is in the Table Generator code that the substance is defined, since it must be explicitly noted in the function that access REFPROP. Consequently, the tables related to the inlet and outlet of the turbine differ in that at the inlet, the substance defined is pure propane, while at the outlet the tables are retrieved for a mixture of propane – 0,2%mass nitrogen.

The implementation of LookUp tables allows to save a considerable amount of time when running the simulation, since the matrixes need to be generated just once. This is a great advantage when working with the model, especially if planning of annexing it to a general model of the plant.

3.3.3 Heat loss calculation

The calculation of the heat loss between the control valve and the turbine is performed in the subsystem that can be seen in Figure 3.8. This subsystem corresponds to the first stage of the model, and its objective is to estimate the enthalpy at the inlet of the turbine ($h_{t, in}$). This is the path chosen to define with the best possible accuracy the conditions at the turbine inlet, as explained theoretically in Chapter 2.4.3. The image shows clearly that the inputs to this block are the mass flow, the temperature and pressure at the control valve inlet, and the ambient temperature.

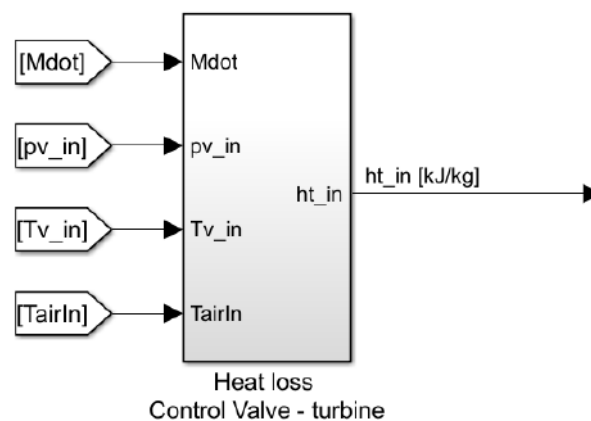


Figure 3.8 Heat loss subsystem.

The Heat loss subsystem is built in accordance with the equations in Chapter 2.4.3 and it is basically composed of three parts: the calculation of the heat lost to the steel pipe, which is most relevant in transient conditions, the calculation of the heat lost to the ambient, which is the main mechanism in stationary conditions, and the enthalpy at the valve inlet calculated by a Lookup table. A schematic of the heat loss subsystem can be seen in Figure 3.9, while an image of the complete subsystem can be found in the Annex, 8.3. The subsystem is built reflecting the order induced by Eq. (2.14). The elements that compose the total heat loss are designated by differencing between transient and stationary heat loss, since the effect of the heating of the pipe can only be observed in the initial stages of the run.

The stationary heat loss is calculated with a rather simple MATLAB function block coded according to the Eq. (2.20), whose inputs are the valve inlet temperature and the ambient temperature. The code also performs the calculation of the value of the thermal conductivity (λ) as a function of temperature, which is done with a polynomial fitting.

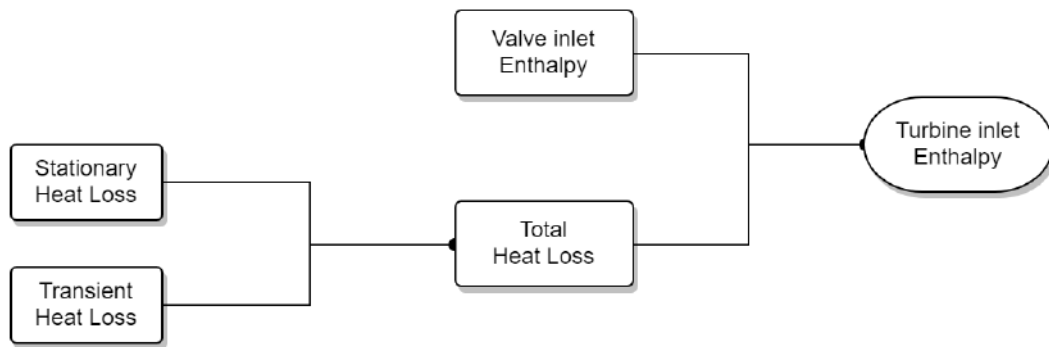


Figure 3.9 Schematic of the Heat Loss subsystem parts.

The enthalpy associated to the control valve inlet is obtained with a LookUp table that is preloaded with propane enthalpy values as a function of temperature and pressure. This specific block is portrayed in the previous section, Figure 3.7. The inputs to this LookUp table are the control valve inlet temperature and pressure.

Modelling of the transient heat loss

The remaining part of the Heat Loss subsystem corresponds to the calculus of the transient heat, which is related to the heating of the steel pipe during the initial stages of the running. This part of the model is ruled by Eq. (2.21) and indirectly calculated using the equalities explained in Eq. (2.21) to (2.24). The heat transfer coefficient α multiplied by the heat transfer area A , is indirectly calculated with the equality portrayed in Eq. (2.23) out of the relation between the time constant τ , the specific heat of the steel and the pipe mass. The other part of the original equation is formed by the difference between the fluid temperature, which is the primary input $T_{v,in}$, and the steel temperature associated to the pipe. At this point, a numerical

method is needed in order to solve the differential equation (2.24) to estimate the value of the steel temperature, since there is no sensor measuring this variable in the facility.

The numerical model built to find the value of the steel temperature is based in the Euler's method called Initial Value Problem [14]. This is a simple method for the solution of Ordinary Differential Equations, that is based in replacing the derivative term in the equation with a numerical derivative and a finite time step Δt . This approximation has the following form:

$$\frac{dT_s}{dt} \cong \frac{T_{s,n+1} - T_{s,n}}{\Delta t} \quad (3.1)$$

Where n denotes the value of T_s at the moment n , and $n+1$ denotes the value of T_s a time step later. By replacing this form in the original differential equation, one can arrive to:

$$\tau \left(\frac{T_{s,n+1} - T_{s,n}}{\Delta t} \right) + T_{s,n} = T_{v,in} \quad (3.2)$$

Finally, the equation needs to be solved for the steel temperature corresponding to the next step $T_{s,n+1}$, thus giving the expression modelled in Simulink:

$$T_{s,n+1} = \frac{\Delta t}{\tau} (T_{v,in} - T_{s,n}) + T_{s,n} \quad (3.3)$$

The final element needed in order to apply this numerical solution is the initial value of T_s , which allows the solution of the equation at the initial time step. This is assumed to have a value between the fluid temperature and the ambient temperature, and can be manually obtained at the beginning of the run with little effort.

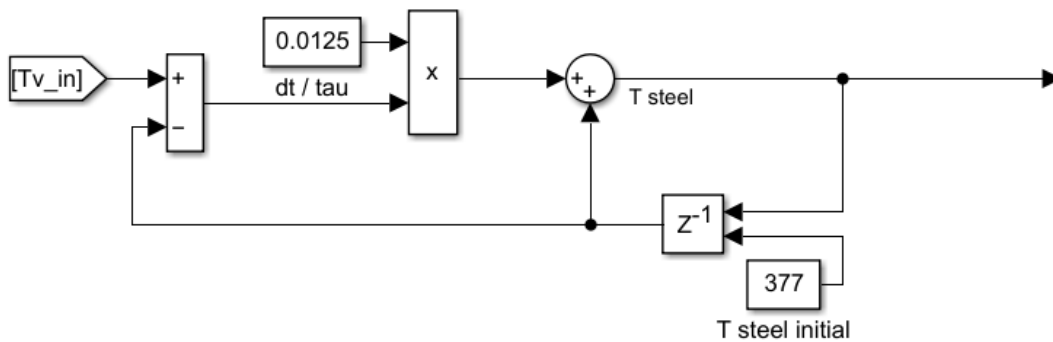


Figure 3.10 Modelling of the numerical solution applied to calculate the steel temperature.

The modelling of this equation can be seen in Figure 3.10. The key element needed to model this numerical method in Simulink is a block called delay (pictured as Z^{-1}), which outputs the value of the input signal in the previous time step. This is employed to simultaneously use the signal of the steel temperature in the time step n ($T_{s,n}$) to obtain $T_{s,n+1}$. The initial value of T_s is inputted to this block as a constant.

The original idea when defining the mathematical model of the transient problem was to solve the differential equation using a transfer function for T_s . Simulink counts with a predefined transfer function block that was considered at the beginning of the modelling process. However, after several attempts to implement this block, the approach needed to be modified since the block was very limited to a certain kind of equation which was not compatible with this particular problem. The results obtained with this block were not consistent, and diverged greatly at the initial stages of the simulation.

Instead, the Initial Value Problem proves to be consistent, and at the same time it is more versatile since it allows to manually define the equation. The counterpart is that the initial temperature, as well as the rate between time step and time constant τ must be manually inputted, and this can be a problem when running the model to varying initial conditions and sample times.

3.3.4 Stodola equation

The objective of the Stodola's law in the model is the calculation of the turbine's inlet pressure and temperature. To do so, the modelling is based on the Eq.(2.13), which corresponds to the corrected expression solved for the turbine inlet pressure ($p_{t,in}$). Even though the equation seems to have a rather simple expression, the calculus gains complexity because the inlet pressure and temperature need to be calculated out of inlet enthalpy and outlet pressure, which leads to an iterative resolution. This approach was defined in order to become independent of the state of the fluid at the inlet of the turbine, given that by knowing the enthalpy associated to the fluid it is possible to find its T and p , regardless of whether it is a supercritical substance or it is inside the two-phase region.

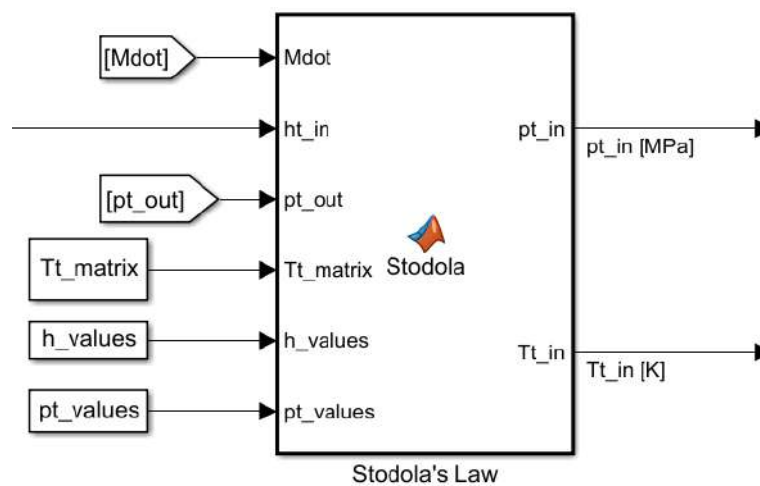


Figure 3.11 Stodola's law modelled block.

An image of the modelled block can be seen in Figure 3.11. This block is located after the heat loss subsystem, from which it receives the calculated turbine inlet enthalpy ($h_{t,in}$) as an input. The other inputs to the block are the pressure at the outlet of the turbine ($p_{t,out}$) and the mass

flow (\dot{m} , defined as “Mdot” in the model). The inputs defined as “Tt_matrix”, “h_values” and “pt_values” correspond to constant data needed to perform an interpolation inside the block.

Unlike the Heat loss subsystem, the Stodola’s equation is modelled using a MATLAB function block, which is a Simulink block that allows the insertion of a coded MATLAB function in the model. This feature is very useful when the ruling equation presents considerable complexity, as it is the case here due to the iterative part.

The original idea was to model the whole equation in the Simulink environment, and to do so the use of Simulink’s “While Iterator subsystem” was considered. After several attempts to build the system with such block, I was forced to follow a different strategy since the block was limited to a basic *while* loop that was not able to model this specific problem. This is the reason why the MATLAB function block was applied, which is much more versatile and easier to code.

The code inside the block is written based on the corrected expression of Stodola’s law, that calculates $p_{t,in}$ as a function of \dot{m} , $p_{t,out}$ and the turbine inlet temperature ($T_{t,in}$). This corresponds to an implicit problem in which $T_{t,in}$ is unknown, and at the same time it is needed to calculate $p_{t,in}$, which is why the iterative method is needed. After definition of constant factors, a guess $T_{t,in}$ value is defined, that allows to start solving the equation. Next, the program enters the “while” loop in which $p_{t,in}$ is calculated with Stodola’s expression.

Still inside the loop, an interpolation is done to redefine the value of $T_{t,in}$ by using the calculated pressure, and the inputted enthalpy. To do so, a table of temperature values associated to pressure and enthalpy values are preloaded to the block, all generated previously by the “Table Generator” through retrieval from REFPROP. This works the same way as the previously explained LookUp tables, except that the process of interpolation needed to be manually coded.

The calculation is repeated inside the “while” loop until the convergence criteria defined for the temperature is reached. When this is achieved, the block outputs the obtained turbine inlet pressure and temperature, which are the inputs of the Energy balance subsystem. The complete code corresponding to Stodola’s law block can be found in the Annex, 8.2.

3.3.5 Energy balance

The Energy balance is a Simulink subsystem that constitutes the final part of the calculation in the turbine model. It is located next to the Stodola’s law block, and receives the signal of the obtained $p_{t,in}$ from this block, as it can be seen in Figure 3.12. The other inputs to the subsystem are the mass flow, the turbine outlet pressure and the inlet enthalpy calculated in the first subsystem. The outputs of the block are the turbine outlet enthalpy, the turbine power and its efficiency, being the first two parameters the main results of the simulation.

The subsystem is built based on the process explained in Chapter 2.4.1, and specifically defined by the Eq. (2.6) and (2.8). The path followed by the calculation inside this subsystem is quite straight forward, and can be understood by the flow diagram shown in Figure 3.13.

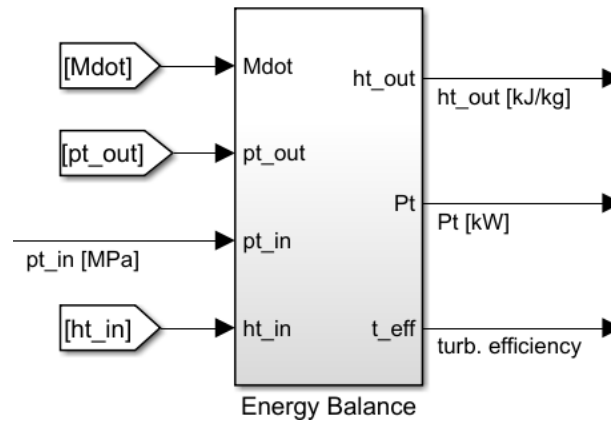


Figure 3.12 Energy balance subsystem.

Initially, the turbine inlet entropy is found as a function of inlet pressure and enthalpy, by using a Lookup table. With this entropy value, the enthalpy associated to the isentropic expansion can be found, also using a Lookup table, as a function of entropy and outlet pressure. Afterwards, the efficiency of the turbine is calculated, and with the isentropic outlet enthalpy the turbine outlet enthalpy can be found. With this, the turbine power (shaft power) is obtained just by relating the outlet enthalpy and the mass flow. An image of the complete subsystem can be found in the Annex, 8.4.

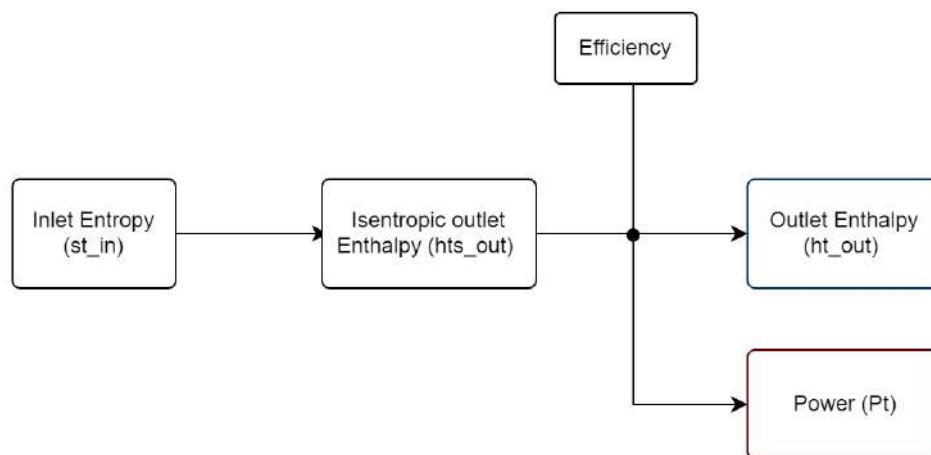


Figure 3.13 Simplified flow diagram of the energy balance subsystem.

The turbine efficiency is obtained as a function of mass flow and turbine inlet pressure, and is calculated in the subsystem that can be seen in Figure 3.14. This correlation is a result of the analysis performed by J. Mardon Pérez in his thesis [1], where he finds that, in the case of this

particular turbine, the efficiency decreases with increasing mass flow and pressure. The correlation used in this model corresponds to a first order equation with the following formula:

$$\eta_t = -0,4399 \cdot \dot{m} + 0,3229 \cdot p_{t,in} + 0,4412 \quad (3.4)$$

Where \dot{m} must be expressed in kg/s and $p_{t,in}$ must be expressed in MPa.

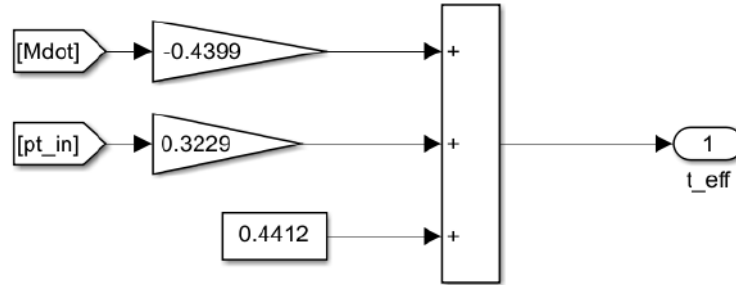


Figure 3.14 Turbine Efficiency block.

3.3.6 Post-processing

The primary analysis of the simulation outputs is done with the Simulink Data Inspector tool. To do so, the signals of interest must be selected using the feature “Log signals”, prior to running the simulation. Once the model has finished running, this tool is used to graphically visualize the results and compare different signals. Since it is able to store a great number of past runs, it allows to compare the shape of the same signal in different runs.

Afterwards, the signals loaded in the Data Inspector are manually exported to an Excel file. This sheet contains the value of every signal selected as a function of Simulink’s time step. This data is contrasted to the measured data and arranged in graphs. The signals analysed are the turbine power, the turbine outlet enthalpy, the efficiency, and the conditions of temperature and pressure related to the inlet of the turbine (Stodola’s block outputs).

By arriving to the end of this Chapter, the explanation of the building process of the turbine model and the detailed description of its characteristics are concluded. In the following Chapters, the validation process of the model is described and the results are exposed.

4. STATIONARY VALIDATION & RESULTS

In this Chapter, the validation and subsequent results obtained for the simplified stationary model are portrayed. To do so, the parameters that are encountered inside the model are numerically defined, and the description of the input data used for validation is explained.

4.1 Stationary model parameters and constraints

The stationary validation was performed on a simplified version of the turbine model. This model only admits constant inputs, as previously pictured in Figure 3.3. As a consequence, the simulation is executed in a unique time step, which is equal to saying that this model is completely independent of time. Therefore, the model receives constant values as inputs, and consequently it outputs constant values.

Some other characteristics that differentiate this simplified stationary model are that the efficiency is inputted as a fixed, constant value, independent of the mass flow and the turbine inlet pressure. Moreover, the heat loss subsystem only considers the heat lost to the ambient in steady state, given that the transient heat loss has no effect in the stationary simulation. The model characteristics and constraints are summarized in the following table:

Stationary model characteristics	
Inputs	Constant, averaged
Turbine efficiency: constant value	$\eta_t = 0,85$
Time-dependence	Independent of time
Heat loss calculation	Only stationary part
Turbine inlet T and p calculation	Iterative Stodola's law

Table 4.1 Summary of Stationary turbine model characteristics.

The model counts with some numeric values that are already fixed in the structure of the system, and deserve a brief explanation about their origin. These correspond to the constant factors that correct the Stodola's law, which are designated as c and c' in Eq.(2.13). Their value was defined by J. Mardon Pérez [1] after the analysis of tendency curves that best fit the behaviour of the turbine. In the model, c and c' are defined in the code corresponding to the Stodola's law block, coded as "c" and "c_dash" respectively. In the Table 4.2, the numeric value of these parameters is shown.

Correction factors - Stodola's law	
c	1,5442 <i>non-dimensional</i>
c'	-1,3352 <i>kg/s</i>

Table 4.2 Correction factors to Stodola's equation.

4.2 Averaged Inputs

All the information used to validate both Stationary model and Transient model was obtained during the running of MoNiKa facility on the 9th, 10th and 11th of November, 2021. The operation of the plant was performed by the ITES-KIT personal. All the data acquired by the instrumentation of the plant during this operation was post-processed by J. Mardon Pérez [1], therefore the data used as an input to validate the model derives from his work.

The input data is organized according to the day of the run as 1st, 2nd, and 3rd day. During each day, several test runs were performed with an approximate duration of between 30 minutes and one hour. Apart from that, each day presents an initial warm-up phase, and a final shut-down phase. For the denomination system, each run and its corresponding day are abbreviated as “D + n° of the day, R + n° of the run”.

Averaged constant inputs							
	Run	CV %	\dot{m} [kg/s]	$T_{v, in}$ [K]	$p_{v, in}$ [MPa]	$p_{t, out}$ [MPa]	$T_{air in}$ [K]
1st day 08.11.2021	1	14,20	2,08	384,68	5,502	0,966	281,65
	2	16,47	2,56	382,42	5,523	1,013	281,88
	3	18,00	2,38	381,30	5,253	1,030	282,91
	4	16,70	2,20	381,31	5,190	1,035	283,25
	5	14,30	1,88	383,05	5,225	1,035	283,68
	6	14,60	1,90	383,07	5,190	1,040	283,62
	7	?	2,46	380,82	5,236	1,063	283,68
2nd day 09.11.2021	1	16,30	2,40	383,58	5,516	1,106	281,02
	2	15,70	2,40	384,61	5,609	1,104	281,80
	3	17,00	2,60	383,56	5,627	1,116	282,67
	4	18,30	2,60	382,50	5,499	1,117	283,01
	5	19,50	2,60	382,07	5,428	1,120	283,32
	6	22,20	2,60	380,77	5,295	1,121	283,66
	7	27,80	2,60	379,93	5,197	1,124	283,80
	8	71,94	2,60	379,15	5,131	1,124	283,74
	9	97,83	2,68	379,89	5,220	1,129	283,77
	10	99,00	2,50	378,96	5,047	1,124	283,90
	11	99,00	2,41	378,04	4,935	1,121	284,00
3rd day 10.11.2021	1	99,50	2,10	374,41	4,546	1,072	279,14
	2	99,50	2,20	373,49	4,599	1,074	279,42
	3	99,50	2,30	377,06	4,824	1,078	279,69
	4	99,50	2,40	375,94	4,840	1,078	279,78
	5	99,50	2,50	376,32	4,920	1,078	279,87
	6	99,50	2,59	377,59	5,056	1,078	279,87
	7	99,50	2,66	376,42	5,005	1,072	279,93
	8	99,50	2,74	376,74	4,985	1,069	280,17

Table 4.3 Complete set of input data used to validate the Stationary model.

The validation of the stationary model was performed employing the averaged values corresponding to each run, for each of the three days. The averaged inputs used to validate

the model can be found in the Table 4.3, where every row corresponds to one input set associated to a run. In addition, the table shows the opening percentage of the control valve (CV%), which is not used as an input, but can be a relevant parameter to consider when analysing the results.

In order to run the Stationary model, a consistent set of inputs must be manually added in the Source block (illustrated in Figure 3.3). Previously, the MATLAB code called TableGenerator must be run such that all the data needed by the Lookup tables is loaded in the Workspace. After proceeding with these steps, the model can be executed and the results evaluated.

4.3 Stationary Results

The validation of the Stationary model is done by comparing the simulated results with the averaged measurements related to the same run. In this section, only the results related to selected runs are discussed, while the output data corresponding to all of the runs can be found in the Annex, 8.5 - 8.7. The test runs selected in this chapter to show the stationary results are also the ones used to validate the transient model.

The relevant outputs discussed are the turbine power (P_t), the turbine inlet pressure ($p_{t,in}$) and inlet temperature ($T_{t,in}$). The comparison between measured and simulated results is also reflected in the percentual difference of the simulated value over the measured value.

In Figure 4.1, the values corresponding to the turbine power can be seen. Firstly, it should be pointed out the fact that the variable actually being measured is the electric power, while the comparison is made against the shaft power, which is obtained using Eq.(2.9). Having said that, the calculated shaft power can be taken as a reliable value whose rate to the measured electric power (related to the efficiencies of the generator and the gear box) is maintained almost constant.

A priori, it can be observed that the simulation is convergent for some of the cases (D1R1 and D2R3) but quite far from the real measurement for the others (especially D2R11 and D3R3). It should be noted that the behaviour of the simulation showed in these selected results are representative of the complete outcome related to all the test runs (see Annex, 8.5).

The majority of the simulated power values obtained present a percentual difference of less than 5% against the real values. However, the runs corresponding to the 3rd day show a tendency to increase this difference. This could be explained by the fact that the 3rd day also presents high overall parameters fluctuation due to a malfunction of the boiler during the running of the plant. Therefore, the employment of averaged data in such conditions produces low quality results, and the prediction can be expected to be inconsistent and ambiguous.

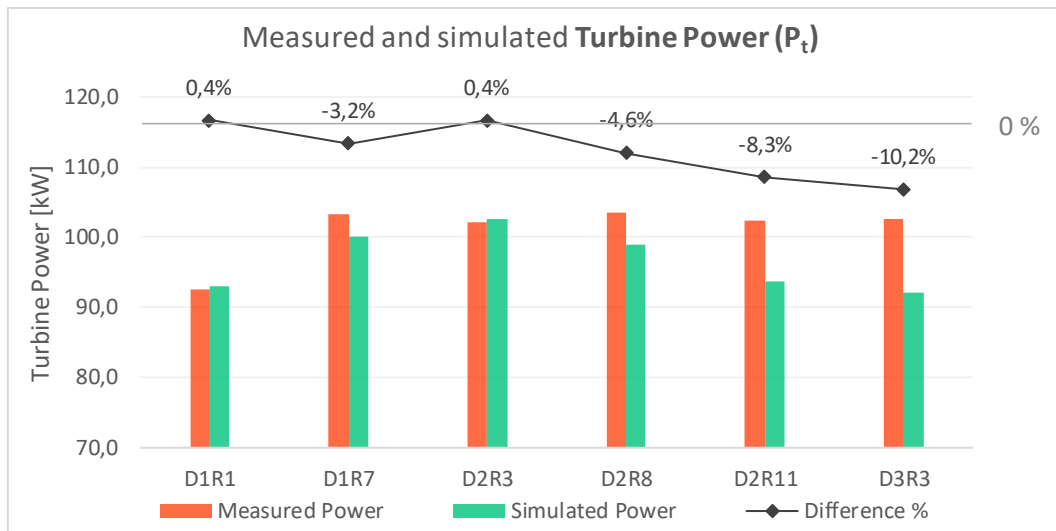


Figure 4.1 Selected results comparing measured and simulated turbine Power.

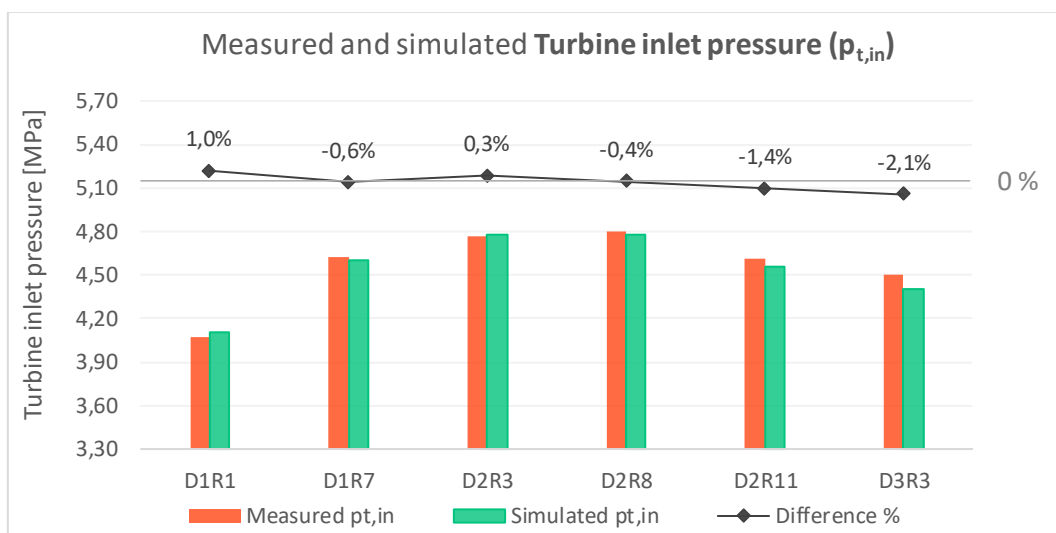


Figure 4.2 Selected results comparing measured and simulated turbine inlet pressure.

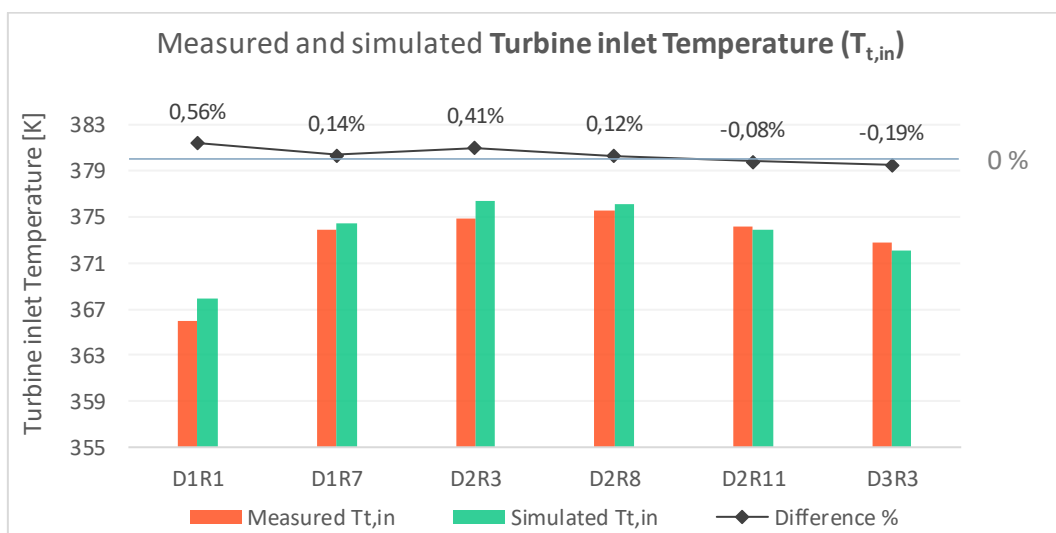


Figure 4.3 Selected results comparing measured and simulated turbine inlet temperature.

In Figure 4.2, the results corresponding to the turbine inlet pressure can be observed. In this case, the pressure calculated by the Stodola's law block is compared against the primary measurements obtained by the PS10-03 sensor (see Figure 2.6). This prediction proves to be consistent, with an oscillating difference of max. $\pm 2\%$ for the majority of all the runs (see complete results in Annex, 8.6).

Something similar to the pressure results can be observed regarding the results corresponding to the turbine inlet temperature, as seen in Figure 4.3, and in its complete version in the Annex, 8.7. The simulated temperature by the Stodola's block is contrasted against the measurements obtained by the FI10-02 sensor. It can be observed that the simulated temperature presents a close approximation to the measured values, differing less than 1%. This suggests that the calculation made using Stodola's law with its correction produce an accurate prediction of the inlet conditions, both for the temperature and the pressure.

An interesting observation that derives from the temperature and pressure results is the fact that the inlet turbine conditions are quite far from the design conditions, as defined in Table 2.1. The principal cause for this is the malfunctioning of the boiler, which fails to achieve the necessary temperature that would verify the supercritical inlet conditions. What is more, the working substance is very close to the Critical Point ($T_{CP} = 369,89 \text{ K}$; $p_{CP} = 4,251 \text{ MPa}$) and even falls in the two-phase region in the case of D1R1.

By presenting the discussed results, the explanation and verification of the stationary model is completed. In the next Chapter, the discussion related to the transient model and its time-dependant validation is exposed.

5. TRANSIENT VALIDATION & RESULTS

In this Chapter, the validation and subsequent results obtained for the time-dependant, transient model are portrayed, as well as the results obtained by GESI for comparison. To do so, the specific parameters that are encountered inside the model are numerically defined, and the input data used for validation both for the Simulink model and for GESI is explained.

5.1 Parameters definition and model constraints

The transient validation is made along with the full version of the model, explained in Chapter 3. This model allows time-dependant inputs, and therefore it outputs this same kind of data. Since it supports the evaluation of temporal events, it is with this model that the study of transient effects is done. Some other relevant characteristics already described of this model are that the efficiency is not a constant, but a function of inlet pressure and mass flow, and that the Stodola's law is applied using an iterative code that calculates the turbine inlet conditions.

Regarding the parameter definition, part of them were already defined in Table 4.2. In the particular case of the transient model, the Heat Loss subsystem has higher complexity, and presents different parameters that need to be defined. This refers specifically to the variables within the calculation of the transient heat loss corresponding to the heating of the pipe, which can be observed in the model layout, Annex 8.3.

Firstly, the mass related to the section of pipe needs to be inputted as a constant. This value derives from the analysis of the facility blueprint [8], considering the existent piping between the sensor TS10-02 (control valve inlet, position 1) and the inlet of the turbine (position 1"), as can be seen in Figure 2.6.

Following with the parameter definition, the time constant τ must be established. This factor originates by implementing a graphical analysis of the curves shown in Figure 5.1. These correspond to the measured temperature of the fluid at the valve inlet (orange curve, TS10-02) and at the turbine inlet (grey curve, T110-03), in a time range corresponding to the warm up phase of the facility, between the firsts 130 to 160 s.

It can be observed that the grey curve shows a quasi-logarithmic behaviour, explained by the warm up of the pipe that produces a progressive rise of the measured temperature at the turbine inlet, while the heat retrieved to the pipe mass decreases over time. When the warming of the pipe is finished, this temperature reaches a stationary condition, and the gap between both temperatures is explained only by the heat lost to the ambient.

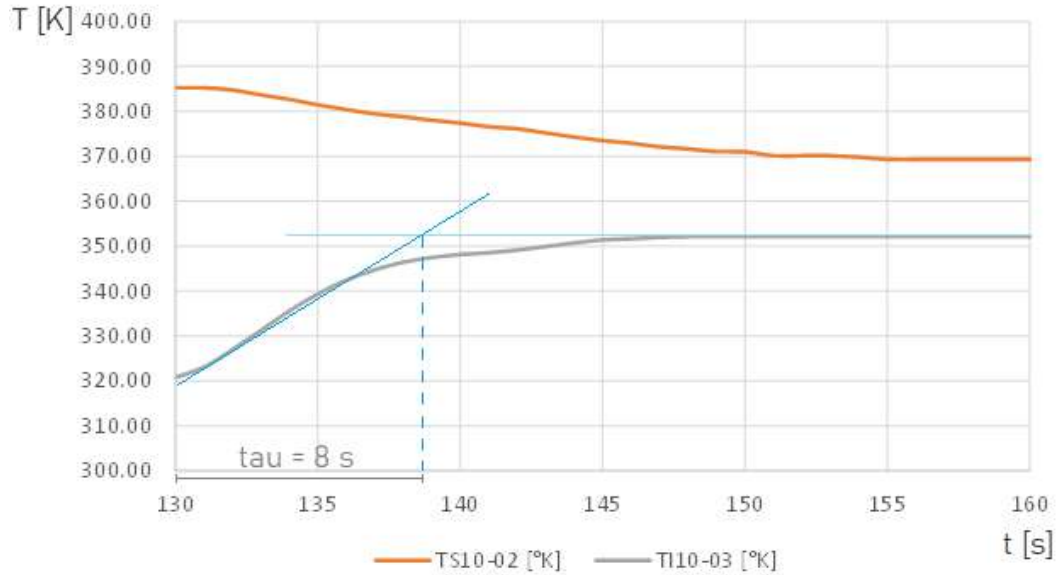


Figure 5.1 Time constant definition from graph of temperature curves vs. time.

The time constant τ is found when analysing the tendency line associated to the warming phase of the pipe, and its value is defined by the time range in which the process can be assumed to be in a transient condition. This approximated factor is defined in the model as a constant block whose value is fixed to $\tau = 8$ s.

Finally, the model presents a block defined as dt/τ , which simply corresponds to the division of the time step used in the simulation by the time constant. Since the time step used is 0,1 s, the value of this block is $0,1 \text{ s} / 8 \text{ s} = 0,0125 \text{ s}$.

5.2 Time-dependant inputs

The final and complete version of the turbine model, which was explained in detail in Chapter 3, was validated employing several sets of selected data retrieved from the test runs performed during November, 2021. From the complete running of the turbine conducted in three different days, eight data sets were selected with a total running duration of ten minutes each. Therefore, the data sets used to validate the model correspond to limited periods within test runs. These selected data sets are defined in Table 5.1.

The selection of these sets was done following specific criteria. In the first place, it was the main objective to validate the model by using time-dependant data corresponding to stationary operation periods of the turbine, with the aim of testing the convergency of the model under stable input conditions. Several data sets that fulfilled this condition were selected, the majority of them corresponding to the last ten minutes of the run, in which the plant tend to achieve its most stationary operation.

Data sets for time-dependant validation		
Data set	MoNiKa run - t period	Overall characteristic
<i>D1 Warm-up</i>	1 st day 12:00:00 – 12:09:59	Period presenting a step corresponding to warm-up phase.
<i>D1R1</i>	1 st day 12:35:00 – 12:44:59	Stationary operation period.
<i>D1R7</i>	1 st day 15:46:00 – 15:55:59	Period presenting transient behaviour due to progressive variation in mass flow.
<i>D2R3</i>	2 nd day 13:10:00 – 13:19:59	Period presenting transient behaviour due to progressive mass flow increase.
<i>D2R8</i>	2 nd day 14:49:00 – 14:58:59	Stationary operation period.
<i>D2R11</i>	2 nd day 15:45:13 – 15:55:12	Period presenting transient behaviour due to progressive variation in mass flow.
<i>D3R3</i>	3 rd day 14:43:00 – 14:52:59	Period presenting oscillation in mass flow and T, p inputs.
<i>D3 Shut-down</i>	3 rd day 16:46:38 – 16:54:57	Period presenting the decay of the variables corresponding to early stages of the shut-down phase.

Table 5.1 Complete sets of time-dependant data used to validate the transient model.

Furthermore, some data sets presenting some variation of the conditions were selected, in order to analyse the capability of the model to follow the variation of the inputs, as a reflection on its outputs. For that matter, cases with progressive variations were selected, as well as a case that presented a clear oscillatory behaviour.

Finally, time-dependant data corresponding to distinctive transient periods were selected. This is the case of the periods corresponding to the warm-up and the shut-down of the turbine, which present a notable step in the variables involved.

As a closing remark, it should be made clear that all the time-dependant data used presents transient periods, even the data associated to stationary operation. This is due to fluctuation of different parameters, the most notable being the variations induced by the oscillating change in the mass flow originated in the piston pump. Furthermore, the complexity of the facility induces the overlapping of many effects that can produce variations in the inputs.

5.3 GESI inputs & results

The comparison with GESI is done in order to picture the capabilities and sensibility of the Simulink transient model. To do so, the same sets of data were selected and averaged to obtain constant inputs, since GESI does not support time-dependant data. Furthermore, the data sets corresponding to the warm-up and the shut-down of the turbine were not tested with GESI, since it is designed to simulate stationary conditions.

GESI requires several inputs not only related to the working substance ORC cycle, but also to the thermal water loop and to ambient conditions relevant to the cooling loop. All the inputs

required were retrieved from MoNiKa's test runs data. In the Table 5.2, the input data used in GESI for each test run is defined.

GESI-Drossel averaged constant inputs							
	Variable / run	D1R1	D1R7	D2R3	D2R8	D2R11	D3R3
<i>ORC</i>	Steam T ($T_{v,in}$)	111,34	107,17	110,27	106,20	104,21	102,23
	Steam p ($p_{v,in}$)	5,50	5,23	5,61	5,14	4,84	4,74
	Condenser outlet T (TI10-05)	11,62	12,96	12,70	13,40	12,90	8,67
<i>Thermal water</i>	Inlet p (PI20-01)	0,82	0,83	0,83	0,84	0,84	0,83
	Inlet T (TI20-01)	150,04	148,44	149,71	149,94	150,63	152,08
	Mass flow [kg/s]	2,4	2,5	2,6	2,6	2,6	2,4
<i>Heat exchanger</i>	T difference	33,3	33,3	33,3	33,3	33,3	33,3
	pressure loss	0,03	0,03	0,03	0,03	0,03	0,03
<i>Condenser</i>	T difference	5	5	5	5	5	5
	pressure loss	0,016	0,016	0,016	0,016	0,016	0,016
<i>Cooling air</i>	Atmospheric p	0,1013	0,1013	0,1017	0,1016	0,1016	0,1014
	T air in	6,6	7,9	7,7	8,4	7,9	3,6
	Rel. humidity %	83,9	61,7	57,8	53,6	52,3	73
<i>Efficiency</i>	Pump	0,96	0,96	0,96	0,96	0,96	0,96
	Turbine	0,85	0,85	0,85	0,85	0,85	0,85
<i>Drossel</i>	pressure loss						
	PS10-02 -> PS10-03	1,439	1,043	0,888	0,334	0,316	0,336

Table 5.2 Complete input data sets used in GESI-Drossel. Temperatures are expressed in [°C], pressures are expressed in [MPa].

In the following images are shown the Rankine cycle diagrams corresponding to each of the data sets studied both with GESI and with the Simulink model. The red points define the beginning of each stage in the cycle, as explained in 2.1.2. In the case of GESI-Drossel, the differentiation is made between the valve inlet and the turbine inlet, since it calculates and shows the effect of the turbine's control valve in the diagram.

These results are briefly analysed with the objective of getting an overview of each run's behaviour. It is interesting to observe the graphical interpretation of each run, especially in order to understand the turbine inlet and outlet conditions. The GESI results can be of great help in order to analyse the Simulink model results, considering that in some of the cases the operation is not optimal and the turbine inlet conditions are too close to the critical point of the propane.

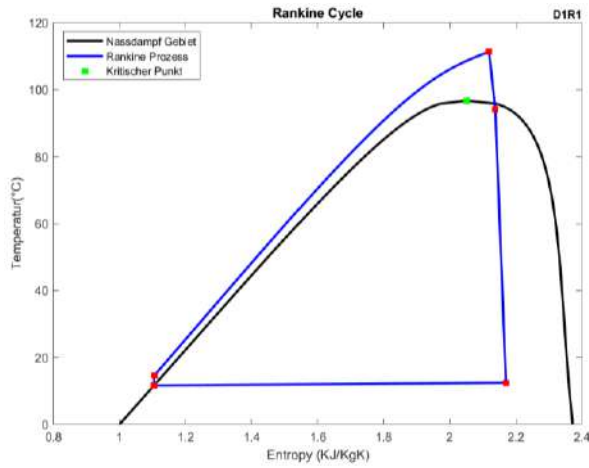


Figure 5.2 D1R1.

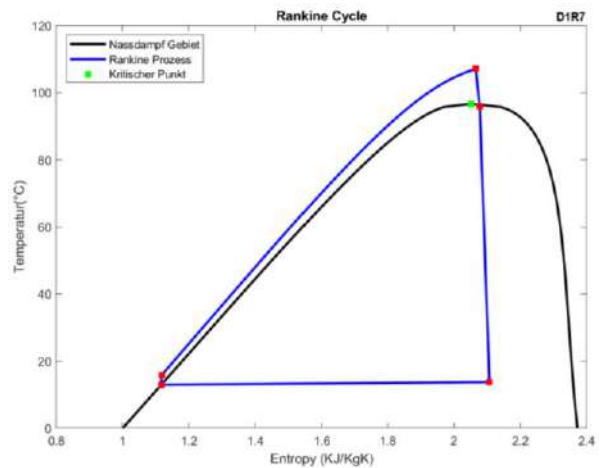


Figure 5.3 D1R7.

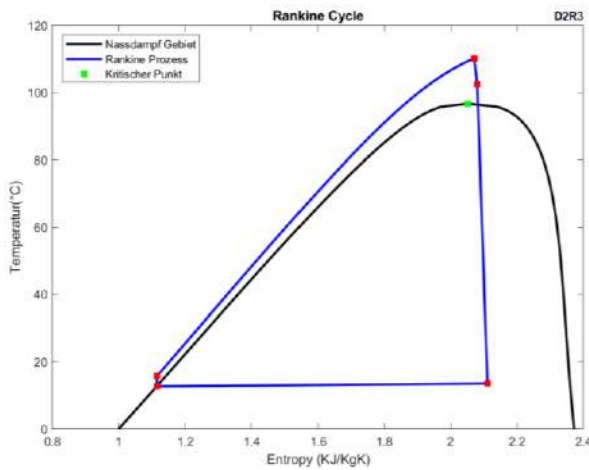


Figure 5.4 D2R3.

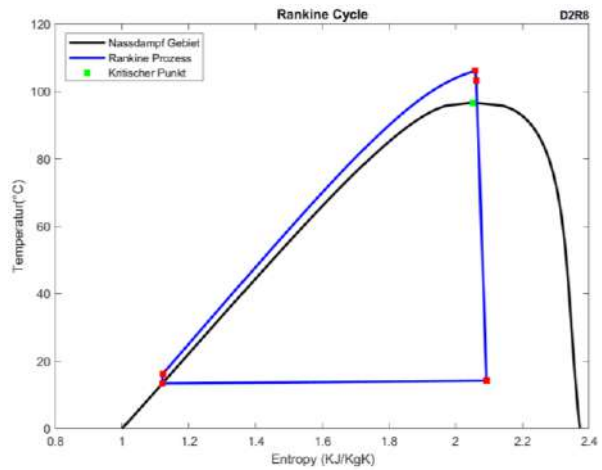


Figure 5.5 D2R8.

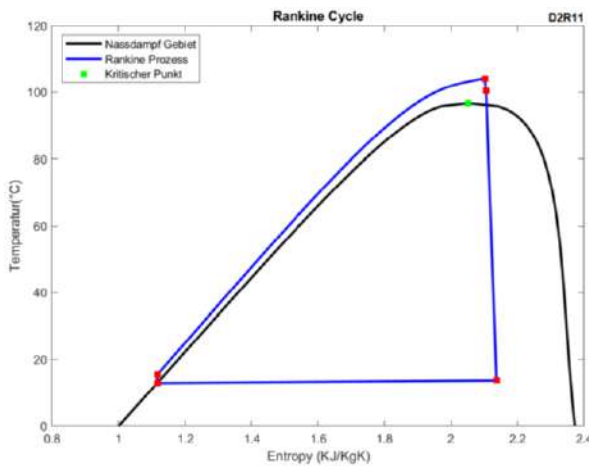


Figure 5.6 D2R11.

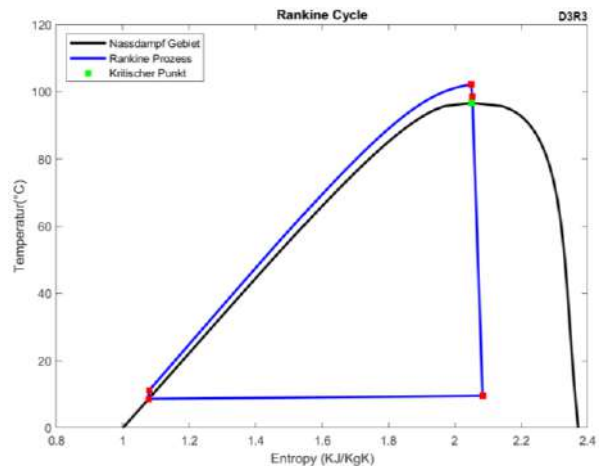


Figure 5.7 D3R3.

According to these results, the test run conditions corresponding to Day 1 (Figure 5.2 and Figure 5.3) show that the fluid at the inlet of the turbine is found at the two-phase region. Regarding the results obtained for the Day 2 (Figure 5.4, Figure 5.5 and Figure 5.6), it is shown that the operation is supercritical in the three cases, which complies with the stable results

obtained for these data sets. Apart from that, in Figure 5.7 can be seen the diagram corresponding to D3R3, showing turbine inlet conditions clearly close to the critical point. This can also be a source of uncertainty in the calculation of the thermodynamic variables, and thus in the simulation results.

5.4 Transient Results

The results presented show the simulation outcome of the turbine power, outlet enthalpy and inlet pressure and temperature values. Furthermore, the resulting turbine efficiency is shown with the aim to present the variability of the efficiency in each run, according to its dependence to pressure and mass flow. Each variable is pictured accompanied by the measurement values and the calculation made with GESI. All the outputs are graphed against Simulink time, which is expressed in seconds.

From all the data sets employed to validate the time dependant model (Table 5.1), only part of them are pictured in this section. The remaining cases can be seen in the Annex 8.8.

5.4.1 Steady state operation

The tested cases corresponding to D1R1 and D2R8 were specially defined out of MoNiKa's test runs data to show the performance of the programme under quasi-stationary running conditions. In this section, the results corresponding to D2R8 are shown, while the results corresponding to D1R1 can be seen in the Annex, 8.8.1.

D2R8 Results

To begin the analysis, it can be observed that the simulated pressure, temperature and power show a characteristic fluctuation of the signal defined by the fluctuation in the mass flow. This is a real variation induced by the feed pump, which being a piston pump kind, generates this characteristic discontinuous flow originated in the back and forth movement of the pistons. The effect in the signals can be repeatedly observed in all the Simulink model results.

The stationary D2R8 results corresponding to the turbine Power can be seen in Figure 5.8. The measured power presents variations but is stationary over time, as the signal can be observed to remain constant around a certain value. This is also true for the simulated power, which follows a constant behaviour. However, the predicted power falls consistently 5 kW approx. below the real power measurement. Furthermore, it can be seen that the simulated constant power obtained by GESI shows a considerable difference of 40 kW approx. from the real power values.

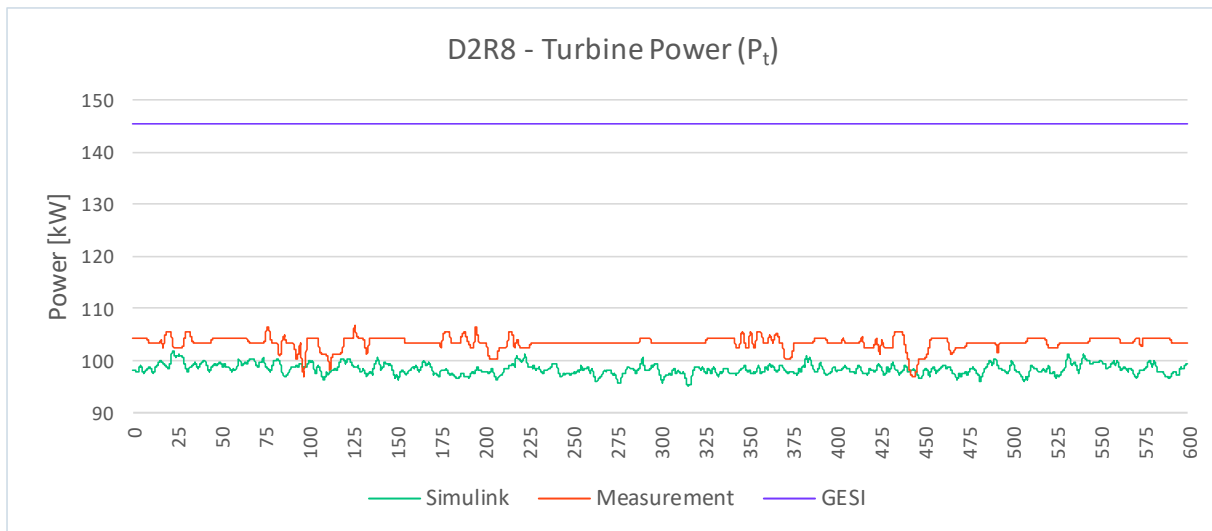


Figure 5.8 Turbine Power results as a function of Simulink time (s), corresponding to D2R8.

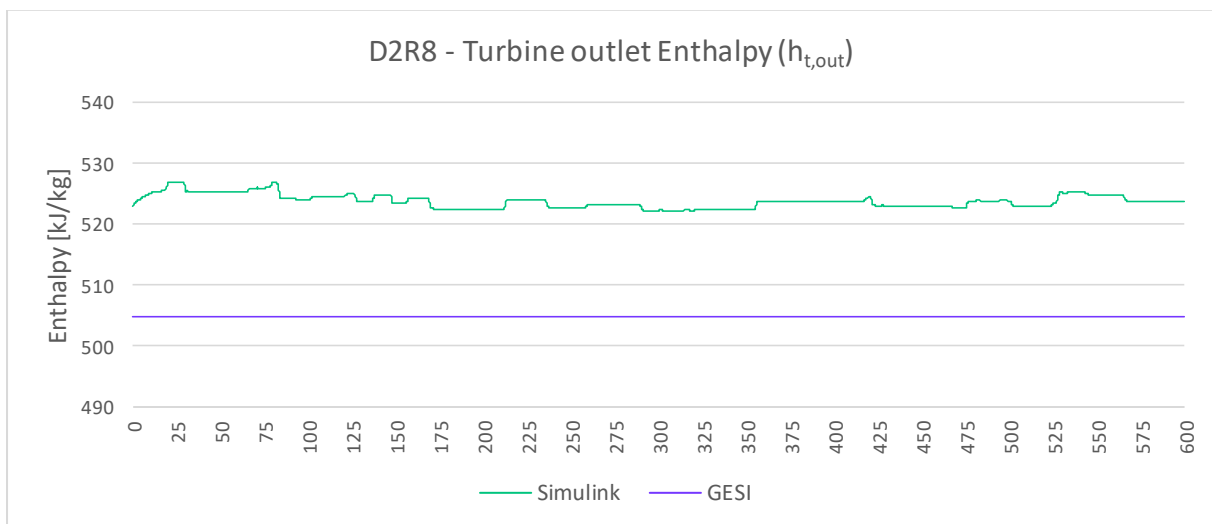


Figure 5.9 Turbine outlet enthalpy results as a function of Simulink time (s), corresponding to D2R8.+

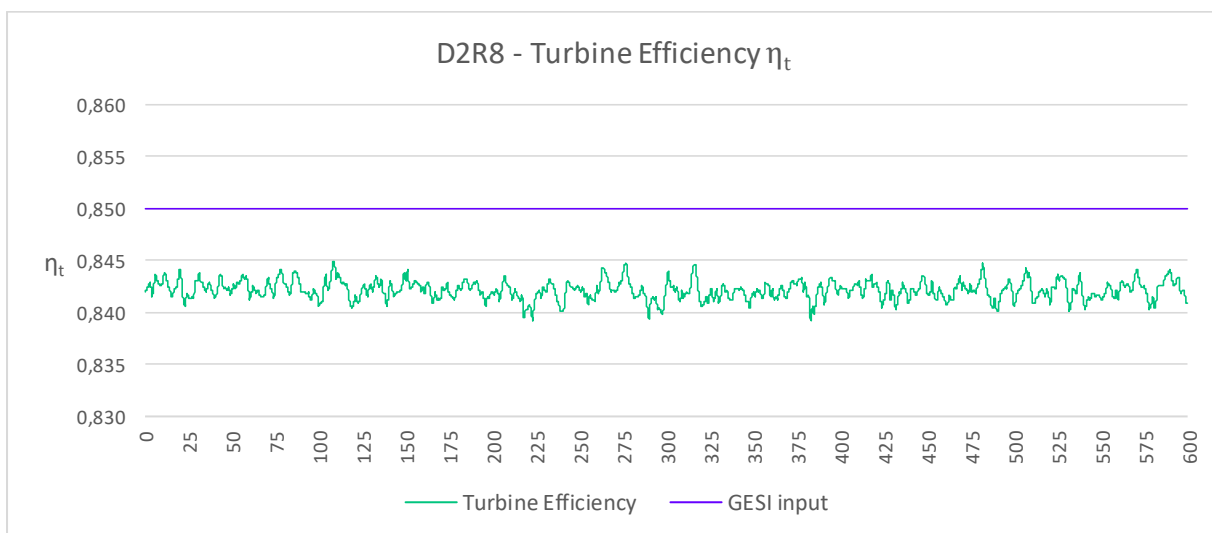


Figure 5.10 Turbine efficiency outcome as a function of time (s), corresponding to D2R8.

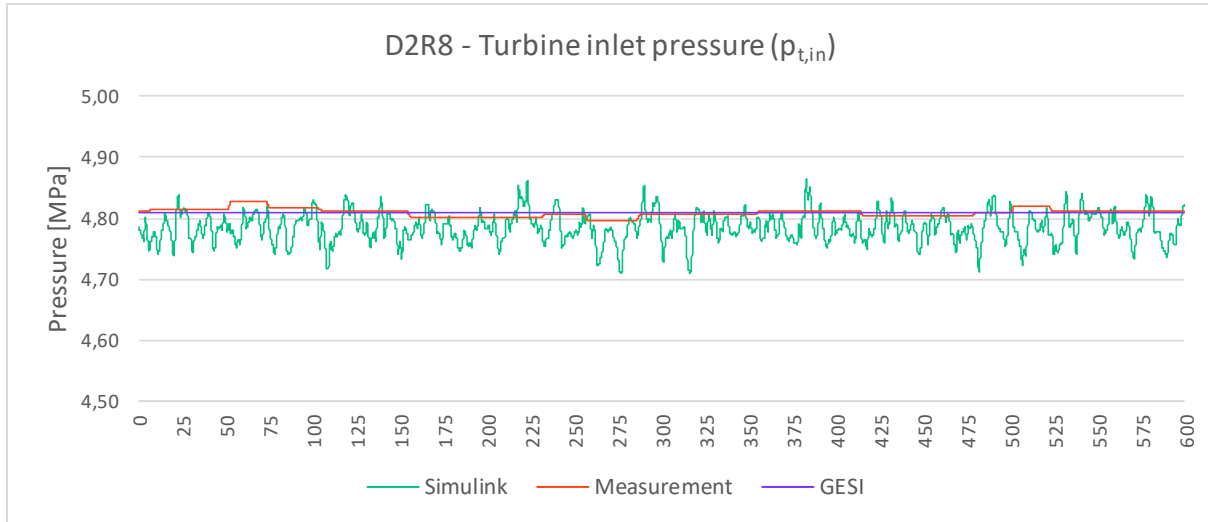


Figure 5.11 Turbine inlet pressure results as a function of Simulink time (s), corresponding to D2R8.

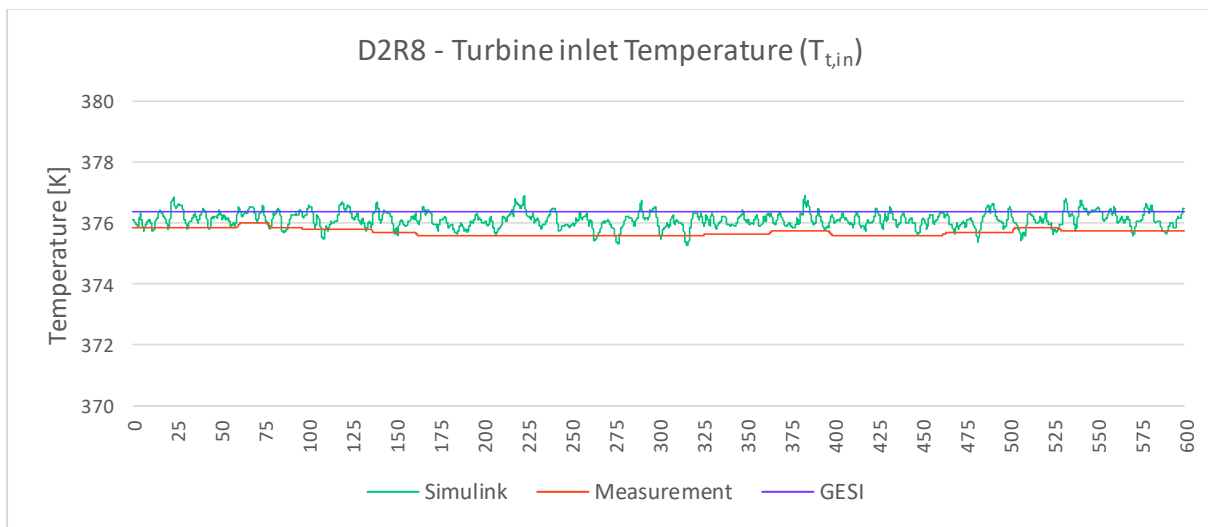


Figure 5.12 Turbine inlet temperature results as a function of Simulink time (s), corresponding to D2R8.

The results corresponding to the turbine outlet enthalpy can be observed in Figure 5.9. It is important to emphasise the fact that the enthalpy is analysed by comparing two simulations. Therefore, none of the curves can be assumed to be the real value of the enthalpy. Nevertheless, it is possible to observe that the Simulink model predicts a higher value of $h_{t,out}$ than the one calculated by GESI, which means a smaller enthalpy change through the turbine and finally a smaller value of power. This is consistent with the fact that the simulated power is lower than the power obtained with GESI.

Before continuing with the analysis of the results, an important observation should be made regarding the power and turbine outlet enthalpy results obtained with GESI. The tendency of low enthalpy values and high power values predicted by GESI is repeated in all the cases analysed. This is actually a consequence of the calculation made with the code, which fixes the condenser outlet pressure as the starting point to calculate all the other variables, assuming

that the state of the propane in that point is of fully saturated liquid. Moreover, nitrogen is not considered in GESI. These assumptions and simplifications are the causes that distance the power and enthalpy predictions from the real behaviour of the turbine. In the analysed cases, it was confirmed that the condenser outlet pressure that GESI employs is lower than the real pressure, thus leading to lower values of predicted enthalpy. Finally, a bigger enthalpy change in the turbine leads to a higher simulated power with GESI.

In the case of the turbine inlet pressure, as seen in Figure 5.11, the results obtained with GESI are definitely accurate. When analysing the output obtained with the Simulink model, it can be observed the foresaid fluctuation due to the mass flow. If one does not consider this fluctuation, the simulation output is also accurate and close to the measured values. Moreover, it can be seen that the amplitude of this fluctuating signal is relatively small, in the order of 0,1 MPa.

A similar analysis can be made regarding the turbine inlet temperature results, as shown in Figure 5.12. Here it can be seen the same kind of signal fluctuation in the Simulink output, but when studying its rough average value, the predicted results are close to the measurement. In this case, GESI outputs a constant result which is briefly higher than the Simulink result, relative to the real measurements.

Regarding the turbine efficiency, as seen in Figure 5.10, it can be observed that for this case, the simulated efficiency according to the correction formula outputs a fluctuating variable with an average value lower than the assumed efficiency of 0,85. This correction could be in part responsible for the accurate prediction of the turbine power.

D1R1 Results

The results corresponding to D1R1 data set can be observed in the Annex, 8.8.1. This case corresponds to a stationary period, which can be observed in the constant tendency of the measured variables. Another important characteristic of this case is that the turbine inlet conditions are subcritical, as can be confirmed by the graphs showing the measured temperature and pressure.

The simulated power results show high compliance with the real power, both the averaged value and the amplitude of both signals. In the case of the comparison between Simulink and GESI predicted enthalpy, Simulink outputs enthalpy values of 15 kJ/kg approx. above GESI result. Regarding the Simulink pressure results, they present fluctuation with an amplitude of 0,2 MPa approx. However, the prediction is close to the measured values. The simulated temperature presents a similar behaviour, though it predicts values that fluctuate 2 K approx. above the measured temperature.

5.4.2 Transient periods

The main objective when validating the model was the testing under conditions that presented a sustained variation over time. To do so, the model was tested under different varying conditions corresponding to the cases D1R7, D2R3, D2R11 and D3R3. From them, the results corresponding to D2R3 and D3R3 were selected to be shown in this section, while the cases D1R7 and D2R11 can be found in the Annex, 8.8.2 and 8.8.3 respectively.

D2R3 Results

Initially, the outputs corresponding to the running D2R3 will be described. In the Figure 5.13, the turbine power results are presented. There it can be observed a progressive increment in the measured power during the first 150 s approx. After that, the power values seem to stabilize around 100 kW. The simulated power tightly follows this increase, thus performing an overall good prediction. However, the model is not able to follow the fluctuation of the signal. With respect to GESI, the simulated constant power is relatively far from the measured power, presenting a difference of near 40 kW above the real values.

The results corresponding to the turbine outlet enthalpy are shown in Figure 5.14. In this case, the enthalpy calculated with Simulink shows higher values than the enthalpy obtained with GESI. With respect to the efficiency outcome, it can be observed in Figure 5.15 an overall decrease of near 0,1 in the efficiency value. This is not exactly what would be expected to find, given that the power is increasing during that period. However, the efficiency reaches a stationary condition of a value around 0,842, which seems to comply well with the power output.

Regarding the turbine inlet pressure and temperature, as seen in Figure 5.16 and Figure 5.17, in both cases it can be observed a good coupling between the measurement curve and the simulated variable during the incremental period and in the stabilization region too. Both outcomes look consistent. However, the T simulation is 2 K approx. higher with respect to the measured values, both in the Simulink output and in GESI result. In these two cases the advantage over GESI is clear, as the program is unable of simulating transient conditions.

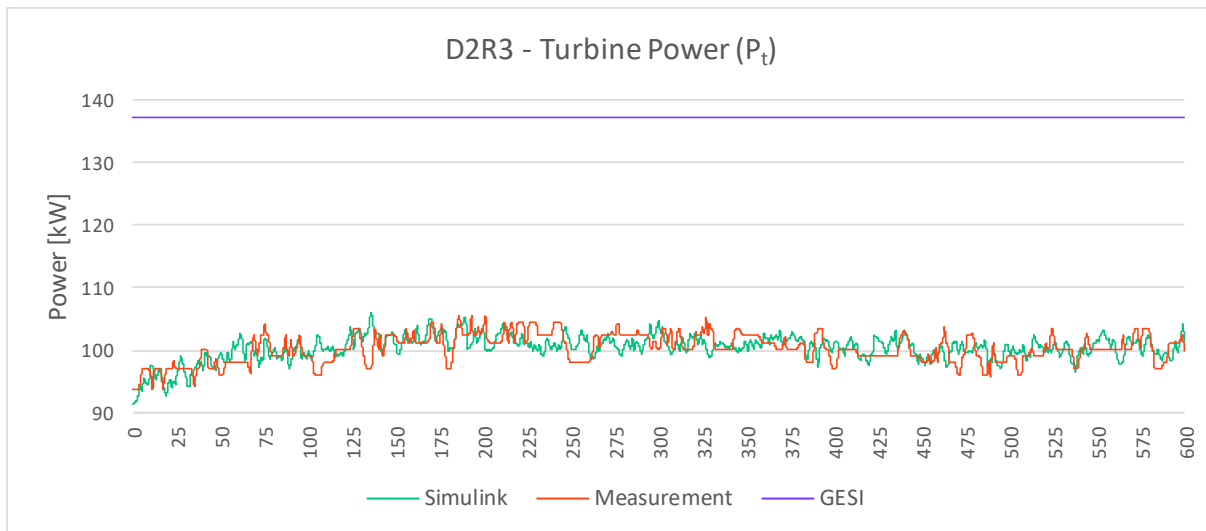


Figure 5.13 Turbine Power results as a function of Simulink time (s), corresponding to D2R3.

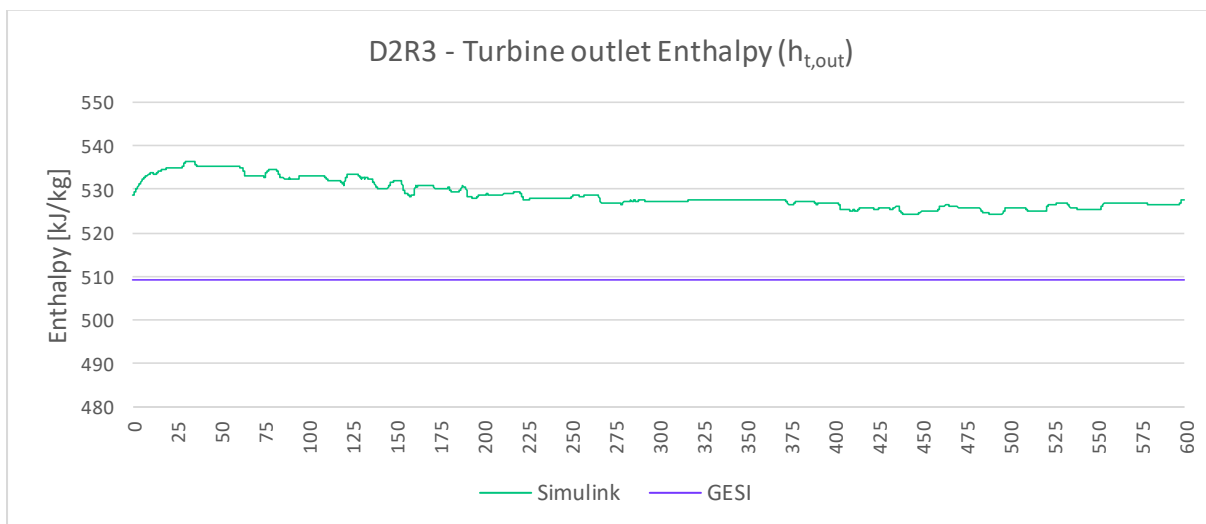


Figure 5.14 Turbine outlet enthalpy results as a function of Simulink time (s), corresponding to D2R3.

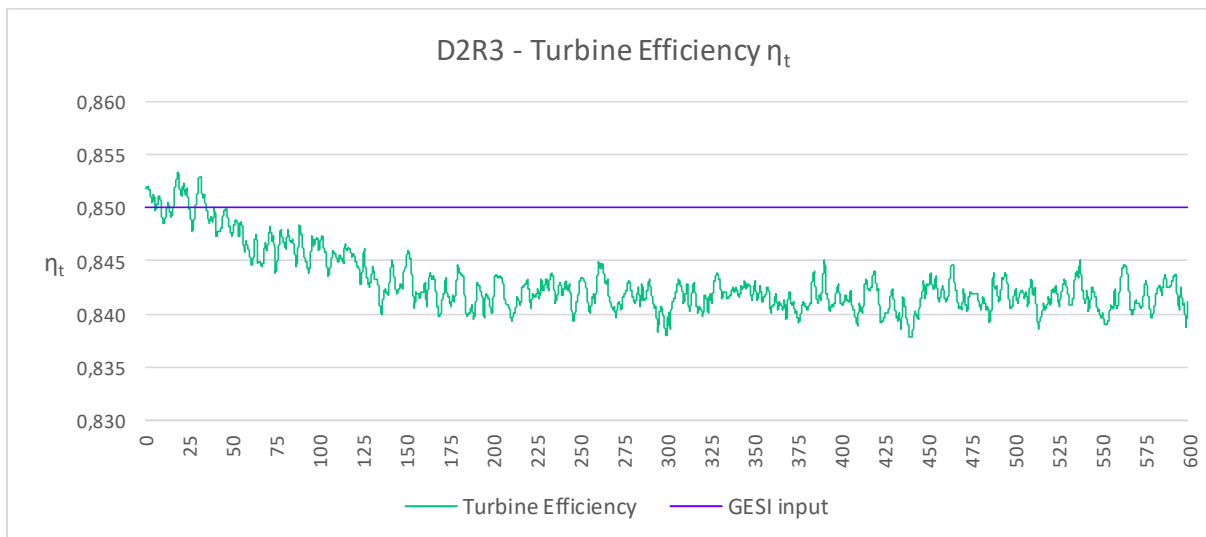


Figure 5.15 Turbine efficiency outcome as a function of time (s), corresponding to D2R3.

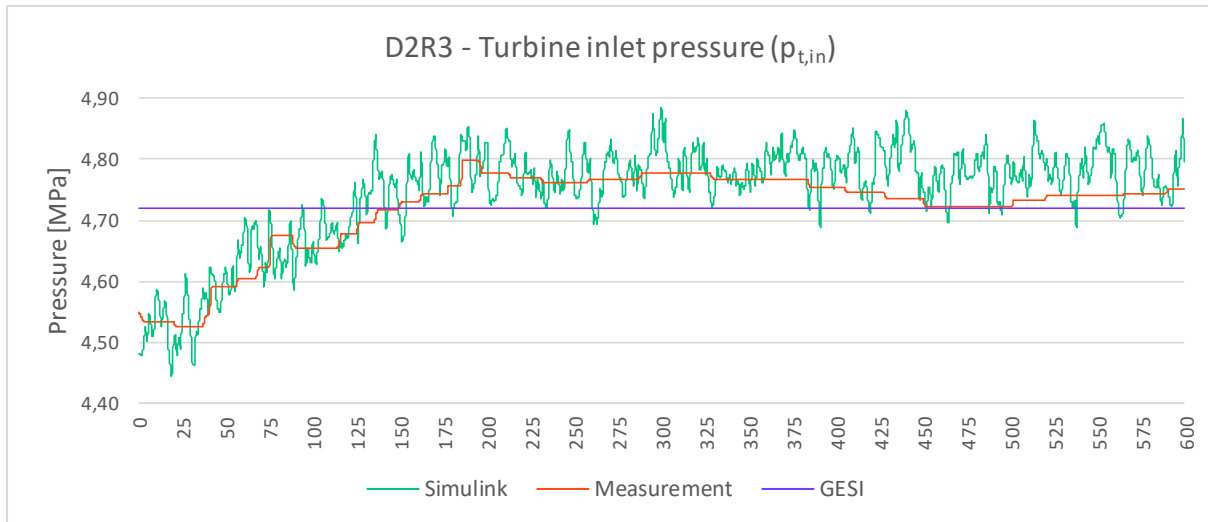


Figure 5.16 Turbine inlet pressure results as a function of Simulink time (s), corresponding to D2R3.

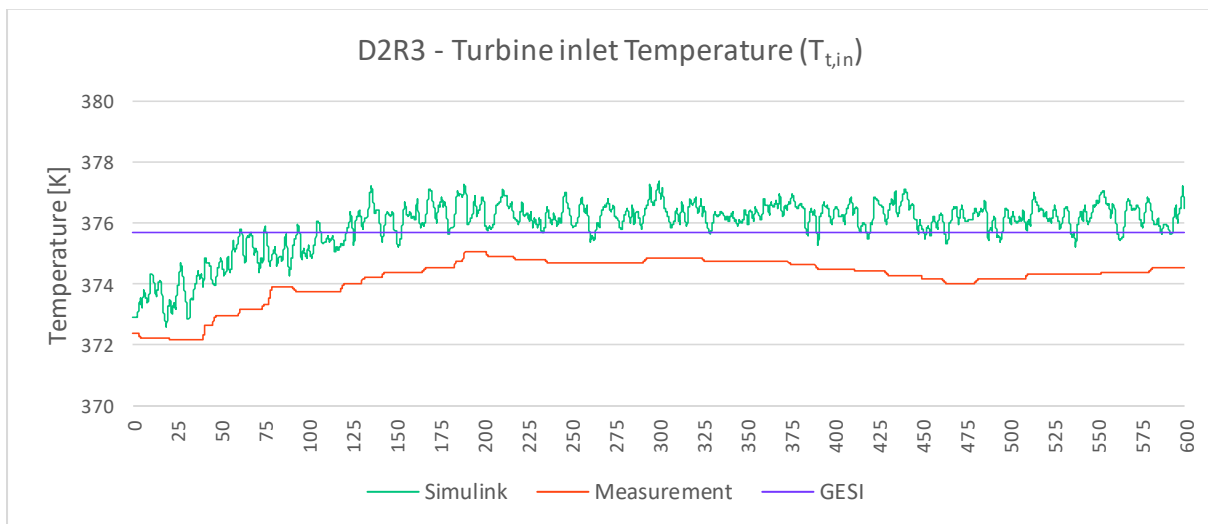


Figure 5.17 Turbine inlet temperature results as a function of Simulink time (s), corresponding to D2R3.

D3R3 Results

Following with the transient condition analysis, the results obtained in the D3R3 case are described. This case was selected for its particular oscillatory behaviour that characterized most of the 3rd day runs. This oscillation has its origin in the conditions reached by the boiler, and replicates in the measurements obtained for the other variables.

In the Figure 5.18, the results corresponding to the D3R3 turbine power are presented. Here the variation of the measured power can be clearly observed, reaching an amplitude of 10 kW approx. At the same time, the Simulink model succeeds to predict the changing behaviour of the power, following the shape of the signal. However, the model consistently falls behind by simulating values of power of around 10 kW less than the actual values. Regarding GESI result, it predicts a value of power that presents a difference of more than 50 kW against the measurement.

Something very similar happens with the outcome corresponding to the turbine outlet enthalpy, as shown in Figure 5.19. As it was observed in the previous cases, the Simulink model again predicts values of enthalpy higher than the ones calculated by GESI. Regarding the turbine efficiency (Figure 5.20), the variable seems to achieve a stationary value fairly above 0,85.

In the case of turbine inlet pressure (Figure 5.21) and temperature (Figure 5.22), neither of the Simulink outputs is able to replicate the oscillatory behaviour of the measured variable. However, the predicted values are close to the real ones, although they present their characteristic fluctuation generated by the mass flow variation. In these simulations, the results obtained with Simulink and the ones obtained with GESI are similar.

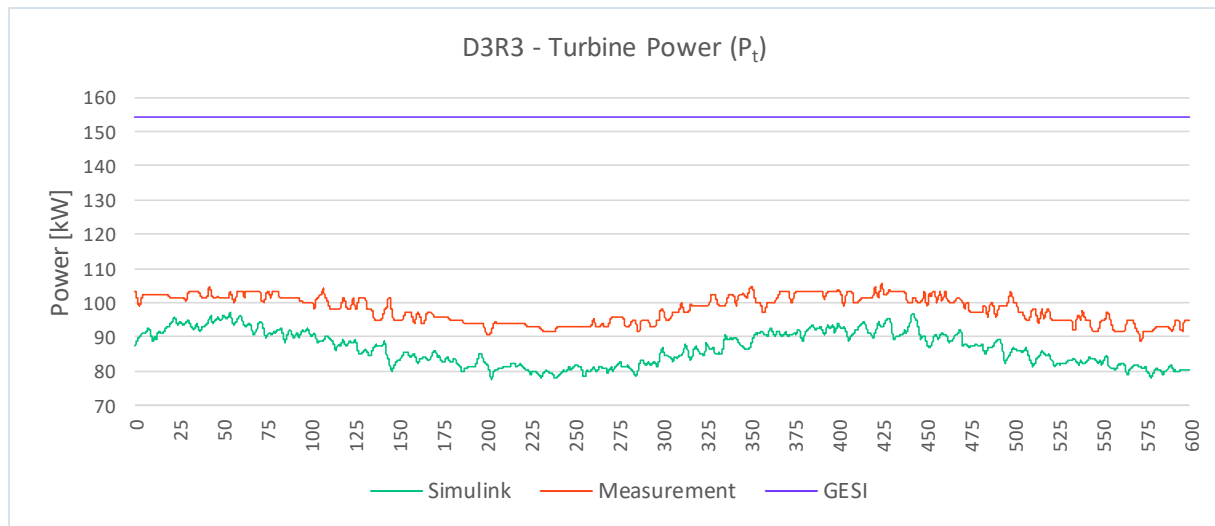


Figure 5.18 Turbine Power results as a function of Simulink time (s), corresponding to D3R3.

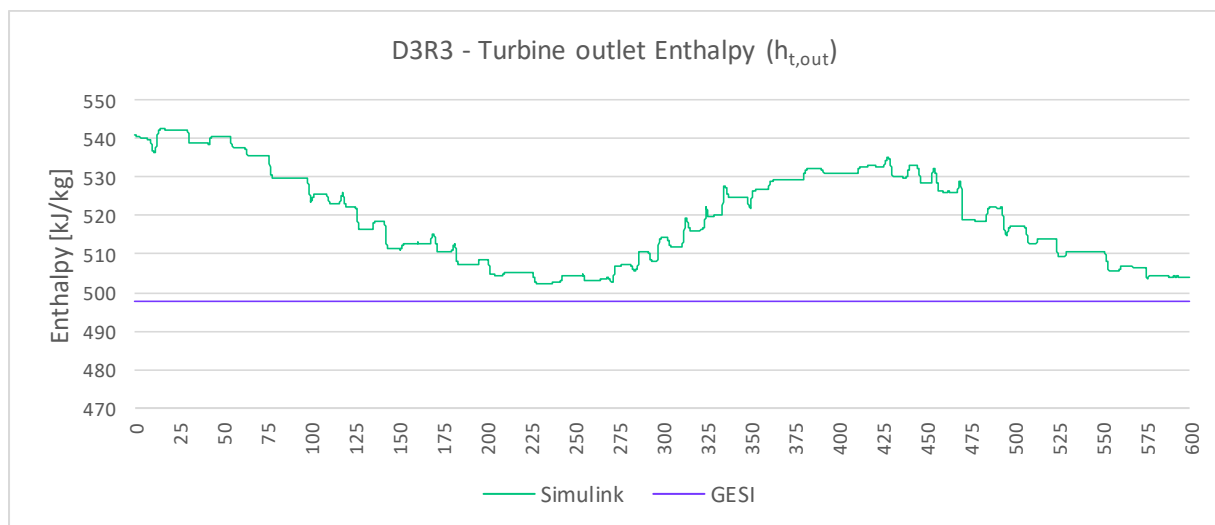


Figure 5.19 Turbine outlet enthalpy results as a function of Simulink time (s), corresponding to D3R3.

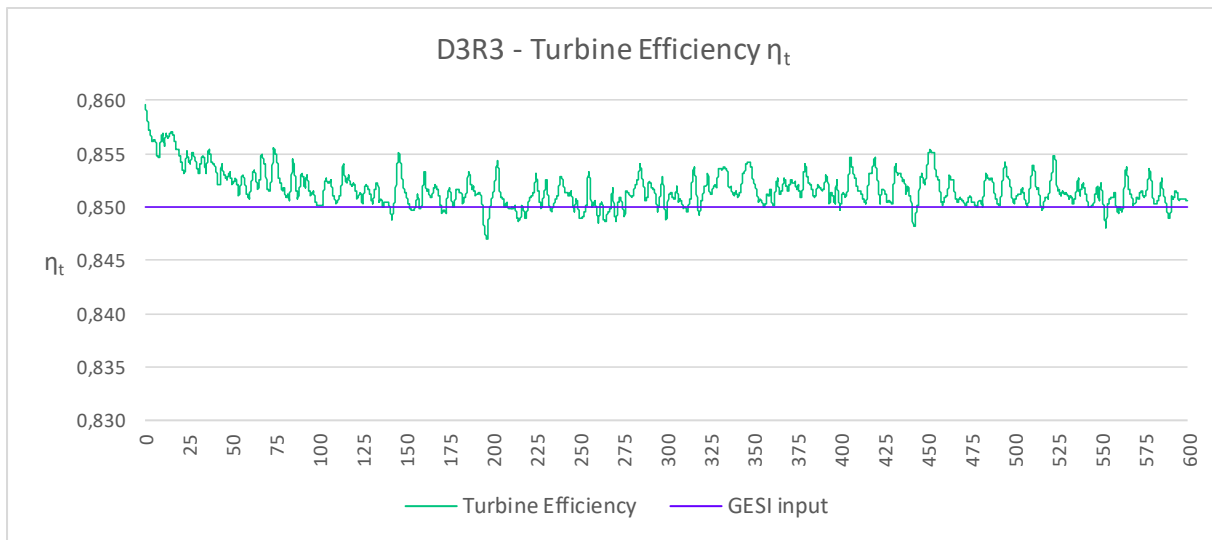


Figure 5.20 Turbine efficiency outcome as a function of time (s), corresponding to D3R3.

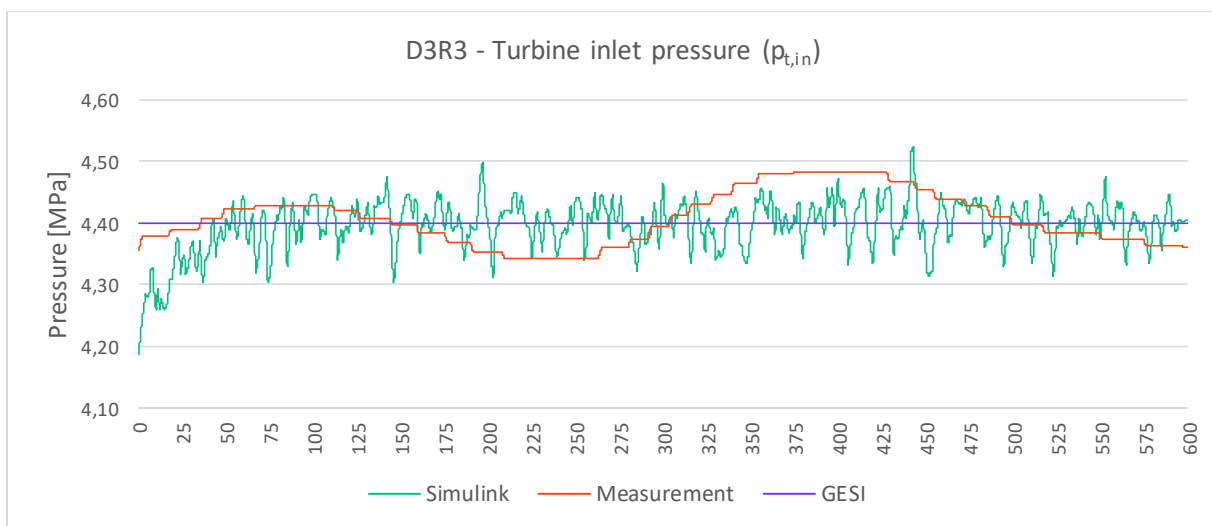


Figure 5.21 Turbine inlet pressure results as a function of Simulink time (s), corresponding to D3R3.

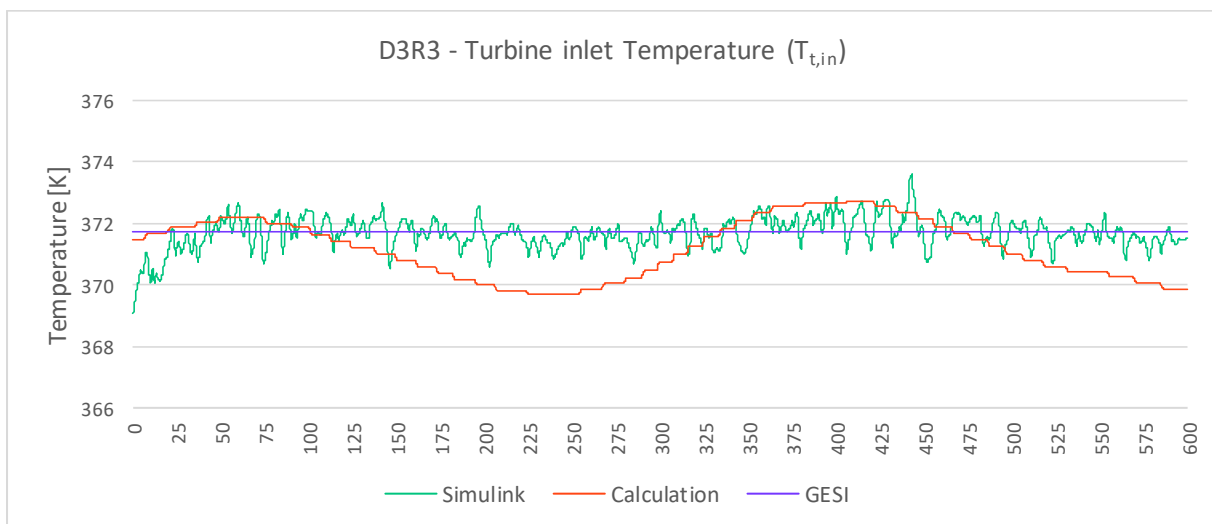


Figure 5.22 Turbine inlet temperature results as a function of Simulink time (s), corresponding to D3R3.

D1R7 Results

The results corresponding to D1R7 data set can be seen in the Annex, 8.8.2. This case is characterized for presenting sharp variations in the measured variables, associated to strongly transient conditions. This test run inlet conditions are located on the limit between the two-phase region and the supercritical fluid. The predicted power in this case matches the measured values only during the first 100 s of simulation. After that, the results diverge. This is repeated also in the outcome corresponding to pressure and to temperature. In these variables it can be clearly observed the variability of the measured signals.

D2R11 Results

In the Annex 8.8.3, the results corresponding to D2R11 can be observed. This case shows a slight transient behaviour in the measured pressure, which drops 0,1 MPa approx. during the first 100 s. Besides this effect, the run can be considered stationary. The simulated power is consistent in following the real signal tendency, although the results are approx. 10 kW behind the real power measurement.

As a difference to the previous cases, the simulated results corresponding to temperature and pressure are slightly lower than the measured values, therefore showing an opposite tendency than what was observed in all the previous cases. Regarding the variation in the measured pressure, the signal shape is followed by the simulation. In both T and p results, GESI is accurate compared to the real values.

Shut-down period

The shut-down simulation results can be observed in the Annex, 8.8.4. In that case, the Simulink results clearly show that the model is not able to follow the strong decreasing of the variables studied. The simulated power, temperature and pressure show a slight decrease, but are far from the real values.

5.4.3 Warm-up effect

The turbine model behaviour under transient conditions was tested using the data corresponding to the warm-up on Day 1. During this period, the turbine's control valve is opened for the first time, and the propane starts flowing through the pipe and into the turbine. This is reflected in the measurements of valve inlet temperature (Figure 5.23) and turbine inlet temperature (Figure 5.24). The $T_{v,in}$ shows constant temperature until 130 s. At that point, the valve opens and the temperature decreases drastically due to the steam expansion. After some time, the temperature stabilizes to a certain constant value.

Apart from that, the turbine inlet temperature remains at ambient condition as long as there is no flow of propane. When the valve opens, this temperature increments quickly and also reaches a constant value after some time.

The warm-up effect can be observed in the steel temperature as a delay in comparison with the fluid temperature. The temperature of the steel follows the value of the fluid temperature, and stabilizes within the period defined by the time constant τ .

Regarding the turbine inlet temperature, it would be expected to also achieve a simulated result which complies with the measured temperature, and that reflects this delayed warm up behaviour. However, the simulated temperature does not correspond the measured values. Moreover, it shows an asymptotic condition in the period corresponding to the opening of the valve, caused by the sudden variation in the model inputs ($T_{v,in}$ and $p_{v,in}$).

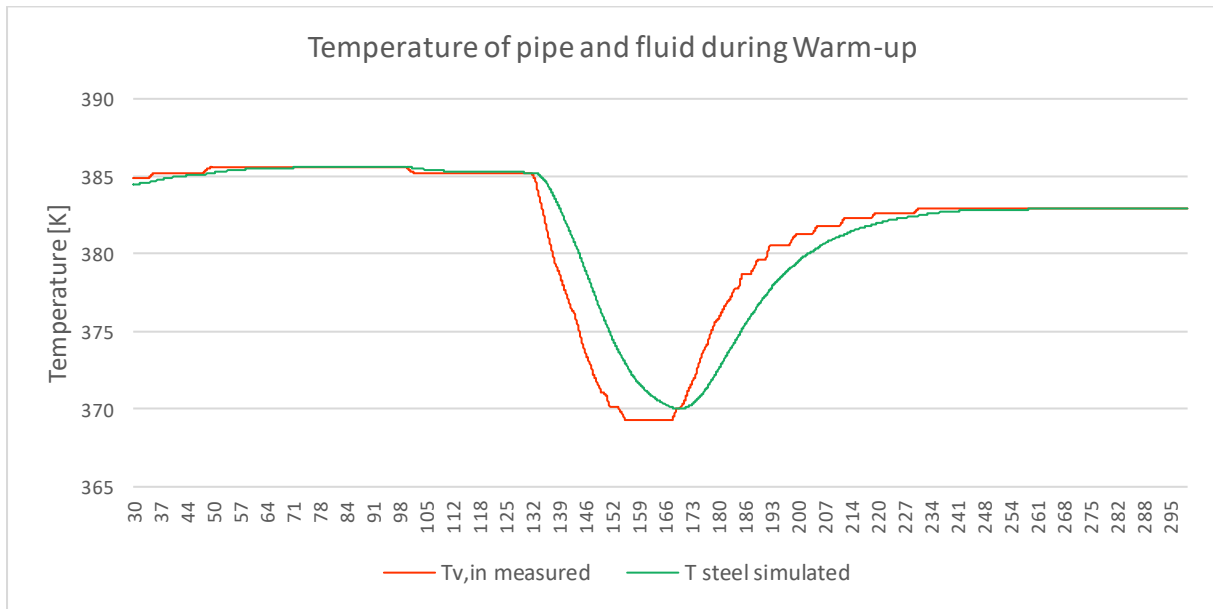


Figure 5.23 Comparison of measured valve inlet T and steel T during warm-up of Day 1.

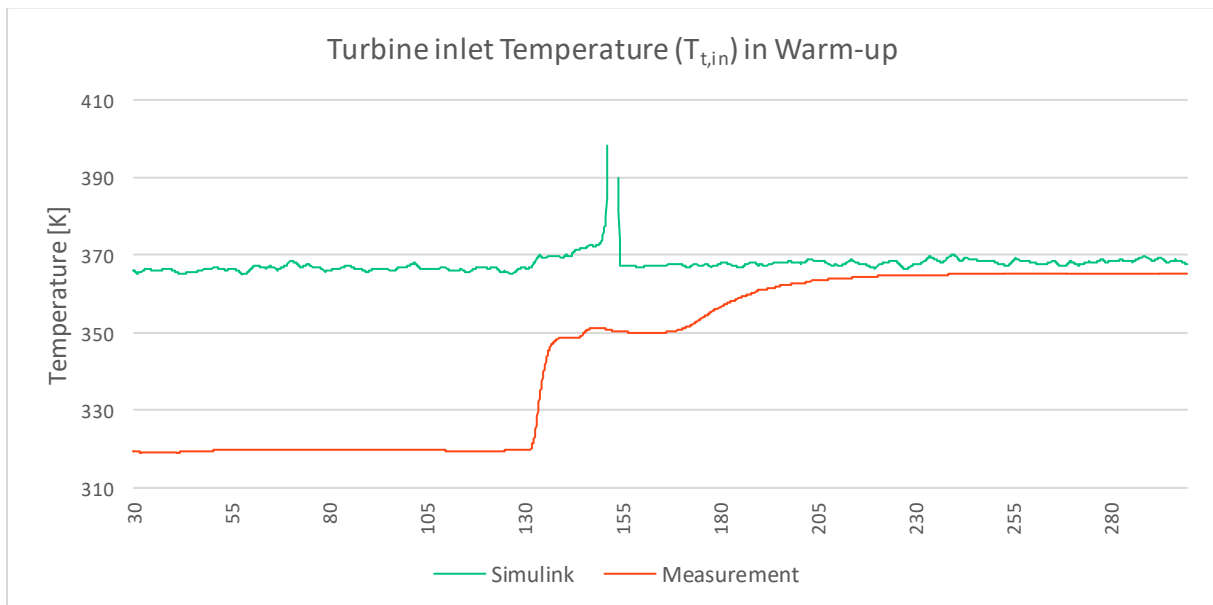


Figure 5.24 Turbine inlet temperature results as a function of Simulink time (s), corresponding to Day 1's Warm-up period.

6. CONCLUSIONS

In this final part, the closing remarks are given to summarize the work done. In the first place, the main objective of the thesis work should be recalled, which was the development of a MoNiKa turbine model capable of obtaining consistent results over a wide operating range, being able to define the fluid state at the inlet of the turbine. After analysing several cases that presented turbine inlet conditions located in the supercritical region and also some that were located inside the two-phase region, it can be concluded that the model is capable of performing accurate simulations in both cases.

For that matter, the temperature and pressure were iteratively found by employing enthalpy values and working with LookUp tables. This way of modelling proved to be successful and brought versatility to the model, making possible to achieve fluid definition results at the turbine inlet which are close to the measurements. However, it should be pointed out that these calculations still need refinement in order to lower the error against the real values.

Apart from that, when considering the temporal behaviour of the test runs, the model is consistent in simulating stationary conditions, and is capable of predicting progressive and relatively slow transient conditions. Since the model is based in Stodola's equation, which is only applicable to stationary conditions, it is not suitable for simulation of fast variations such as the transient conditions encountered during the warm-up and shut-down of the turbine.

The simulated results show some marked tendencies on each of the variables. In general, the model predicts power results consistently below the measured values. With respect to the turbine inlet temperature, it is observed a sustained prediction of values approx. 2 K above the measured data. In the case of the pressure, the results show accuracy and fluctuate 0,1 MPa approx. around the measured pressure values.

Another important subject to assess is the modelling of transient effects upstream the turbine. This was achieved by the addition of the transient heat transfer section, that calculates by applying an Initial Value Problem method. The results showed that it is possible to model the steel temperature with delayed warm up effect, but no validation could be made since there is no measured data related to this temperature. In this period, the turbine inlet conditions cannot be successfully predicted by the model given its sharp variability.

Regarding the turbine efficiency behaviour, it was observed that the calculated efficiency is not completely accurate since its dependence with pressure and mass flow leads to fake variation tendencies, as it was previously prognosed in J. Mardon Pérez thesis [1]. An example of it is that according to the correlation, when power increases, efficiency decreases. It is also

relevant the fact that the turbine efficiency should not be taken as a fixed constant. Therefore, the analysis seems to have potential to achieve an optimal correlation, but more work must be done in order to understand the complete influence of other variables over the efficiency.

Due to the simple, linear equations that compose the programme, the error between the measurement and the simulated values is limited to finite quantities. Therefore, the model does not show divergency over time. However, there is a great impact of the mass flow signal variation in all of the outputs, since they have a direct dependence with it. A possible improvement is to include a signal filtering block to smooth the fluctuation of the mass flow, which could lead to better lecture and understanding of the simulation outcome.

Recalling the use of the LookUp tables, another important feature is the ability to load the tables just once, and then work with the stored data in the Workspace. This is very advantageous since it drastically reduces the compilation and simulation time needed to run the model, and therefore allows its coupling to a bigger model of the plant.

With respect to the structure of the model, even though the inputs and parameter loading is well conducted, there are still some specific parameters that must be manually loaded. This is uncomfortable to work with, and could even be a source of error specially in the case of running many simulations with differing conditions. An improvement would be also to automatize the inputting of these values from a centralized block.

Regarding the comparison against GESI, it proved to be of great help in order to better understand the cycle, specially the turbine inlet conditions. However, it should be pointed out that the employed version of the program is not able to accurately simulate the turbine outlet conditions and the condenser behaviour, given the current characteristics of the real test runs. This could be caused by the increased content of N_2 in the cycle, among other reasons that deserve a detailed future study in order to improve the code.

Based on this work, a relevant future study would be to further analyse and understand the relation between the variables that compose the plant, trying to set correlations between coupled effects from the different elements which are part of the cycle. Furthermore, a logical next step would be to develop a one-dimensional model of the turbine that considers the variation of the parameters progressively inside it.

Another interesting task would be to make a new effort in connecting the turbine model to the condenser model. To do so, real run data should be obtained with the objective of producing data sets that can be coherent both with the condenser and the turbine model. Furthermore, another approach should be made regarding the calculation flow of the turbine model, in order to achieve a linear resolution method that first calculates the turbine outputs and then enters the condenser model.

7. REFERENCES

- [1] Mardon Pérez J. Experimental examination of the MoNiKa-ORC-Turbine and comparison of the results with thermodynamical calculation. KIT. Karlsruhe; 2022.
- [2] Breeze P. Power Generation Technologies. 3rd ed.: Elsevier. 978-0-08-102631-1; 2019.
- [3] Wiemer H-J, Schneider VB (eds.). Thermodynamical and Economical Valuation of low-temperature ORC with Alternative Working Fluids. Reykjavik, Iceland; 2020.
- [4] Kuhn D. MoNiKa am ITES, 2022; Available from: <https://www.monika.kit.edu/index.php>.
- [5] DiPippo R. Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact. 3rd ed.: Elsevier. 978-0-08-098206-9; 2012.
- [6] Çengel Y, Boles M. Termodinámica. 7th ed.: McGraw-Hill. 978-607-15-0743-3; 2012.
- [7] REFPROP: Reference Fluid Thermodynamic and Transport Properties: NIST Standard Reference Database; 2010.
- [8] M+M Turbinen-Technik GmbH. GT 120-4 Turbine Datasheet.
- [9] Vetter C. Thermodynamische Auslegung und transiente Simulation eines überkritischen Organic Rankine Cycles für einen leistungsoptimierten Betrieb. KIT. Karlsruhe; 2014.
- [10] Fossati MJ. Transient Simulation and Validation of a Condenser for a Supercritical Organic Rankine Cycle. KIT. Karlsruhe; 2020.
- [11] Strauß K. Kraftwerkstechnik: zur Nutzung fossiler, nuklearer und regenerativer Energiequellen. 4th ed.: Springer. 3-540-64750-3; 1998.
- [12] Kreith F, Manglik R. Principles of Heat Transfer. 7th ed.: Cengage. 0-495-66770-6; 2011.
- [13] Gardella L. Analysis and Evaluation of MoNiKa's first results in bypass configuration. Karlsruhe; 2019.
- [14] Yang WY. Applied Numerical Methods using MATLAB: John Wiley & Sons. 0-471-69833-4; 2005.

8. ANNEX

8.1 Table Generator – MATLAB code

```

%% Table generation code to be used by Simulink in Lookup tables
% Julia Filipe. ITES-KIT. April 2022.

% The code generates a matrix with enthalpy values taken from REFPROP, for
% different values of p and T. Only supercritical data (control valve inlet
% assumed supercr.)

% result = refpropm(prop_req, spec1, value1, spec2, value2, substance1)
% p_crit = 4251.2; % [kPa] Propane critical pressure

pv_in_values = 4260:50:7250; % turbine inlet pressures seed vector
(Refpropm: kPa)

Tmin = 369.70; % [K] Propane critical T
Tmax = 399.60; % [K]
Tv_in_values = Tmin:0.2:Tmax; % turbine inlet Temperatures seed vector

% Enthalpy table generation h,s = f(p,T)
hv_in_matrix = zeros(size(pv_in_values,2) , size(Tv_in_values,2));

for i = 1:size(pv_in_values,2)
    for j = 1:size(Tv_in_values,2)
        hv_in_matrix(i,j) =
refpropm('H','T',Tv_in_values(j),'P',pv_in_values(i),'PROPANE'); % [J/kg]
        hv_in_matrix(i,j) = hv_in_matrix(i,j)*10^-3; % h conv. to [kJ/kg]
        j=j+1;
    end
    i=i+1;
end

% Entropy table generation s = f(p,h)
h_min = min(hv_in_matrix, [], 'all')*10^3; % [J/kg]
h_max = max(hv_in_matrix, [], 'all')*10^3; % [J/kg]
h_values = h_min:2600:h_max; % turbine inlet entropies seed vector
st_in_matrix = zeros(size(pv_in_values,2) , size(h_values,2));

for i = 1:size(pv_in_values,2)
    for j = 1:size(h_values,2)
        st_in_matrix(i,j) =
refpropm('S','H',h_values(j),'P',pv_in_values(i),'PROPANE'); % [J/(kg*K)]
        st_in_matrix(i,j) = st_in_matrix(i,j)*10^-3; % Conv. to [kJ/(kg*K)]
        j=j+1;
    end
    i=i+1;
end

pv_in_values = pv_in_values*10^-3; % p conv. to [MPa]

%% Isentropic outlet Enthalpy table - w/ 0.2% N2
% The code generates a matrix with enthalpy values taken from REFPROP, for
% different values of p and s. Used to calculate turbine outlet isentropic
% enthalpy with Nitrogen content of 0.2%

pt_out_values = 500:50:3450; % turbine out pressures seed vector [kPa]

```

```

s_min = min(st_in_matrix, [], 'all')*1000; % [J/kg*K] min s given by s
matrix (minimum st_in signal)
s_max = 2370.5; % [J/kg*K] sat. entropy for pt_out_max
s_values = s_min:5:s_max; % turbine inlet entropies seed vector

% Enthalpy table generation h = f(p,s) - isentropic expansion
hts_out_matrix = zeros(size(pt_out_values,2) , size(s_values,2));
% result=refpropm(prop_req, spec1, value1, spec2, value2, substance1,
substance2, ..., x)

for i = 1:size(pt_out_values,2)
    for j = 1:size(s_values,2)
        hts_out_matrix(i,j) =
refpropm('H','P',pt_out_values(i),'S',s_values(j),'PROPANE', 'NITROGEN',
[0.998 0.002]);
        hts_out_matrix(i,j) = hts_out_matrix(i,j)*10^-3;

        j = j+1;
    end
    i = i+1;
end

pt_out_values = pt_out_values*10^-3; % p is converted to [MPa]
s_values = s_values*10^-3; % s is converted to [kJ/kg*K]

%% Temperature table as f(p,h)
% The code generates a matrix with T values taken from REFPROP, for diff.
% values of p and h. Used inside MLfunction block to find Tt_in - iterative

pt_values = 2000:80:5920; % turbine inlet pressures seed vector
Tt_matrix = zeros(size(pt_values,2) , size(h_values,2));

for i = 1:size(pt_values,2)
    for j = 1:size(h_values,2)
        Tt_matrix(i,j) =
refpropm('T','P',pt_values(i),'H',h_values(j),'PROPANE');

        j = j+1;
    end
    i = i+1;
end

pt_values = pt_values*10^-3; % p is converted to [MPa]
h_values = h_values*10^-3; % h is converted to [kJ/kg]

```

8.2 Stodola's law – MATLAB function block code

```
function [pt_in, Tt_in]= Stodola(Mdot, ht_in, pt_out, Tt_matrix, h_values,
pt_values)

%% Iterative determination of turbine inlet T and p
% Julia Filipe. ITES-KIT. April 2022.

% Prediction of turbine inlet temperature (Tt_in) and pressure (pt_in) by
% iteration of T. This calculation can obtain T and p at subcritical
% (two-phase) conditions.

% Inputs (measured / calculated from measurements):
% Mdot          [kg/s] mass flow
% ht_in         [kJ/kg] turbine inlet enthalpy
% pt_out        [MPa] turbine outlet pressure

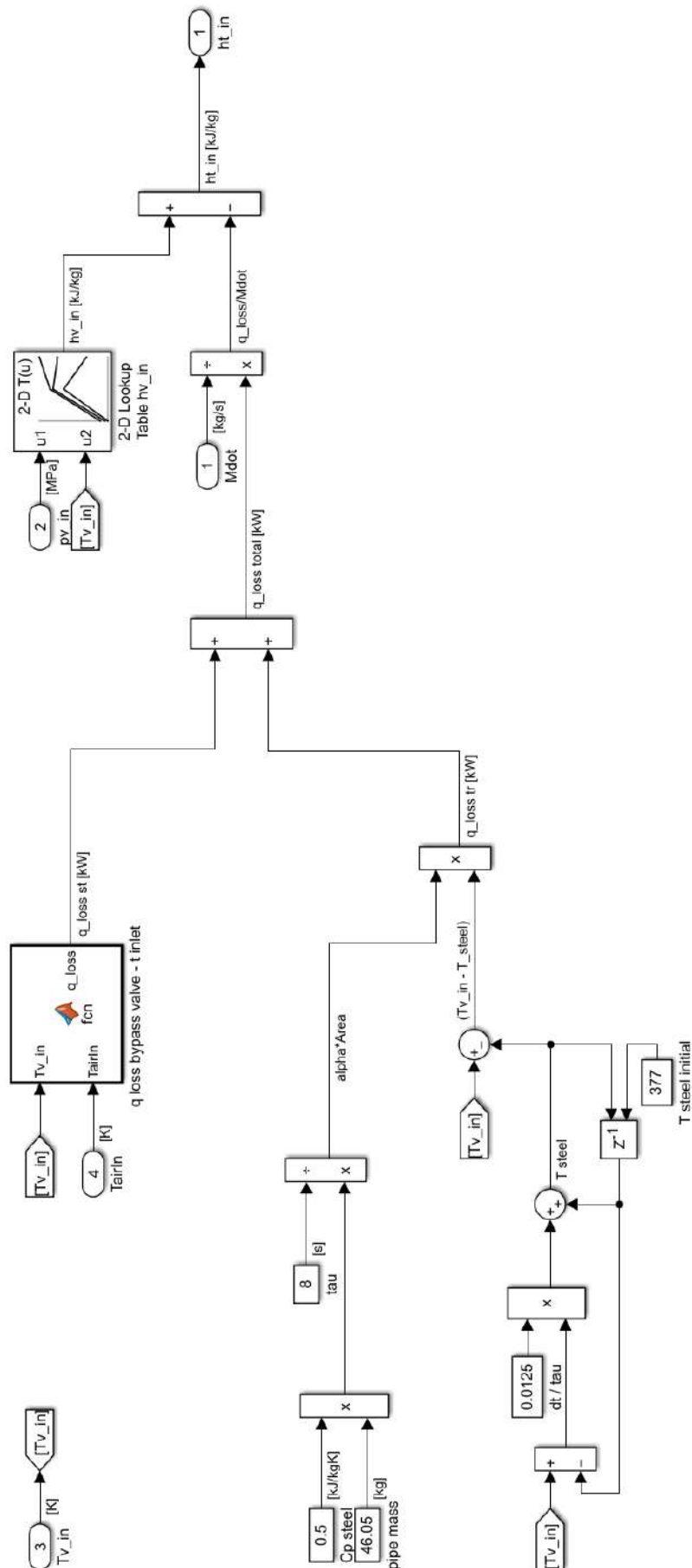
Mdot_des = 2.9;      % [kg/s] design mass flow
pt_in_des = 5.5;     % [MPa] turbine inlet design pressure
pt_out_des = 1.1;    % [MPa] turbine outlet design pressure
Tt_in_des = 390.15;  % [K] turbine inlet design T
F_des = Mdot_des^2*Tt_in_des/(pt_in_des^2 - pt_out_des^2); % [kg^2*K/MPa^2]
% Design constant factor

% Stodola correction factors, results obtained by J. Mardon Perez (ITES-
% KIT, April 2022)
c = 1.5442;          % non-dimensional; = a in linear equation: y = ax + b
c_dash = -1.3352;    % [kg/s] = b in linear equation: y = ax + b

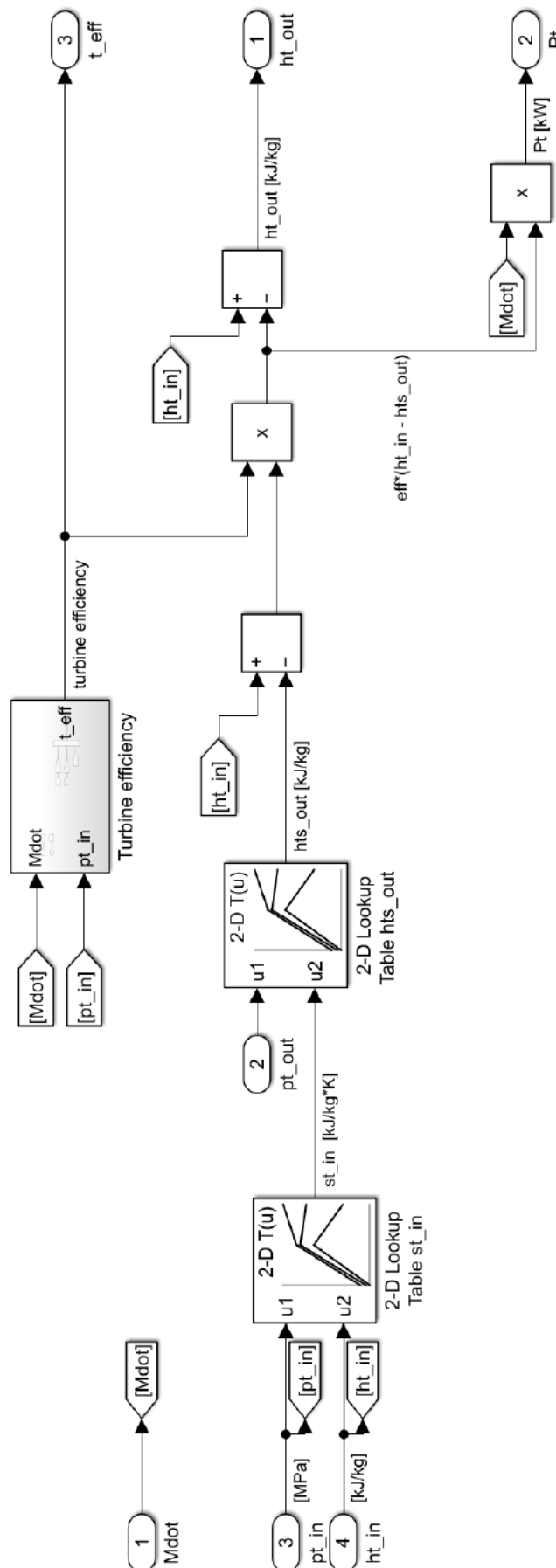
Tt_in = Tt_in_des;   % [K] Initial iteration guess
pt_in = 0;
i = 0;               % iteration
imax = 10;           % max iteration
Tdifff = 10;         % difference bt. consecutive T obtained by iteration

while Tdifff > 0.01 && i < imax
    pt_in = sqrt(pt_out^2 + (Tt_in*(Mdot - c_dash)^2)/(F_des*c^2)); % [MPa]
    Tt_in_new = interp2(h_values, pt_values, Tt_matrix, ht_in, pt_in); % [K]
    Tdifff = abs(Tt_in_new - Tt_in); % [K]
    Tt_in = Tt_in_new; % [K]
    i = i + 1;
end
end
```

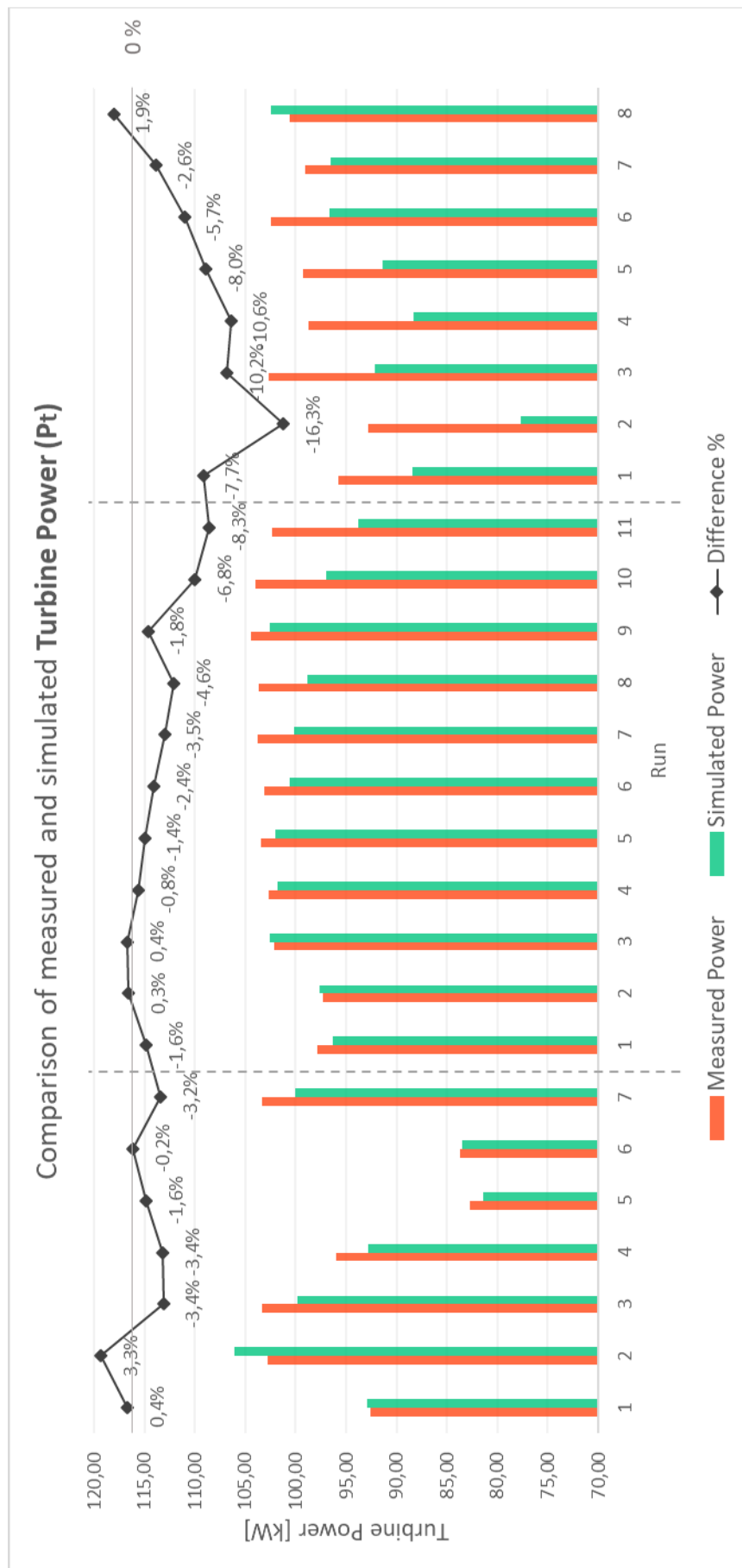
8.3 Heat Loss subsystem – Simulink model



8.4 Energy Balance subsystem – Simulink model

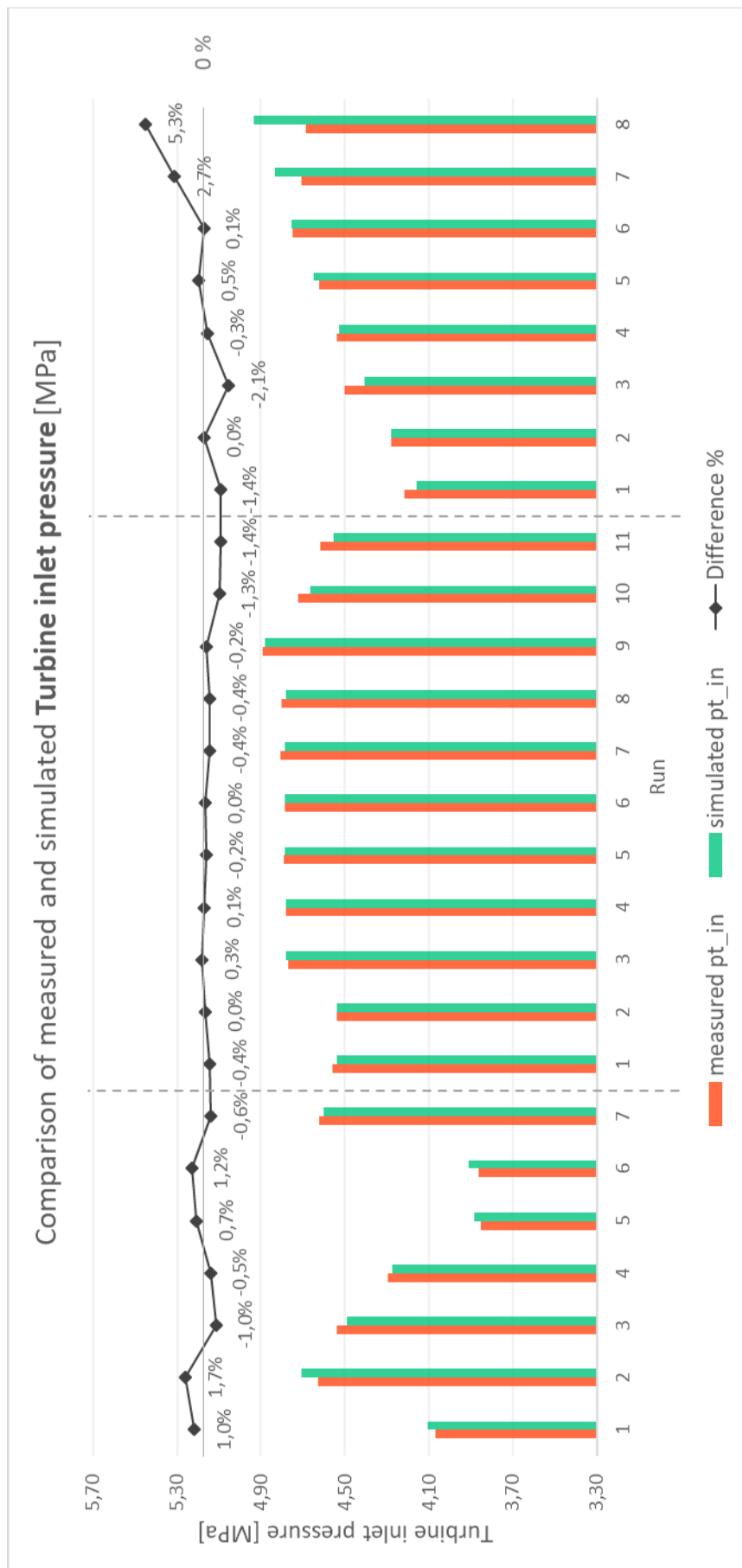


8.5 Stationary Results – Turbine Power



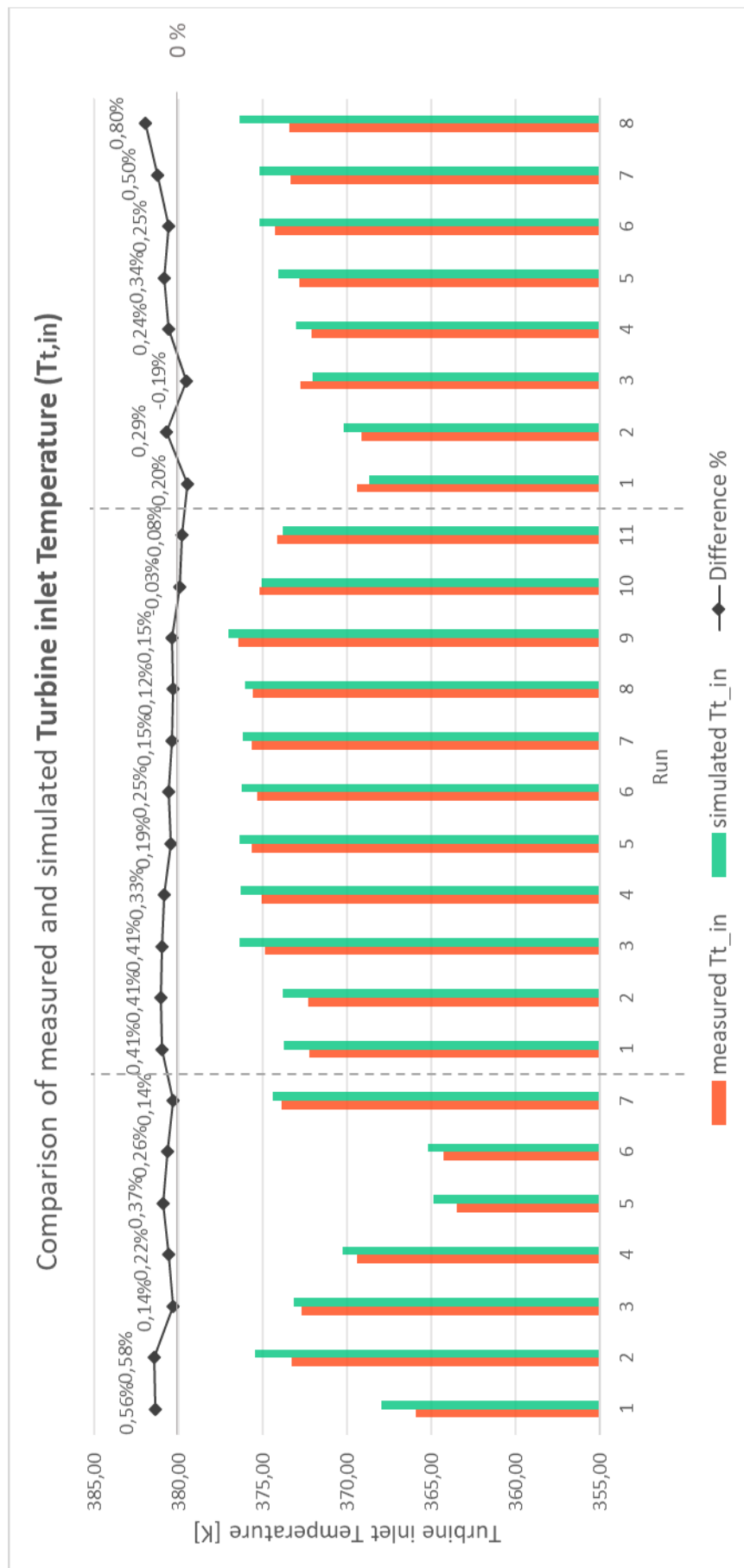
Stationary results: Turbine Power [kW]				
	run	Measured	Simulated	% Diff
1st day 08.11.2021	1	92,59	92,95	0,4%
	2	102,73	106,12	3,3%
	3	103,34	99,79	-3,4%
	4	96,02	92,80	-3,4%
	5	82,73	81,39	-1,6%
	6	83,66	83,49	-0,2%
	7	103,36	100,09	-3,2%
2nd day 09.11.2021	1	97,80	96,28	-1,6%
	2	97,29	97,59	0,3%
	3	102,16	102,60	0,4%
	4	102,63	101,83	-0,8%
	5	103,44	101,99	-1,4%
	6	103,07	100,61	-2,4%
	7	103,81	100,15	-3,5%
	8	103,62	98,87	-4,6%
	9	104,40	102,55	-1,8%
	10	104,01	96,97	-6,8%
	11	102,31	93,77	-8,3%
3rd day 10.11.2021	1	95,78	88,39	-7,7%
	2	92,79	77,67	-16,3%
	3	102,66	92,17	-10,2%
	4	98,78	88,27	-10,6%
	5	99,29	91,35	-8,0%
	6	102,46	96,64	-5,7%
	7	99,09	96,53	-2,6%
	8	100,54	102,47	1,9%

8.6 Stationary Results – Turbine inlet pressure



Stationary results: Turbine inlet Pressure [MPa]				
	run	Measured	Simulated	% Diff
1st day 08.11.2021	1	4,07	4,11	0,97%
	2	4,63	4,71	1,75%
	3	4,54	4,49	-0,97%
	4	4,29	4,27	-0,49%
	5	3,85	3,88	0,74%
	6	3,86	3,91	1,20%
	7	4,62	4,60	-0,56%
2nd day 09.11.2021	1	4,56	4,54	-0,43%
	2	4,54	4,54	-0,01%
	3	4,77	4,78	0,26%
	4	4,78	4,78	0,09%
	5	4,79	4,78	-0,15%
	6	4,79	4,78	-0,04%
	7	4,81	4,78	-0,44%
	8	4,80	4,78	-0,44%
	9	4,89	4,88	-0,16%
	10	4,72	4,66	-1,25%
	11	4,62	4,55	-1,38%
3rd day 10.11.2021	1	4,22	4,16	-1,39%
	2	4,28	4,28	0,04%
	3	4,50	4,41	-2,11%
	4	4,54	4,53	-0,26%
	5	4,62	4,65	0,54%
	6	4,75	4,76	0,11%
	7	4,71	4,84	2,71%
	8	4,68	4,93	5,32%

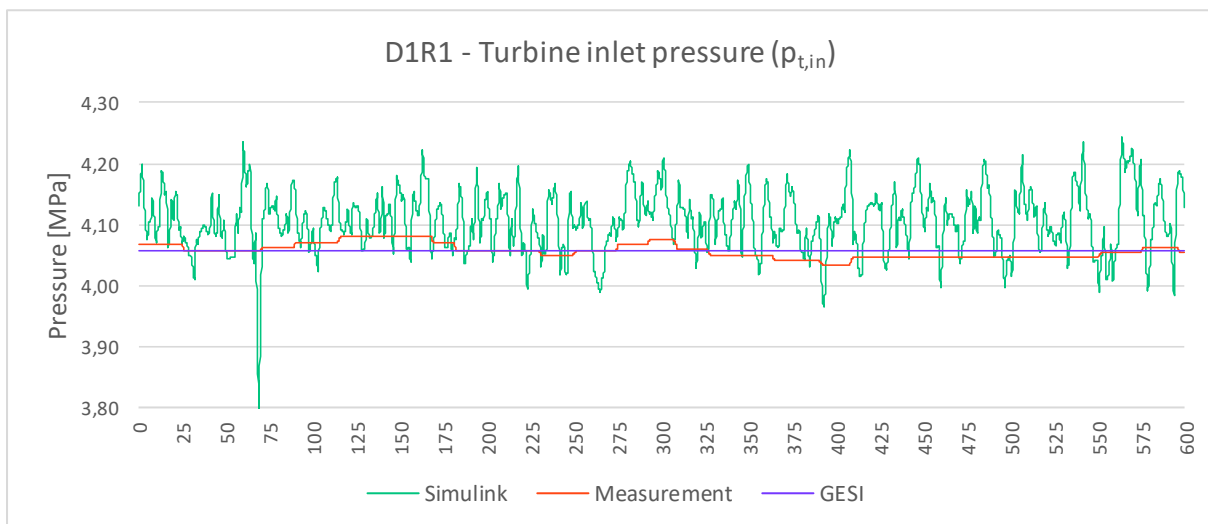
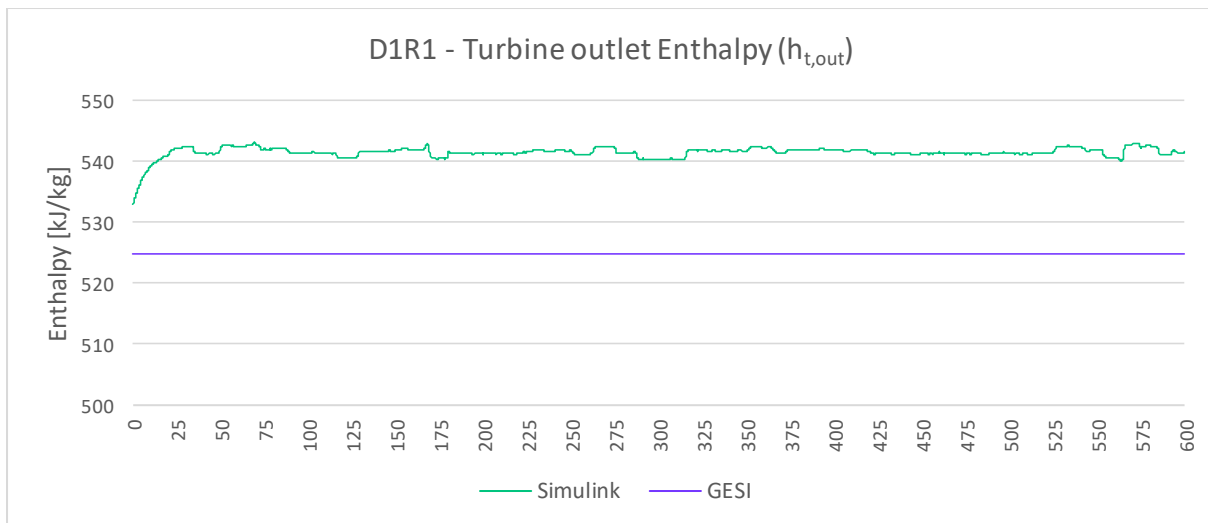
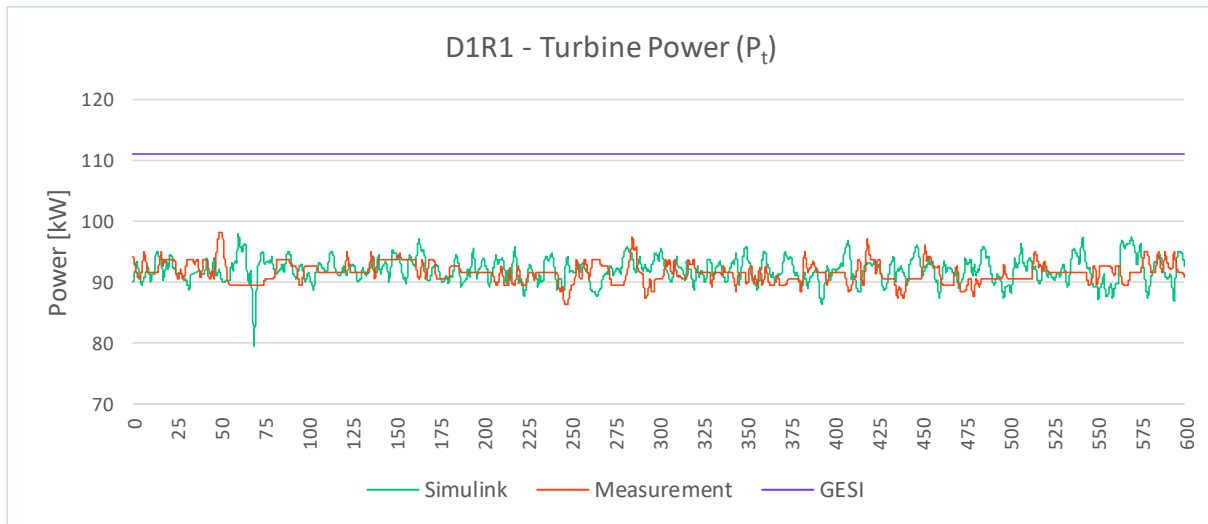
8.7 Stationary Results – Turbine inlet Temperature

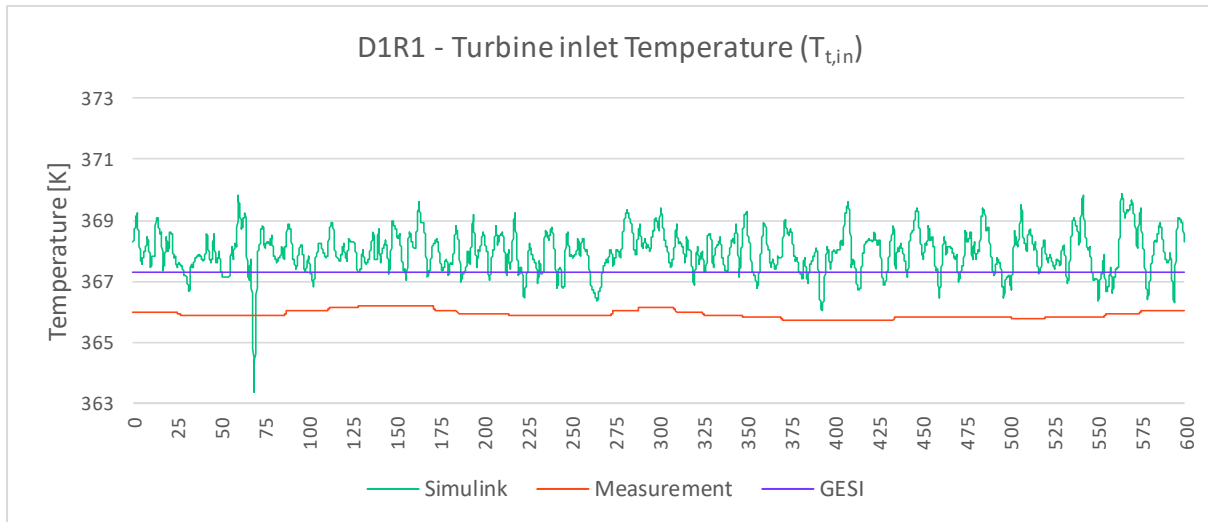


Stationary Results: Turbine inlet Temperature [K]				
	run	Measured	Simulated	% Diff
1st day 08.11.2021	1	365,91	367,97	0,56%
	2	373,26	375,44	0,58%
	3	372,67	373,18	0,14%
	4	369,43	370,26	0,22%
	5	363,52	364,85	0,37%
	6	364,29	365,22	0,26%
	7	373,88	374,40	0,14%
2nd day 09.11.2021	1	372,26	373,78	0,41%
	2	372,32	373,85	0,41%
	3	374,88	376,40	0,41%
	4	375,08	376,32	0,33%
	5	375,67	376,37	0,19%
	6	375,31	376,23	0,25%
	7	375,64	376,19	0,15%
	8	375,60	376,05	0,12%
	9	376,47	377,02	0,15%
	10	375,18	375,06	-0,03%
	11	374,12	373,83	-0,08%
3rd day 10.11.2021	1	369,41	368,68	-0,20%
	2	369,16	370,23	0,29%
	3	372,76	372,04	-0,19%
	4	372,12	373,01	0,24%
	5	372,80	374,05	0,34%
	6	374,25	375,18	0,25%
	7	373,35	375,23	0,50%
	8	373,39	376,37	0,80%

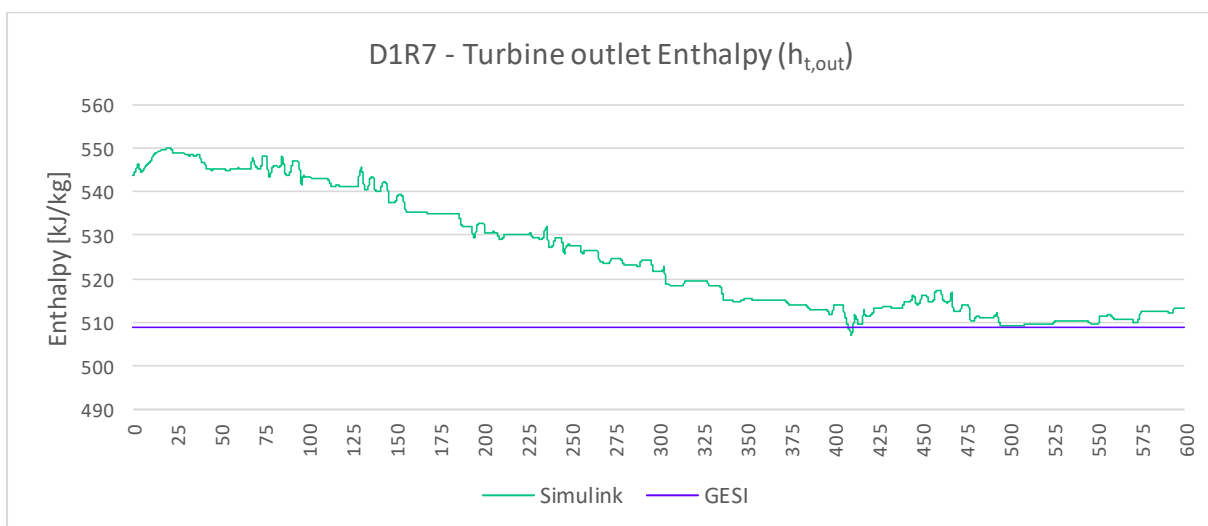
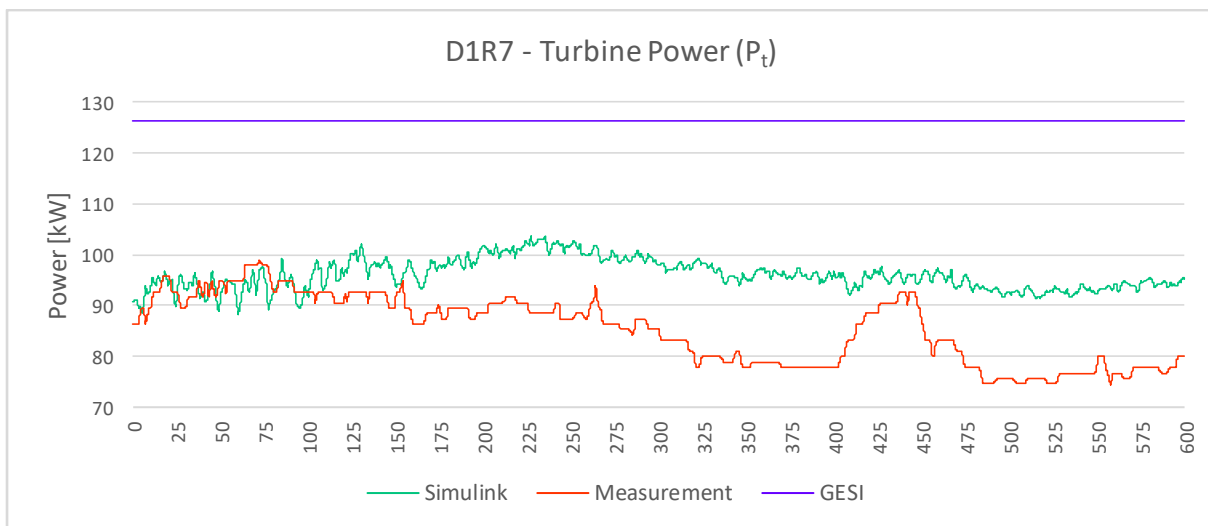
8.8 Time-dependent Results

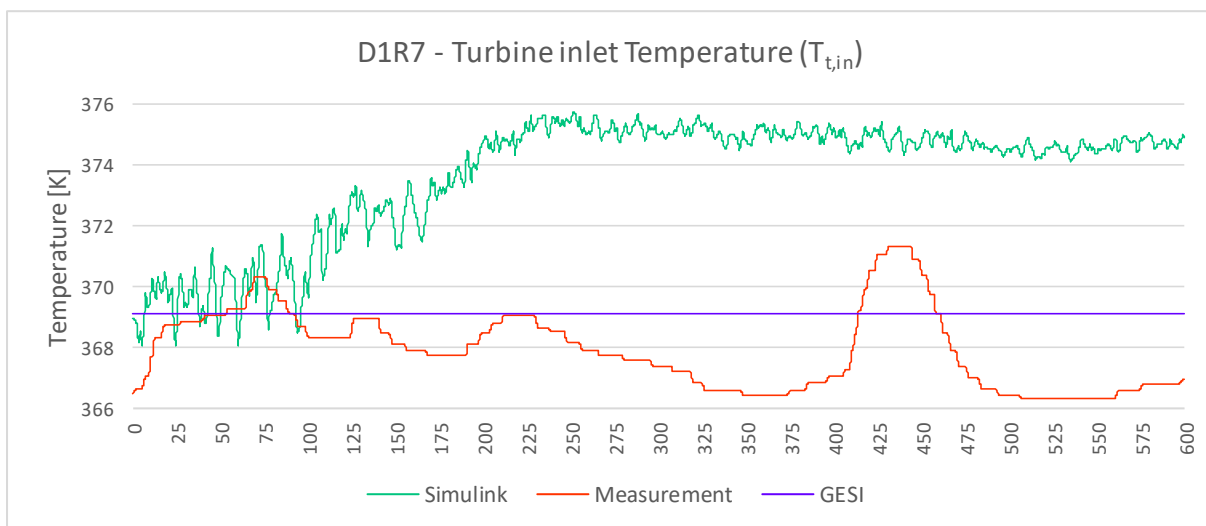
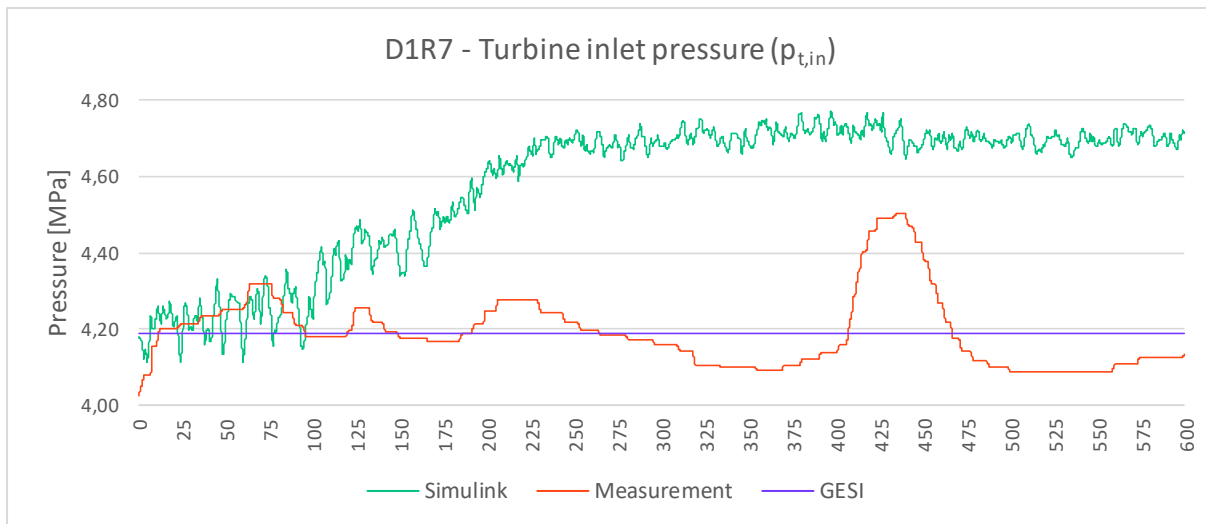
8.8.1 Stationary operation – D1R1 data set



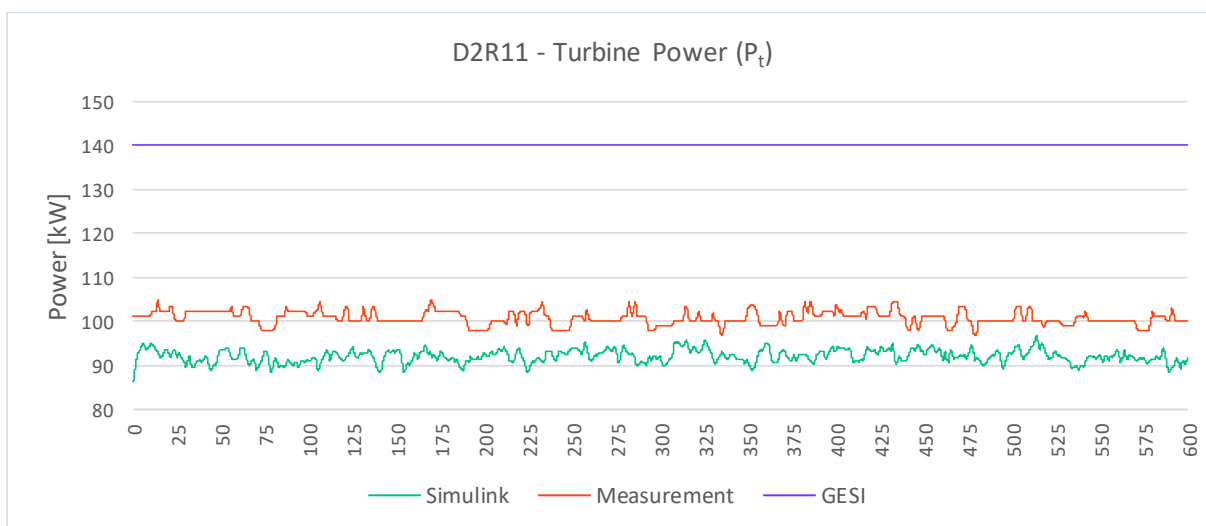


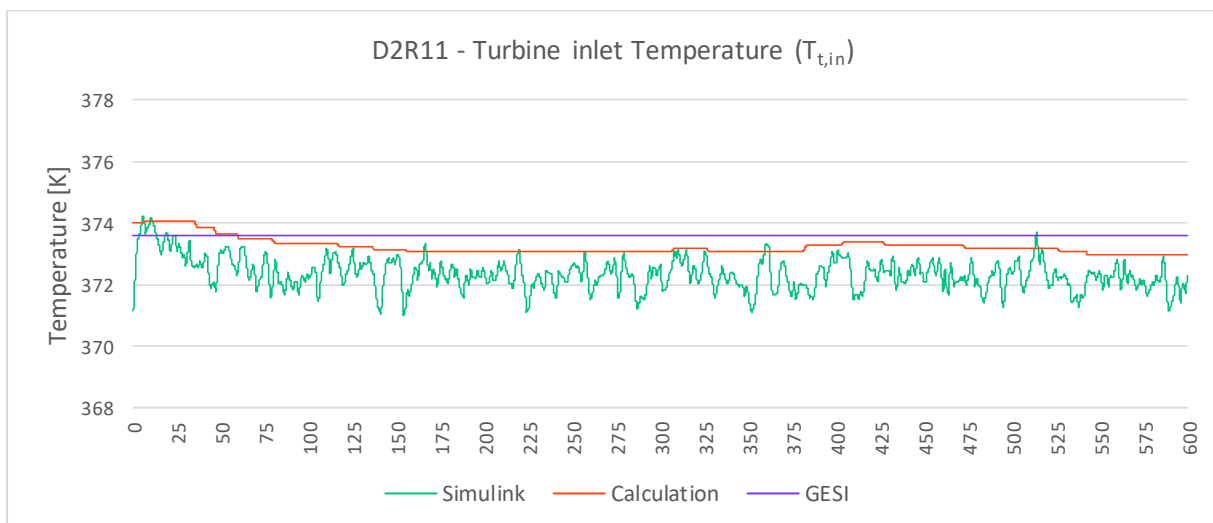
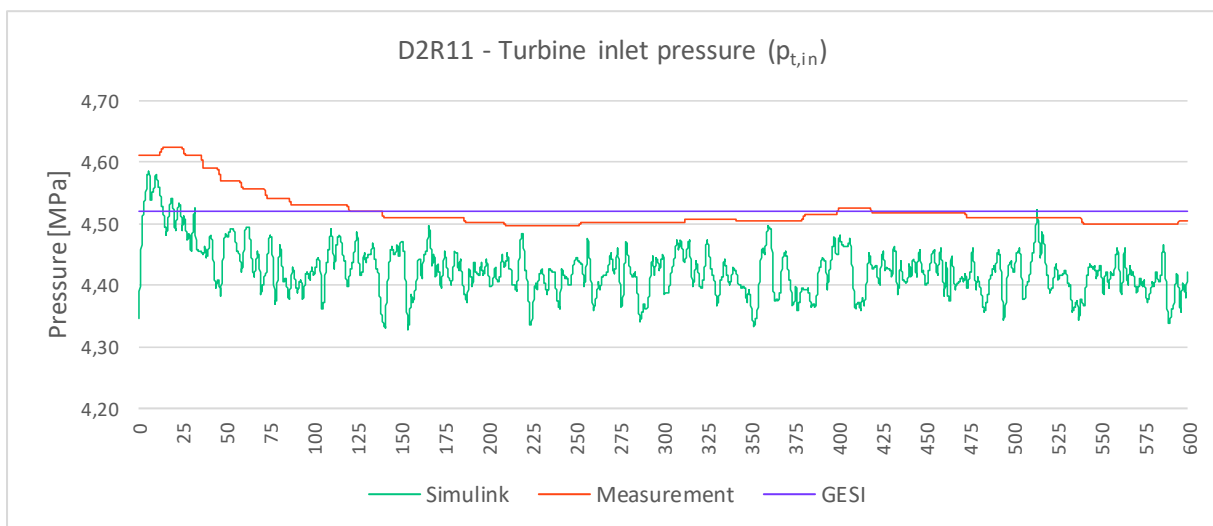
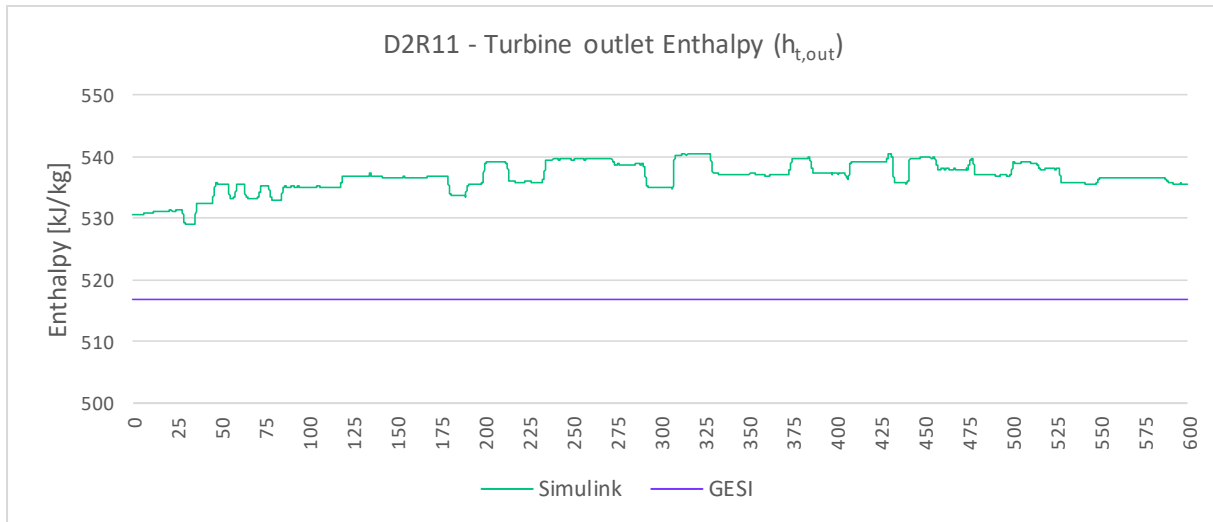
8.8.2 Transient periods – D1R7 data set





8.8.3 Transient periods – D2R11 data set





8.8.4 Shut-down

