CZECH TECHNICAL UNIVERSITY IN PRAGUE

FACULTY OF MECHANICAL ENGINEERING

VVER 1000 PRESSURIZER SYSTEM AND CONTROL MODELLING IN DYMOLA

2018

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ZADÁNÍ DIPLOMOVÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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Studijní program: **Jaderná energetická zařízení**

Studijní obor: **Jaderná energetická zařízení**

II. ÚDAJE K DIPLOMOVÉ PRÁCI

Název diplomové práce:

Systém a řízení kompenzátoru objemu VVER-1000 v prostředí Dymola

Název diplomové práce anglicky:

VVER 1000 pressurizer system and control modelling in Dymola

Pokyny pro vypracování:

1) Rešerše popisující přístup k řízení hladiny a tlaku v KO bloků VVER 1000 ETE a popis prostředí Dymola a knihovny ClaRa
2) Fyzikální model vlastního KO a model řízení KO VVER 1000 ETE v prostředí Dymola - fyzikální model bude vycházet z definice komponent prostředí Dymola a bude obsahovat popis důležitých fyzikální vazeb reálného KO potřebných pro jeho simulaci v matematickém modelu bloku.
3) Popis rozhraní a návod pro integraci modelu komponenty KO do případného modelu jaderného bloku.
4) Ověření vyvinutého modelu připojením do zjednodušeného modelu IO (respektujícího chování chladiva IO) v prostředí Dymola a ověření jeho funkčnosti provedením zjednodušených simulací přechodových procesů a srovnáním s průběhy reálných dat.

Seznam doporučené literatury:

Nuclear systems I, Todreas, Kazimi
Nuclear systems II, Todreas, Kazimi

Jméno a pracoviště vedoucí(ho) diplomové práce:

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Jméno a pracoviště druhé(ho) vedoucí(ho) nebo konzultanta(ky) diplomové práce:

Datum zadání diplomové práce: **24.10.2017** Termín odevzdání diplomové práce: **15.01.2018**

Platnost zadání diplomové práce: **30.06.2019**

Podpis vedoucí(ho) práce Podpis vedoucí(ho) ústavu/katedry Podpis děkana(ky)

III. PŘEVZETÍ ZADÁNÍ

Diplomantka bere na vědomí, že je povinna vypracovat diplomovou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v diplomové práci.

30. 10. 2017

Datum převzetí zadání Podpis studentky

Affidavit:

I hereby declare that this master's thesis has been written only by the undersigned and without any assistance from third parties, except for consultation with my consultants.

Furthermore, I confirm that no sources have been used in the preparation of this thesis other than those indicated in the references. Sources [2], [3], [6], [15] and [16] are classified, hence no detail information about these are provided.

In Prague on 15.1.2018

Fořtová

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Annotation sheet

Author's name:	Bc. Anna Fořtová
Title of thesis:	VVER 1000 Pressurizer System and Control Modelling in Dymola
Czech title:	Systém a řízení kompenzátoru objemu VVER 1000 v prostředí Dymola
Academic year:	2017/2018
Department/Specialization:	Department of Energy/Nuclear Energy Devices
Supervisor:	doc. Ing. Václav Dostál, Ph.D.
Consultant:	Ing. Václav Hakl
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Bibliographic data:	Number of pages: 88
	Number of figures: 62
	Number of attachments: 1

Abstract:

The pressurizer is responsible for controlling the pressure and temperature in the primary circuit of nuclear power plant. It is basically a pressure vessel, that is partially filled with water and partially with steam at saturation state. The controlling process can be described by two regimes, either by the self-control regime or by the automatic control regime. This work deal with the simplified automatic control regime on the model of pressurizer in the primary circuit of VVER. The physical model contains important physical properties of the real pressurizer and is described with respect to ClaRa features. This model is used for dynamic simulation of the pressurizer behaviour. Control of the coolant level and pressure in the pressurizer during normal operation (with transient) is described and implemented into the model. The pressurizer model is integrated to the primary circuit and its functionality is verified by several simulations of the transient.

Abstrakt:

Kompenzátor objemu je součást primárního okruhu zodpovědná za vyrovnávání tlakových a teplotních změn v primárním okruhu tlakovodních jaderných elektráren. Jedná se v podstatě o tlakovou nádobu, částečně zaplněnou vodou a částečně parou při parametrech nasycených par. Proces řízení této komponenty může být popsán dvěma způsoby. Samoregulací nebo automatickým řízením. Tato práce se zabývá zjednodušeným automatickým řízením na modelu kompenzátoru objemu primárního okruhu VVER 1000. Fyzikální model komponenty obsahuje důležité vazby a vlastnosti reálného kompenzátoru. Tento model je popsán v závislosti na možnostech knihovny ClaRa. Finální model je použit po dynamické simulace chování kompenzátoru. Model obsahuje popis a samotný systém řízení tlaku a hladiny chladiva využívaný při normálních a jistých přechodových stavech. Celý tento model je součástí primárního okruhu, taktéž vytvořeného pomocí knihoven ClaRa a funkčnost tohoto modelu je ověřena na několika simulacích přechodových jevů.

Keywords: Pressurizer, control, pressure, coolant level, Dymola, ClaRa

Klíčová slova: Kompenzátor objemu, řízení, tlak, hladina chladiva, Dymola, ClaRa

Acknowledgment

First, I would like to thank my consultants for the time, for very valuable advices they gave me and for helping me, especially with the introduction to Dymola and ClaRa library. My great thanks also goes to Dassault Systèmes for providing a Dymola trial license.

I must express my gratitude to my family for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis.

Contents

List of abbreviations and indexes:

p … Pressure [MPa]

T … Temperature [K]

α_{nom} … Nominal heat transfer coefficient (to the wall) [W/m^{2}K]

Δ … Difference [depending on property]

τ_{cond} … Time constant for condensation [s]

τ_{evap} … Time constant for evaporation [s]

α_{ph}… Heat transfer coefficient (between phases) [W/m^{2}K]

A_{heat_ph} … Heat transfer area at phase border [m^2]

expHTphases … Exponent for volume dependency on inner phase heat transfer [-]

d … Diameter [m]

L … Length [m]

z … High [m]

ρ … Density [kg/m^3]

g … Gravitational acceleration [m/s^2]

v … Velocity [m/s]

Z_p … Pressure loss [MPa]

$\dot{m}$ … Mass flow [kg/s]

h … Specific enthalpy [kJ/kg]

V … Volume [m^3]

$\frac{dx}{dt}$ … Time derivative [Δ]

$\dot{Q}$ … Heat transfer [W]

ξ … Mass fraction [-]

q … Steam fraction [-]

N_{tubes} … Number of tubes [-]

N_{passes} … Number of passes through the tube [-]

N_{ax} … Number of axial elements [-]

U … Inner energy [J]

$delta_x$ … Length of one wall element [m]

c_p … Specific heat capacity of material [J/kgK]

λ … Heat conductivity of storage material [W/mK]

CF_λ … Correction factor of heat conductivity [-]

P_{hyd} … Hydraulic power [W]

η_{hyd} … Hydraulic efficiency [-]

η_{mech} … Mechanical efficiency [-]

Δp_{eps} … Numerical factor for computational stability [Pa]

set … Set values

min … Minimal value

max … Maximal values

in … Property an inlet

out … Property at outlet

inner … Inner (diameter)

outer … Outer (diameter)

vap … Vapour

liq … Liquid

cond … Condensation

evap … Evaporation

fric … Friction

dew … Dew point

bub … Bubble point

phases … Property of phases

tot … Total value

nom … Nominal values

NPP … Nuclear power plant

PWR … Pressurized water reactor

MATLAB … Matrix Laboratory

REALP … Reactor Excursion and Leak Analysis Program

MCP … Main circulation pump

Dymola … Dynamic Modelling Laboratory

ClaRa … Clausius – Rankien (library)

I&C … Instrumentation and Control

LS … Limitation system

PS … Protection system

DiD … Defence-in-Depth

TG … Turbogenerator

SG … Steam generator

RS … Regulated system

R … Regulator

O … Output

A … Actuator

S … Sensor

MB … Measuring block

y … Control variable

x … Regulated quantity

w … Setpoint

e … Regulation deviation

k … Regulator gain

EH … Electric heaters

DN … Nominal diameter

HT … Heat transfer

ODE … Ordinary differential equations

DAE … Differential algebraic equations

BDF … Backward Differential Formulas

RADAU IIA … Runge-Kutta method for solving ODEs

ESDIRK … Runge-Kutta method for solving ODEs

SDIRK … Runge-Kutta method for solving stiff ODEs

DASSL … Runge-Kutta method for solving DAEs

VLE … Vapour-liquid equilibrium

IAPWS95 … Thermodynamic properties of water and steam

EHFC … Electric heat flow connector

1. Introduction

The pressurizer is a very important component of the primary circuit of PWRs. It is one of the critical components that is ensuring safety during the operation of the nuclear power plant (NPP). For such sophisticated system, as NPP, there is a need for continuous development or improvement of dynamic analysis, that can be done by many different tools such as MATLAB, RELAP etc. With dynamic analysis, the expected behavior of the system (e.g. pressurizer) can be modelled, and so the prediction is possible. Nowadays, hand in hand with modernization of the physical systems on NPP, the modernization of dynamic analysis systems occurs. This is why the Dymola program was chosen for this work. Dymola is an abbreviation, that stands for "Dynamic Modelling Laboratory" and it is a program that is suitable for modelling various kinds of physical systems. The advantages of this program include its ability to handle large and complex models, usage of graphical model composition, fast and real-time simulation. The transition from currently used systems to Dymola can be expected and this work may be the initial step for this transition in one part of the process.

NPPs are controlled or regulated, based on dynamic analysis results, by an instrumentation and control (I&C) system, that is an integrated part of every project. NPP construction and safety system projects are designed to prevent loss of safety properties. These may be due to component, system or construction failure caused by a single failure or a common cause failure. This design is called I&C architectural design. The fundamental principle of the I&C architectural design is using multiple divisions, systems or pipelines (redundancy) that are reliable enough to provide required safety function while working individually. A part of fundamental principle of I&C is using technical systems or components with different properties (diversity) and keeping those components or systems apart from each other (separation).

2. The instrumentation and control system (I&C) description

The I&C system is, together with operation personnel, the “central nervous system” of NPP. It consists of various kinds of equipment, modules, sensors, transmitters etc. These are used to sense basic physical parameters, to monitor performance and to make an automatic adjustment to plant operations if necessary. It ensures achieving the goal of efficient and safe power production. Results of these measurement and technological processes are applied to signalization, safety regulations and many other fields and are applied in the in the informational system use. The I&C assures a cooperation of inter-connected technological components and their proper function in case of any failure. The I&C can be logically divided into several sub-categories according to their function [1] [2]:

a) Measurement system

Its main purpose is to get the right value of a parameter that is directly related to the technology.

b) Regulation system

It serves the most important purpose, which is to control the operation of technological devices within certain operational bounds.

c) Safety system

Nuclear safety regulation requires each project to ensure a certain level of reliability. Hence both development and the defense-in-depth (DiD) approach was implemented. To follow this requirement a very sophisticated, extensive and financially demanding system, called safety system was implemented in every project. If any of the safety limits are reached, the safety system (limitation system – LS; protection system – PS) should prevent any potential accident or minimalize its consequences.

d) Information systems

All data from measurement or from calculations, system state, operational regimes and many others are gathered by a system called informational system.

e) Control centres

Despite the fact almost the whole operation of NPPs is automatically controlled, the human factor is still an integral part of it. For this purpose, control centers are on site in NPPs. Moreover, personnel are an active part of an operation of an NPP.

The I&C is implemented in several levels, as shown in the fig. 1. The lowest level is represented by sensors, which provide an actual state of the system and by actuators that can provide control over the system. Next level contains systems with algorithms which are directly controlling the system or technological devices, based on information obtained from the sensors. The highest level represents the processing and imaging information for staff in control centers so that they can manually intervene in the operation. All data are transferred by transducers between levels. [2]

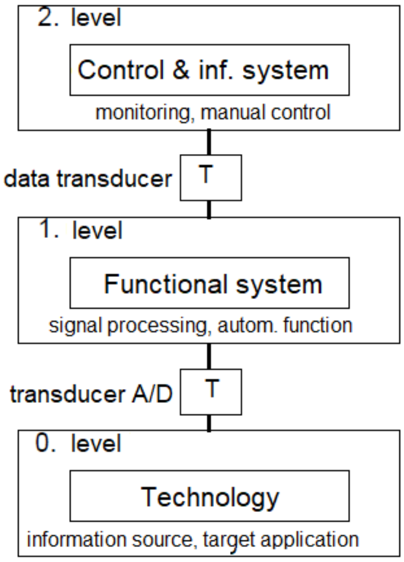

Figure 1 – Scheme of level structure of I&C [2]

Due to the nuclear industry's graded approach to safety, the system with higher importance should be of noticeably higher quality, more tolerant of failures and more resistant to any possible outside or inside hazards. So, considering this approach, the I&C's safety class and its DiD level have a direct impact on the qualification requirements, quality assurance, and the physical layout within the NPP. Classified technical means of I&C are known as 1E class devices (safety classification of electrical equipment and systems that are fundamental for emergency reactor shutdown, containment separation, active zone cooling and residual heat removal from the reactor and containment or are directly related to the significant release of radioactive materials to the environment). These 1E class devices should follow criteria provided by national or international regulation. Other devices are known as N-1E. [2]

Based on the foregoing division, the I&C system can be described in a way of systems (devices), that are regulated **or** controlled and to those systems (devices) that fulfill both previous functions. [1]

Main control functions are following:

- Reactor shutdown
- Limitation system action
- Activation of safety systems

Main regulation functions are described as:

- Regulation of reactor power output
- Regulation of pressure and coolant level in pressurizer
- Regulation of turbogenerator power output (TG)
- Regulation of dump to the condenser, to atmosphere
- Regulation of power of steam generator (SG)
- Regulation of pressure and feedwater level in feedwater tank
- Regulation of water in main condenser

Regulators are the basic in terms of operation control. In the fig. 2 the regulators ensuring the safe operation on all three circuits are shown (green numbered). The left blue part is the primary circuit, the red part is the vapor in the secondary circuit and the blue part at the bottom of the figure is the feedwater circuit. On the left-hand side, there is a reactor that is controlled by regulator 1 or 2 with respect to the control type (from the reactor to the turbine by 1 or from the turbine to the reactor by 2). Currently, the most common control type is the one from turbine to the reactor. Hence based on the turbine power needs (properties) the reactor is controlled. Then there is a pressurizer, that controls the pressure in the primary circuit. The regulator 3 controls the pressure and the regulator 4 controls coolant level in the pressurizer, based on the current regime (as described in chapter 4.3). Another part of the primary circuit is the steam generator. It is a heat exchanger, which generates the steam and that is controlled by the regulator 5, that controls the feedwater level and the pressure in the secondary circuit. Regulator 6 takes care of the steam release from the secondary circuit if needed, through the control of the valve. Regulator 7 and 8 are tied to the reactor regulators, so they control the turbine power output. Regulator 9 is mainly used during the start-up of during turbine failure, this regulator controls the valve, that is on the pipeline leading to the condenser. The last regulators 10,11 take care of feedwater replenishment and maintain feedwater level in the feedwater tank or condenser. [1]

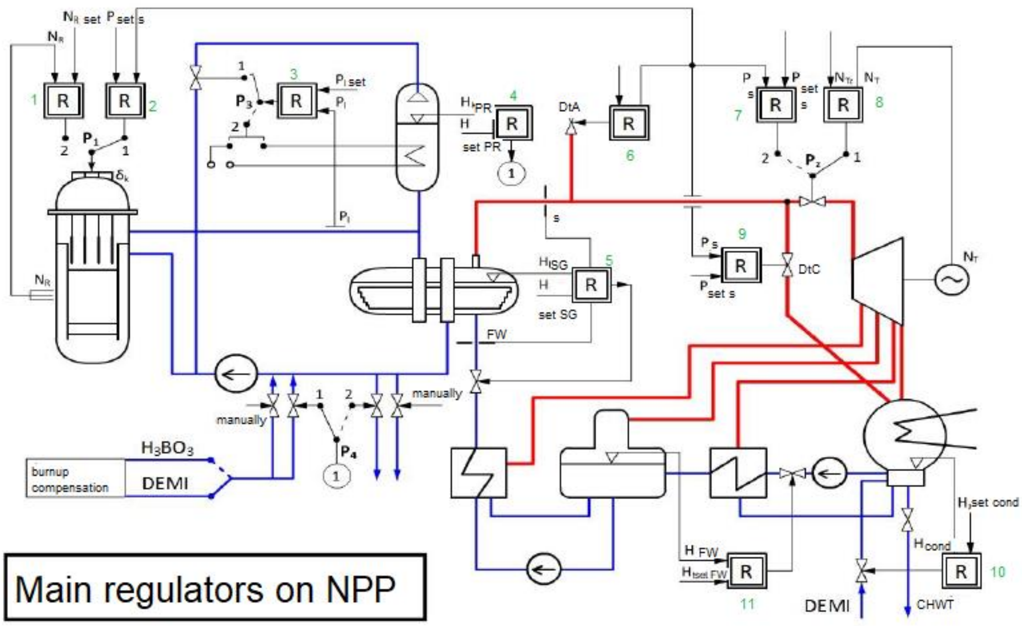

Figure 2 – Main regulators on NPP [1]

The whole composition of I&C systems in Temelin NPP is based on modern technical means including microprocessors working with digital information. Individual components are integrated together into control systems. These form independent systems cooperating with each other onto the basic structure level through upper architecture level of I&C systems. [2]

Basic elements of the digitalized structure of I&C systems are microprocessor unit, data collector and input/output transducers. The basic structure of a functional block is shown in fig. 3 [2]

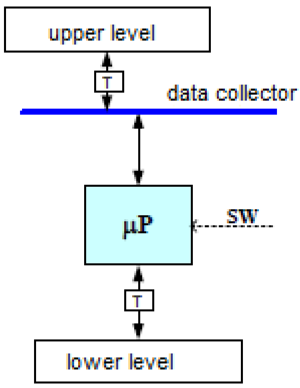

Figure 3 – Scheme of digitalized structure of I&C [2]

This configuration has several advantages such as the application of automatic diagnosis, technical unification and a possibility of simple modification by replacing the software etc. As a result, the reliability is increased, the maintenance is easier and the lifespan is increased. In comparison to analog technique, data displaying is more accurate for reading and evaluation. [2]

3. Control circuit

Automation was being developed together with the process. Using it, some human control functions can be replaced by machines. Control, as a process itself, can be divided into two categories using feedback function – control or regulation as shown in fig. 4. [2]

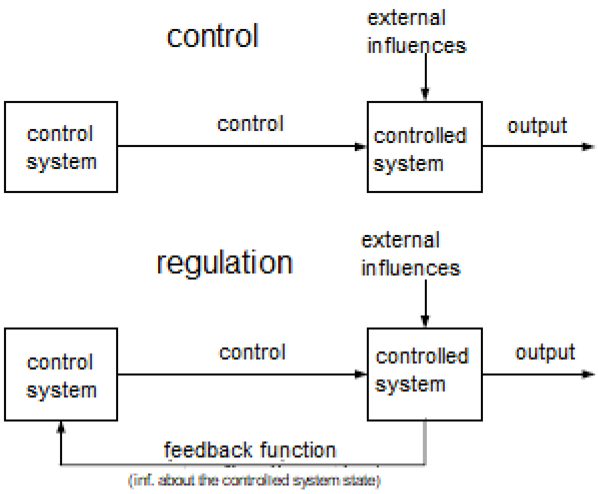

Figure 4 – Block diagram of control type [2]

Control is an easier form of the process, since one or more quantities as an output quantity influence the system based on known set quantities. The signal for control is an output from an opened circuit for individual transfer element or string control. [2]

Regulation, on the other hand, is a process, where one quantity (regulated) is still measured and compared to another quantity (control) and depending on the result of the comparison (adjustment to control quantity) the system is regulated. This process occurs in a closed circuit with the use of feedback function, i.e. a regulation circuit. [2]

The purpose of automatic regulation is to keep a set of the quantity on required values (setpoint) (constant or variable). The regulation circuit consists of two elementary parts, regulator (R) and regulated system (RS), which are connected and form a closed circuit. The regulator is a device, that performs the regulation either continuously (more/less) or discretely (open/close or on/off). Regulation system represents an object of regulation, where under the influence of the regulator, the regulation is performed. [1] [2] The regulation circuit is shown in fig. 5.

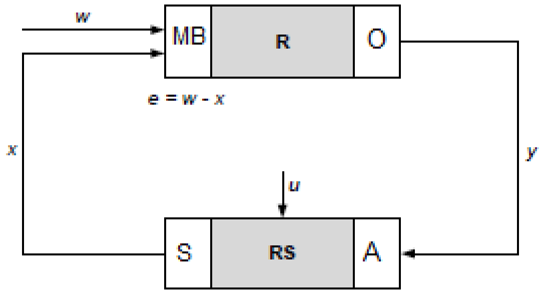

Figure 5 - Block diagram of the control circuit [2]

Regulator creates a control variable ***y*** on its output (O). Control variable ***y*** leads to actuator (A). The task of the actuator is to perform the regulation. The change of A is followed by the change of regulated quantity ***x***. This change is delivered by the sensor (S) to the regulator, where on its output, there is a measuring block (MB). The MB compares the current value with setpoint ***w***. On the output of MB, regulation deviation ***e*** is created, representing the difference between the setpoint and the regulated quantity value. [1] [2]

The signal of regulation deviation is processed by the regulator and on its output, the new value of signal control quantity is created. The principle of regulation is to set regulation deviation close enough or equal to zero. Once this is accomplished, the goal of regulation is reached and the value of the regulated quantity is equal to the requested value. [1] [2]

The reason for requiring implementation of an automatic regulation is disorder quantities ***u***. Disorders (ex. change of values of influencing quantities, change of regime or state, outer conditions…) may be present anywhere in the regulation circuit and that is the reason for changes in regulated quantity. Because of this, the non-zero regulation deviation is created. An example of regulation circuit implementation is shown in the fig. 6. The response of regulatory action to regulation deviation can be performed via several different procedures (by used regulator). [2]

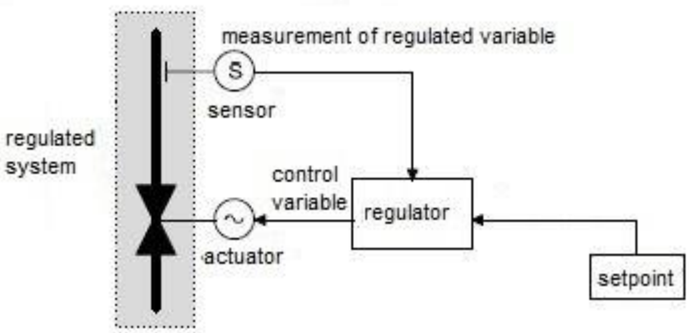

Figure 6 - Block diagram of control circuit in the technology [2]

The simplest regulator type is regulator **P – proportional**. The correlation between the control variable and regulation deviation is proportional, where ***y = k .e***. Value ***k*** is a value, that describes the regulator amplification and represents the constant of regulator setting. This type or regulator works with permanent regulation deviation. Where the zero-regulation deviation needs to be reached, **I – integrational** regulator must be used. The correlation between control variable and regulation deviation has integral character and is represented by the equation $y = \int e\, dt$. Setting of characteristics of this regulator is created by the time constant T_i. Regulator of this type is thus precise (constantly ***e = 0***), but on the other hand it is very slow and mostly does not fit the time needs of regulation circuit. That is why the combination of **P** and **I** type is mostly used. So called proportional-integration regulator **PI.** The last regulator type is **derivation - D** regulator. In this regulator, the correlation between control variable and regulation deviation is represented by equation ***y = de/dt***. Setting of this regulator is done by time derivation constant T_d. This regulator is not used separately, but together with **P** regulator, where this combination improves dynamical properties of regulation circuit. So, the possible combination of usage of this regulator is **PD** or **PID** regulators. [1] [2]

The regulator operates in two possible regimes – regulation regime and tracking regime. The regulatory regime is a primary function of the regulator. In some cases, the regulator is switched to tracking regime. Typical case of the tracking regime being applied when the operator controls the processes manually. When the regulator is in the tracking regime, it allows the operator to adjust the current value himself. After transferring to the automatic regime, the regulation takes over smoothly without any shocks. [2] The regulator schema is in the fig. 7.

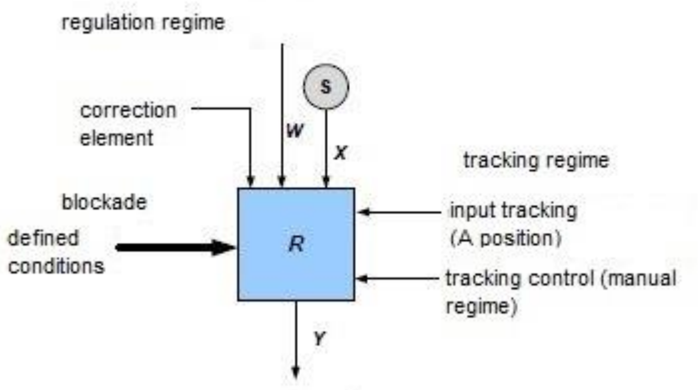

Figure 7 - Mode of operation of the regulator [2]

4. Volume compensation system description

The main purpose of the volume compensation system is to

- Compensate the volume changes of the coolant in primary circuit caused by small temperature differences
- Maintain the pressure in the primary circuit during bigger differences caused by the primary or secondary circuit changes
- Heating up and cooling down the pressurizer
- Continuously increase or decrease the pressure during heating up or cooling down the primary circuit
- Secure the primary circuit during accident regimes, caused by sudden pressure increase

The whole system consists of a pressurizer YP10B01, a bubbler-condenser YP20B01, a steam dumping pipeline with two safety valves YP22S01 and YP23S01, a relief valve YP21S01. Relief and safety valves are parts of the safety systems while a spray system and a pressurizer are parts of safety-related systems[1]. [3]

4.1. Pressurizer

A pressurizer (with auxiliary piping shown in fig. 8) is a vertical cylindrical vessel with dimensions of the inner diameter of 2 998 mm and high of 13 514 mm. The body is composed of 3 parts. In the upper part, a spray system with dimensions of DN 200 and a steam dumping pipeline with dimensions of DN 250 are situated. The steam dumping pipeline is connected to a relief valve system and a safety valve system. The spray system is connected to "cold leg", through which the coolant is transported to the reactor vessel. The connection is performed between the reactor vessel and the main circulation pump. The middle part of the body, called heater ring, has a wall thickness of 260 mm and it is 1500 mm high. In this part, there are 28 holes with diameter of 205 mm used for 28 blocks of electric heaters (EH). These heaters are assembled in groups, where the power output of the I. and II. group is 540 kW and they are controlled continuously by continous regulation. The power output of the III. group is 720 kW and of the IV. group is 1260 kW. Control

[1] **Safety systems**
Safety systems are systems relevant to nuclear safety. They are designated for safe reactor shutdown, to remove residual heat from active zone and to limit consequences of abnormal operation and emergency conditions. [2] [3]
Safety-related systems
Systems related to safety are other systems relevant to nuclear safety, but their malfunctions do not affect meeting security criteria. [2] [3]

and regulation of the heaters is performed by the YPC01 regulator. The lower part of the body has a wall thickness of 175 mm and is equipped with the pipe system with diameter of 426x40 mm that is connected to the "hot leg". This is the part of the pipe system through which the coolant is transported from the reactor to the steam generator. The spray system is connected to the 1st loop and the "hot leg" connection is connected to the 4th loop. The spray system injects the coolant either from the "cold leg" or from the boron acid replenishment systems into the vapour cushion inside the pressurizer. The spray itself is composed of two pipelines that are drawn into one with the dimensions of DN 200. [3]

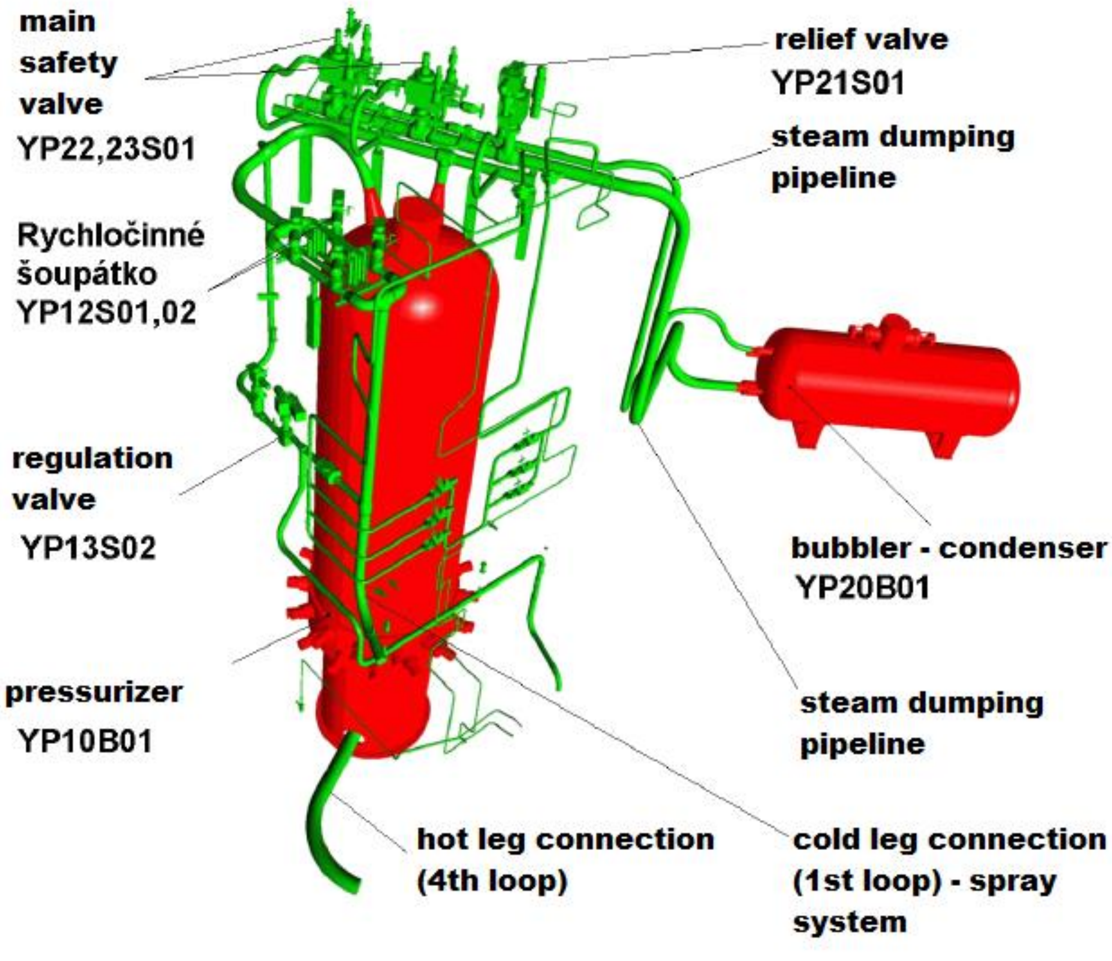

Figure 8 - Pressurizer with auxiliary piping and bubbler-condenser [3]

The relief valve system consists of the relief valve and an electromagnetic valve. The power of the control valve is 180 t/h and it is controlled by the electromagnetic valve. Opening pressure for this system is 17,1 MPa and closing pressure is 16,6 MPa. [3]

Safety valve system consists of two identical safety mechanisms that differ by the pressure setpoint. These mechanisms are "major", so that there shall be no closing valve in front. The main safety valve is controlled by two control valves and its power is 270 t/h. The control valve is composed of a safety valve controlled by the force of the spring and of the return control valve. [3]

Additionally, there are some gate valves YP11,12S01, quick acting gate valves YP11,12S02 and regulation valve YP13S02 on the spray system pipeline. [3] Following parameters of the pressurizer taken from [3]:

Basic parameters:

Type	KO 1000
Nominal pressure	15,7 ± 0,2 MPa
Nominal temperature	346 ± 2 °C
Total volume	79 m^3
Nominal vapour volume	24 m^3
Nominal liquid volume	55 m^3
Total power of heaters	2,52 MW
EH groups I	270 kW
II	270 kW
III	720 kW
IV	1260 kW

4.2. Function of the system

The pressurizer is during normal operation partially filled with liquid and partially with vapor. All valves, regulating the coolant injection, are closed. The spray system pipeline is continuously heated by the flow rate of 1 m^3/h. Parameters inside the pressurizer are equivalent to a saturated steam state. In case of small pressure drop, the balance is violated and due to the pressure drop, the evaporation is more intense. This phenomenon is caused by the temperature in the pressurizer being higher than the saturated steam temperature. Due to the evaporation of the coolant, the steam volume is increased and so the pressure is increased. Hence the parameters are re-balanced. If the pressure in the pressurizer is slightly increased, the balanced is violated and condensation occurs, due to the temperature inside the pressurizer being lower than the saturated steam temperature. Due to condensation, volume of the steam is decreased and thus the pressure is decreased again. Parameters are re-balanced again. This so-called self-regulation can handle small pressure differences. If the differences are higher, the spray system and electric heaters are put into operation. These are controlled by the regulator YPC01. [3] [4] [5]

When electric heaters are in operation, the coolant temperature is increased, evaporation occurs and the steam volume is increased, so the pressure is increased. These electric heaters are divided into four groups. First two groups are working in a parallel regime and are controlled by thyristor continuous regulation. Continuously regulated heaters are always in operation so that they can compensate heat losses. [3] [4]

The spray system is connected to the "cold leg" of the 1st loop. The pipeline has dimensions of 219x20 mm and is connected to pressurizer in its upper part. In case of small pressure increase, the surge is performed via pipeline YP13S01,2,3 with a full open flow rate of 24,88 kg/s. This pipeline has dimensions of 133x14 mm and is equipped with a non-return valve, regulation fitting, and closure fitting. If this system is not efficient enough, the coolant flows through second spray pipeline YP11S01,2 or YP12S01,2. There are two wedge gate valves and two quick acting wedge gate valves. Each branch may have different coolant flow rate. If only one branch is opened, the flow rate is 29,4 kg/s, with both branches opened, then it is 44 kg/s. If none of these systems can prevent pressure from increasing, then relief or safety valve systems are actuated[2]. [3]

For low temperature and pressure in the primary circuit, there is a nitrogen cushion in the pressurizer. This nitrogen cushion is present only if the temperature is < 230°C, otherwise, a steam cushion is present. [3]

During nominal operation, the volume compensation system maintains the pressure value in primary circuit at 15,7 MPa and temperature at 346°C by the regulator YPC01 (electric heater groups I. and II. and valves YP11,12S02). The coolant level in the pressurizer is maintained at 8,77 m by the regulator YPC02 (replenishment system TK31,32S02). If the pressure is increased to more than what these regulators can handle, other systems are put into operation to compensate this deviation. [3]

4.3. Regulators and algorithms of the volume compensation system

This chapter describes the settings for control and regulation of pressure in the pressurizer, temperature and coolant level in a simplified way. Such simplification does not influence the functionality of the system though.

[2] These valves are closed during normal operation. In case of abnormal operation, the steam would go through these valves via piping to bubbler-condenser. Since this pipeline is not used during normal operation, it is not described in detail in this work. [3]

Regulator YPC01 – regulation of pressure/temperature in pressurizer

This regulator maintains the pressure level during start-up, operation (15,7 ± 0,2 MPa), shut down and cooling down the reactor. It uses I. to IV. group of electric heaters, opening/closing regulation valve YP13S02 and quick acting gate valves YP11,12S02. The I. and the II. group of electric heaters and regulation valve YP13S02 are controlled continuously with respect to the regulation deviation. The III. and the IV. group of electric heaters and quick acting gate valves YP11,12,S02 are controlled discretely based on the deviation from the setpoint. Control of pressure in the pressurizer is performed in two regimes [3]:

- Pressure control regime “P”
- Temperature control regime “T”

Temperature control regime “T” is used when there is nitrogen cushion in the pressurizer. This is present during heating up and cooling down the primary circuit since the ordinary relation between temperature and saturated pressure is violated. This regime can be only maintained if $T_{max} < 230$ °C, otherwise the “P” regime is set. [3]

Temperature control regime “T”

In this regime, the regulator maintains the required temperature difference between the primary circuit and the pressurizer. This difference is set by the personnel in the range of 40 – 60°C. This value is then added to the T_{max} in the “hot leg”, but only if T_{max} is higher than 145°C. The regulation deviation between the setpoint and the measured temperature of the pressurizer and the primary circuit enters the PID regulator PPTC101. This regulator has a gain dependent on the T_{max} in the “hot leg”. This gain increases with the temperature from 0,05 to 0,07 MPa/°C by the functional generator PPTY102 in fig. 9 [6]

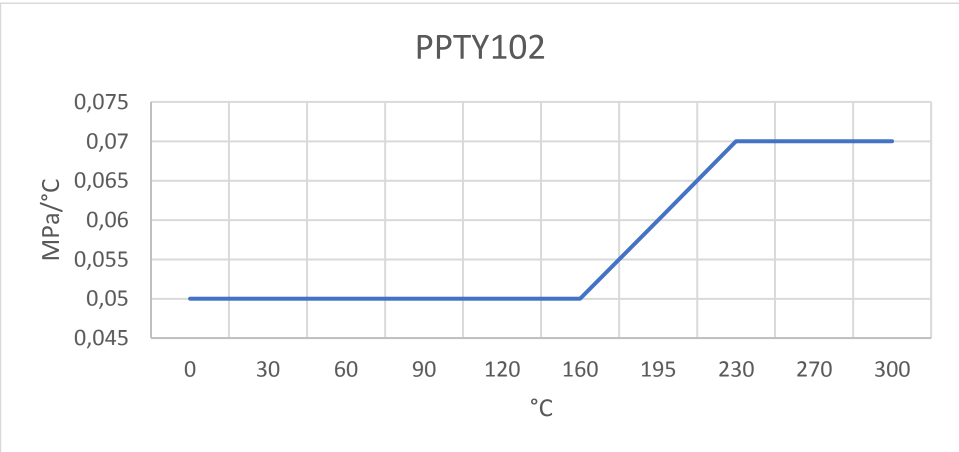

Figure 9 - Functional generator PPTY102 [6]

The PID output enters the common regulation part if the "T" regime is set. This regime contains also an alarm signalization in case of failure. This signalization informs the personnel, that the difference between the setpoint and the measured value is higher than 10°C or lower than -10°C. This signalization is blocked in case, if "T" regime is not active. [6]

Pressure control regime "P"

In the "P" regime, the regulator maintains the pressure in the pressurizer at the required value. The regulation deviation between the setpoint and the measured value enters the PID regulator PPPC101. PID output of which under "P" regime enters the common regulation part. The gain of this regulator is dependent on the T_{max} in the "hot leg". This value, however, is currently equal to 1 MPa/MPa in the whole temperature range. Due to the setting, the derivation constant is equal to zero. [6]

The setpoint is calculated based on the following equation [6]:

$$p_{set} = MIN\begin{Bmatrix} MAX\begin{bmatrix} p_{set}^{min} \\ p_{sat}(T_{set}) \\ A + B(T_{max} - C) \end{bmatrix} \\ \\ p_{set}^{max} \end{Bmatrix} \tag{5.3.1}$$

p_{set} – set pressure in the pressurizer, MPa

T_{set} – set temperature in the pressurizer, °C

T_{max} – maximal temperature in the "hot leg", °C

p_{set}^{min} – minimal required pressure in the pressurizer = 2 MPa

p_{set}^{max} – maximal required pressure in the pressurizer = 15,7 MPa

$p_{set}(T_{set})$ – saturation pressure at a required temperature in the pressurizer, MPa

A,B,C – constants, where A = 11,2 MPa; B = 0,44 MPa/°C; C = 265 °C

The behaviour of the pressure dependence on the temperature, with the temperature difference between the pressurizer and the T_{max} in the "hot leg" being dT = 55 °C, is set by the functional generator PPTY105 in the fig. 10. [6]

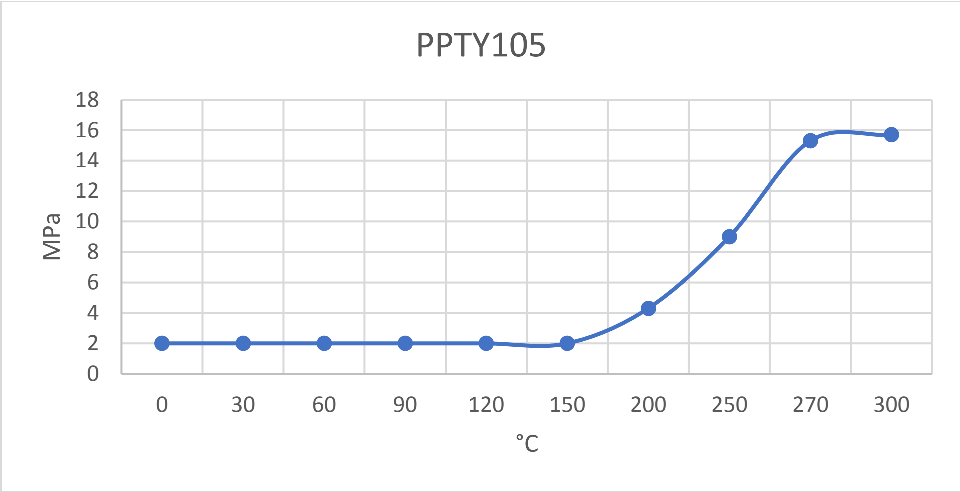

Figure 10 - Functional generator PPTY105 [6]

The value entering the regulation is determined by the pressure measured in the pressurizer or below the reactor lid. In the range from 0 to 14 MPa, the real value is the one measured below the reactor lid. If the pressure is higher than 14 MPa, then the real value is an average from three sensors in the pressurizer, which is more accurate. [6]

This regime contains an alarm signalization in case of failure, as in the case of the “T” regime. This signalization informs the personnel, that the difference between the setpoint and the measured value is higher than 0,3 MPa or lower than -0,3 MPa. This signalization is blocked in case if “P” regime is not active. [6]

The continuous regulation is composed of the PID regulator PPC102 and functional generators PPPY102 and PPPY103. They transfer the PID output into the required positions of valves or power output of the EHs. The discrete regulation is controlled by the pressure difference between the setpoint and measured value as described further. [6]

Electric heaters

I. group YP10W01 is controlled continuously according to the regulation deviation

II. group YP10W02 is controlled continuously according to the regulation deviation

I. and II. group work in a parallel regime. Both groups are controlled by the PID regulator PPC102 and functional generator PPPY102 (fig. 11). [6]

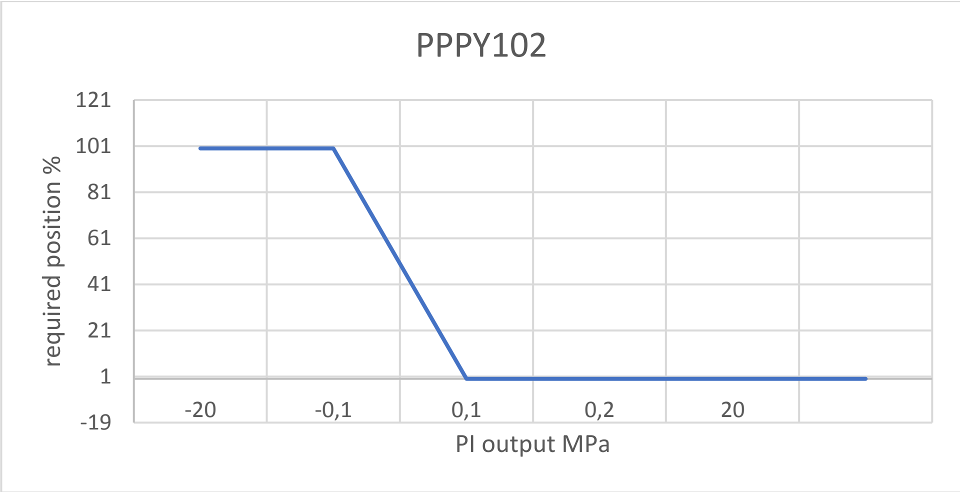

Figure 11 - Functional generator PPPY102 [6]

Turning on:

III. group	YP10W03 YP10W05	In case of pressure drop to more than 0,5 MPa below the setpoint [3]
IV. group	YP10W04 YP10W06	In case of pressure drop to more than 0,4 MPa below the setpoint [3]

Turning off:

III. and IV. group	In case of pressure drop to less than 0,3 MPa below the setpoint [3]

Regulation valve YP13S02 on spray system pipeline

This valve is continuously controlled by the PID regulator PPC102 and functional generator PPPY103 (fig. 12). [6]

- superiorly open if the pressure in the primary circuit is greater than 16,4 MPa
- superiorly close if the pressure in the primary circuit is smaller than 15,5 MPa

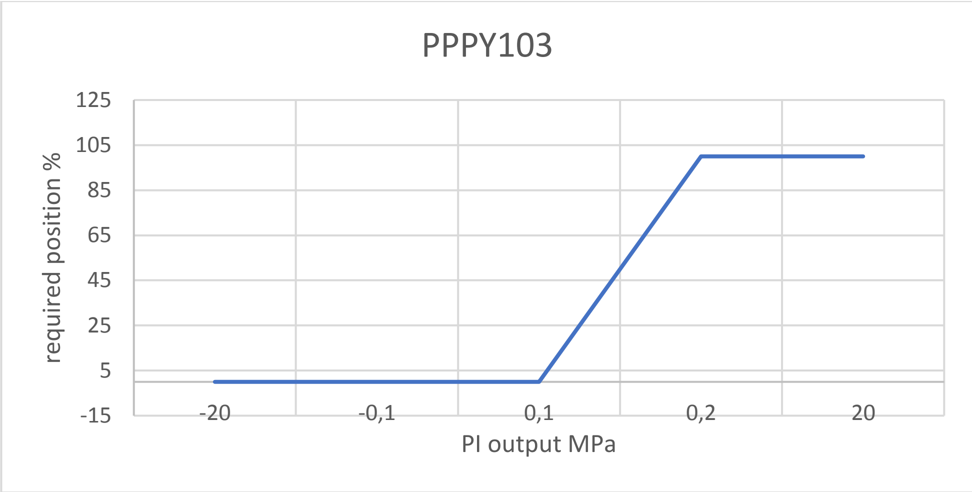

Figure 12 - Functional generator PPPY103 [6]

Quick acting gate valves YP11S02 and YP12S02 in spray system pipeline

- they take care of spraying the steam cushion in the pressurizer

Opening:

YP11S02	In case of pressure increase to more than 0,3 MPa above the setpoint [3]
YP12S02	In case of pressure increase to more than 0,5 MPa above the setpoint [3]

Closing:

YP11S02	In case of pressure increase to less than 0,2 MPa above the setpoint [3]
YP12S02	In case of pressure increase to less than 0,4 MPa above the setpoint [3]

Closing gate valves YP11,12S01 on spray system pipeline

- automatically close, if all main pumps are off or if the pressure in the primary circuit is lower than 15,5 MPa and YP11,12S02 are not closed [3]

Closing valve YP13S03 on spray system pipeline

- if YP13S02 is not closed

Regulator YPC02 – regulation of coolant level in pressurizer

During reactor power fluctuations, the temperature of the coolant in the primary circuit is changed. Together with the temperature change, the coolant volume is changed due to thermal dilatation. These volume changes cause coolant level differences in the pressurizer. Regulation valves TK31,32S02 with closing valves TK31,32S01 are the control elements of this regulation. [3] [6]

The coolant level in the pressurizer is maintained at required values 496 cm; 1060 cm or 1110 cm that are set by step or continuously by personnel in a range from 0 to 1200 cm. The regulator processes the regulation deviation of coolant level based on a measured real value in the pressurizer adjusted to mean coolant temperature value. Setting of level setpoint is a difficult procedure with attribution or subtraction of temperature correction. If cooling down is occurring, the regulation valves TK31,32S02 are in a manual mode or if the system is in the normal operation, the mode is automatic. This procedure is used to provide a non-shocking transition between those two modes and so the more accurate coolant level changes. [3] [6]

The coolant level regulation is performed by balancing regulator with the correction element derived from the coolant level as mentioned before. The following flow rates are entered to the balancing sum [3] [6]:

- Replenishment flow rate into the primary circuit
- Flow rate of chokings to all main circulation pumps
- Flow rate of chokings from all main circulation pumps
- Flow rate of the drain from the primary circuit

The correction element from coolant level in pressurizer is also added to the balancing equation. This element equals to the output from PI coolant level regulator PPLC202. The input value to this regulator is a deviation between the measurement and the setpoint coolant level in the pressurizer. [6]

The output value from the balancing sum can be either positive or negative. The positive value means that the replenishment is insufficient, whereas the negative value means, that there is too much coolant being replenished. The balancing sum is compared with the limitation from the TK pumps and the lower value enters the PI flow rate regulator PPFC203. The output from this regulator determines the amount of replenishment in range of 0 – 100% or 0 – 200%. The flow rate is performed through the functional generators PPFY204,205,206,207 (behaviour in fig. 13, 14) and regulation valves TK31,32S02. Regulation valves TK31,32S02 work in a cascade regime, i.e. one is the main one (open priory) and the other one is in the cascade. [6]

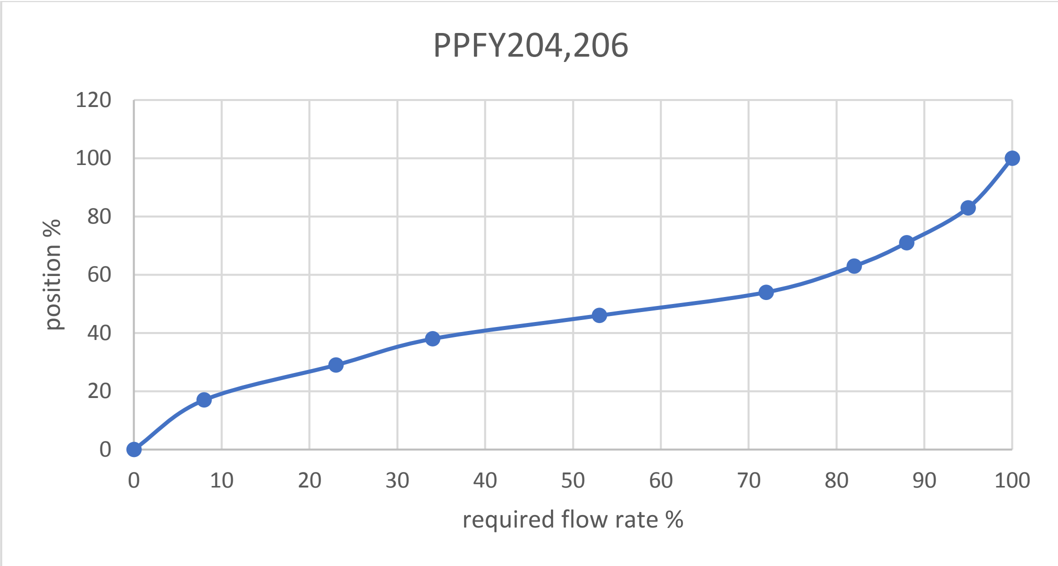

Figure 13 - Functional generator PPFY204,206 [6]

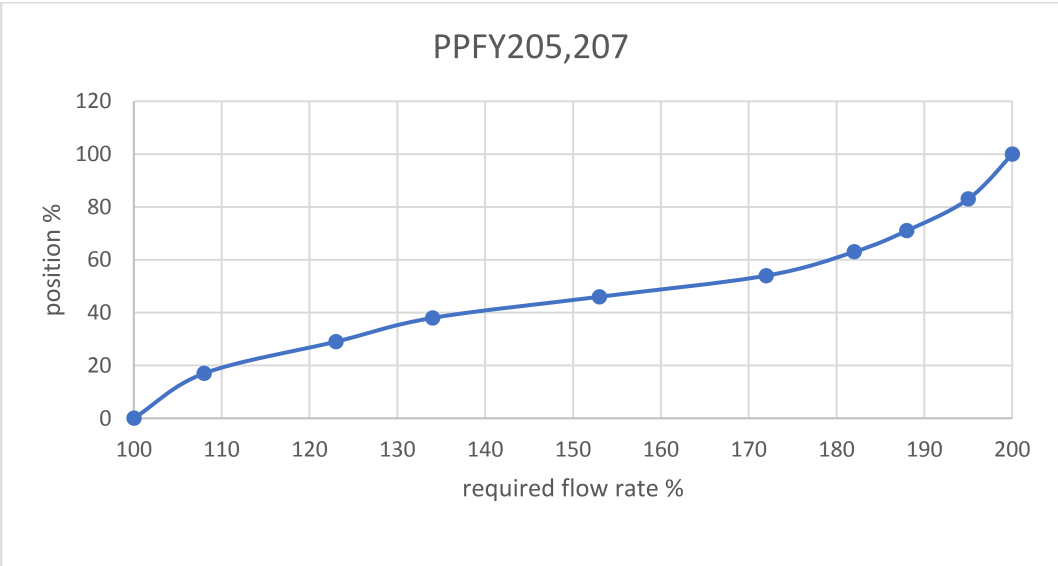

Figure 14 - Functional generator PPFY205,207 [6]

These valves are a part of a sub-system TK30, that is a part of the TK20 system with replenishment pumps TK21,22,23D02. These pump the coolant through pipeline DN 100 and through the TK30 sub-system into the primary circuit. The length of the pipeline was not found, but it was estimated to be 7 m based on another auxiliary systems dimension. The pressure at the pump outlet is 17,65 MPa (max 19,6 MPa) and the volume flow rate is 60 m^3/h. The connection to the primary circuit is performed between the pressurizer and the MCP. [6]

Closing valve TK31,32S01

- Opens if the difference between the setpoint and measured level is ≤ 20 cm
- Closes if the measured level is above the setpoint for more than 100 cm

Regulation valve TK32S02

- Superiorly closes if TK31,32S01 are closed

This regulation contains an alarm signalization in case of failure. This signalization informs the personnel, that the difference between setpoint and measured level is higher than 50 cm or lower than - 50 cm. If the flow rate through regulation valve TK31,32S02 is limited due to the limited pump flow. If the level in the pressurizer is lower than 360cm or higher than 834 cm.

5. Dymola program and ClaRa library

The program that was used for this thesis is called Dymola. Dymola is an abbreviation, that stands for “Dynamic Modelling Laboratory” and it is a program that is suitable for modelling various kinds of physical systems. Many types of components and connections can be used and that is the reason for using it in this work. The modelling methodology is based on object orientation and equations. The advantage of this program is that it can handle large and complex models and uses graphical model composition. Simulation in Dymola is fast and done in a real-time. It is opened for users to define model components and the interface is opened to other programs. Dymola is in fact a simulation environment of Modelica language. Modelica is a multidomain programming language, which means that it is possible to describe and connect model parts from varying domains such as electrical, mechanical, thermodynamic, hydraulic, biological, and control applications. It has a general class concept that unifies classes, generics and general subtyping into a single language construct. This feature makes it easier to reuse components and aids in the development of the models. Finally, Modelica has a strong software for designing and connecting components, meaning that this language is suitable for an architectural description of complex physical and software systems. [7] [8] [9]

A model developed in the Modelica language consists of several sub-models with causal connectors which allow an exchange of outgoing and incoming information. The Modelica language then works with subcomponents, that are connected via connectors, representing instances of classes. Connectors are exactly defined interfaces for connection of certain sub-models. They define variables which are part of the communication interface and therefore external interfaces for interaction is specified. The connection is possible only between same connector classes and this connection is resistant to errors. Another advantage is that by connecting the sub-models, the connection of sets of equations from each component occurs. [8] [9]

The Modelica language has however its disadvantages, like the severity of numerical stability for complex models, which may lead to results out of expected range and complex debugging. Determining the cause of errors in models of physical systems is currently time consuming difficult process, bounded by the limitations of the current techniques of debugging. The user must execute the simulation model in order to determine and fix the cause. Another disadvantage may be the computational time for complex models using difficult connections. The initialization of the simulation is complex as well, because depending on the system composition and initial values, the system may have problems with it, which leads to another difficult problem solving in some cases.

The interface consists of two basic windows. The main window and the library window are shown in the fig. 15. The main window operates in two modes: modelling and simulation. The modelling mode offers users to use the library to compose the model from the components and connections presented in the library or to create their own model. In the upper bar, there are icons for ordinary commands like “save as”, “print” etc., then commands for creating the model’s shape, colour etc. and then commands for examining the models and components. In the last package of commands, the user can observe an icon of the model or the diagram. It shows a set of components connected to each other and information about each component or the component compositions. In the library window, there is an implemented Modelica library and an option to download other libraries compatible with Dymola. [7]

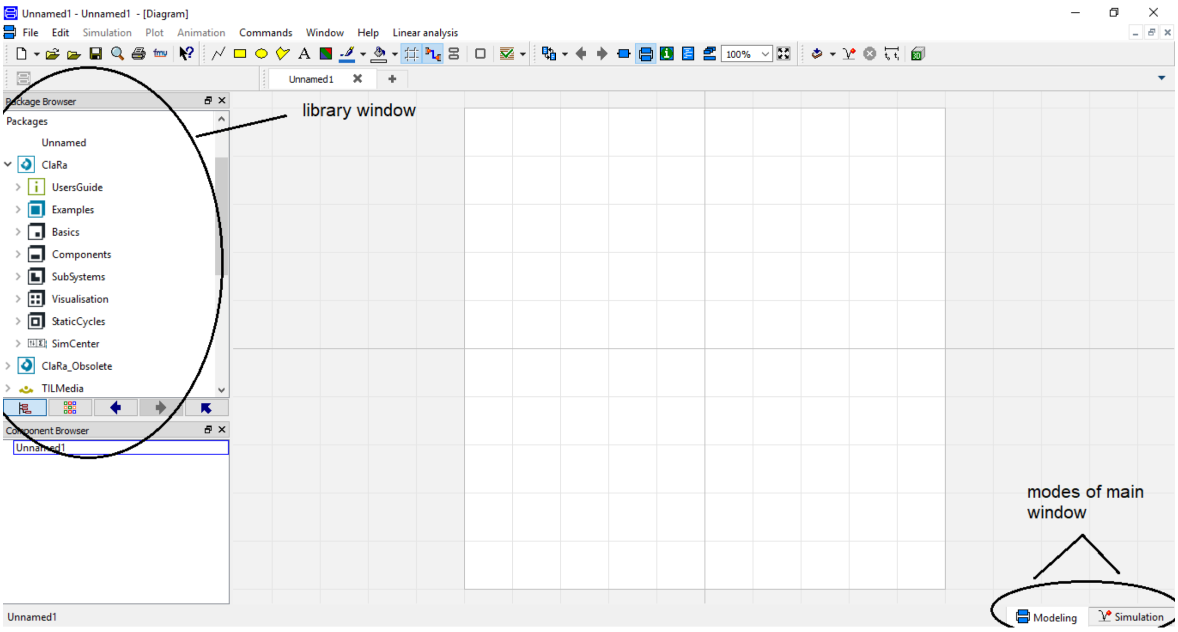

Figure 15 - Dymola main and library window

The simulation mode is used for experiments, plotting results, and animation of the created model. For simulating the created model, it is necessary to check, whether the model is correct and then to set a simulation interval, an output interval and an integration method as shown in the fig. 16. [7]

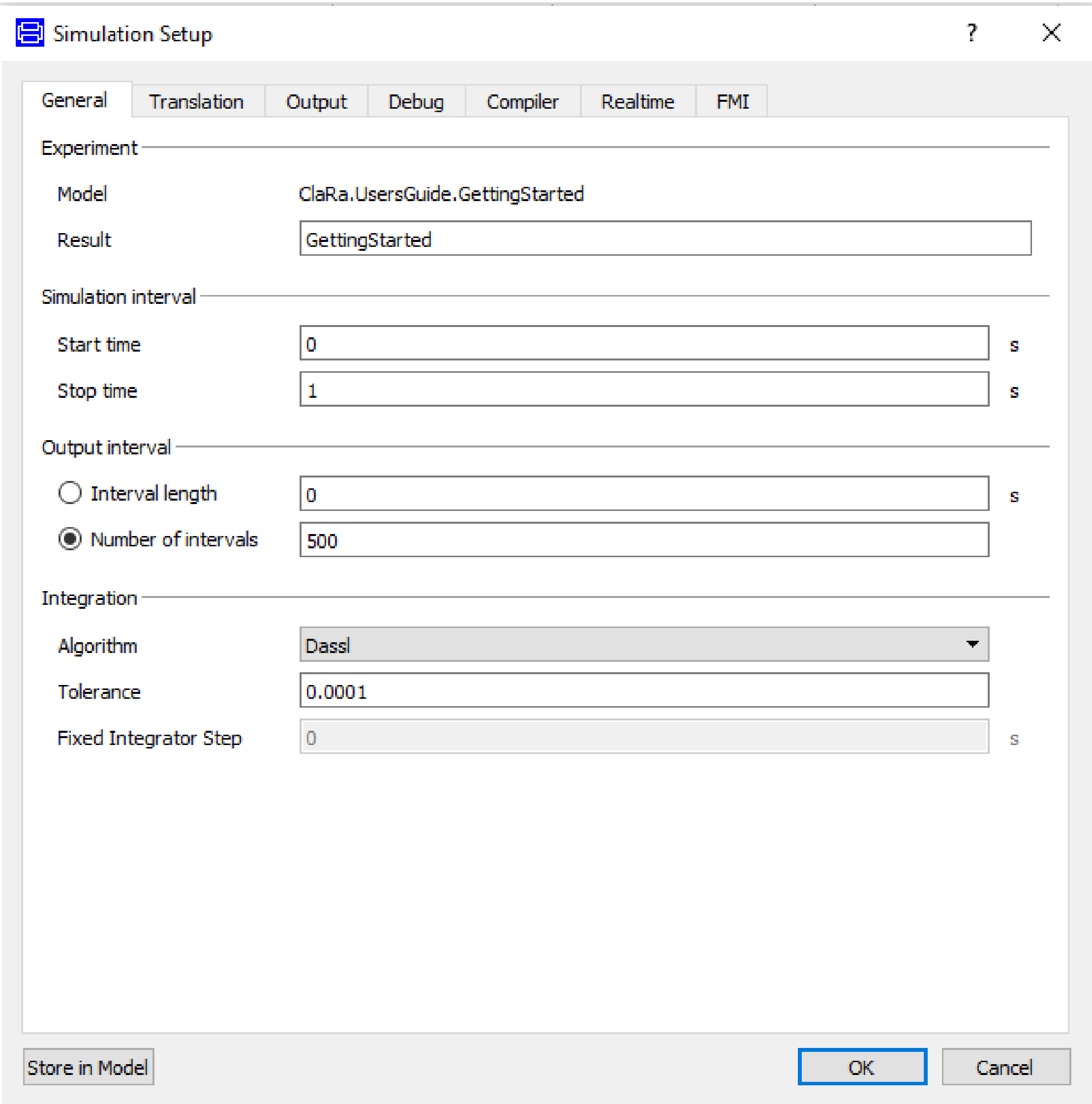

Figure 16 - Dymola simulation setting

The simulation interval describes the start and the stop time. Output interval specifies how the results should be stored. There are two options for this specification, either a number of intervals of the interval length. The integration method specifies the algorithm used to solve the differential equations and tolerance specifying required accuracy. The integration is currently offered in several variable step-size methods. These methods differ by the system stiffness, level of accuracy required and equation compositions in the systems. In total, there are 14 different methods (that are subdivided), that differ by features of ordinary differential equations (ODEs) or differential algebraic equations (DAEs). Differences like composition, order, stiffness, dense output and root finder. Once the simulation is completed, the results can be found in the simulation window on the left-hand side. It is possible to plot everything the model contains. [7]

Since this thesis is based on modelling the pressurizer behaviour, special library fulfilling the need was used. This library is called ClaRa (written in Modelica language), which is an abbreviation of Clausius-Rankien and it specializes in the Clausius-Rankien cycles. The top level content of the ClaRa library is shown in the fig. 17. [10]

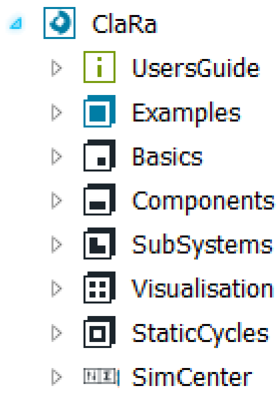

Figure 17 - ClaRa library top level content [10]

The **User guide** is an introduction into the library, which provides with help with it usage and updates recently made. In the **Examples** package, the user can find helpful models at different stages of complexity. These models serve either for the demonstration purposes or they can be used as a manual for similar model creation. In the **Basics** package, the user can find all fundamental models contained in the library. These fundamentals are divided into several sub-packages as shown in the fig. 18. [10]

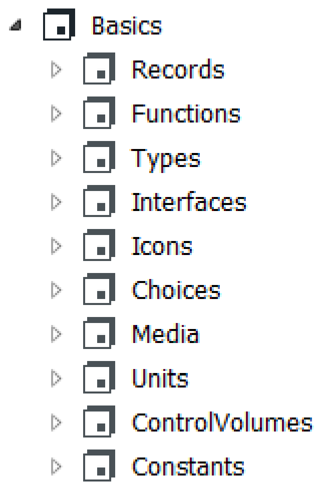

Figure 18 - ClaRa library Basic package [10]

The ***Records*** is a sub-package that contains communication commands for different properties and their complexities. The ***Function*** sub-package contains basic functions used in the calculation, that are integrated in fundamental models. ***Interfaces*** sub-package is composed of different ports that are used for connection between components and which specifies the direction of the media flow (in/out). The user can use different types of fuel, which can be found in the ***Media*** sub-package. ClaRa library ***Units*** system contains units derived from SI units. The ***ControlVolume*** sub-package contains basic definition of different control volumes, that is Fluid, Solid and Gas and their fundamentals (geometry, heat transport, spatial distribution, pressure loss and chemical reactions). All three volume types can be found in various complexity level for various purposes. [10]

The **Components** package provides all basic models necessary for building up a power plant or partial circuit. This package contains a lot of sub-packages based on different components categories as shown in fig. 19, e.g. ***VolumesValvesFittings***, ***Sensors***, ***BoundaryConditions***. [10]

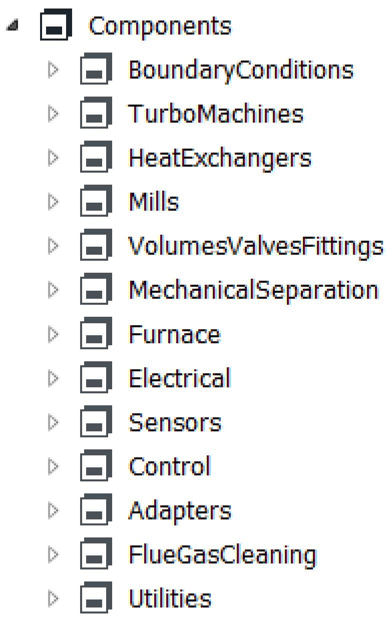

Figure 19 - ClaRa library Components package [10]

The package **SubSystems** contains complex systems, that are created to be used as one. This model is composed of sub models and in the 1.2.2. version, it forms coal supply boiler and two steam generators differing by the complexity. The **Visualisation** package contains elements for displaying and plotting dynamic simulations. There is for example ***Quadruple*** option, which is displaying mass flow rate, pressure, temperature and enthalpy in one diagram, so the user can observe the dependencies during the simulation. The **StaticCycles** package contains simplified versions of almost all dynamic models in the library and they are used to initialize complex models in a systematic way. Outputs from simulation of the static model are then transferred into the dynamic model. The last package is a **SimCenter**, which is a mandatory top-level model for every complex simulation. It provides global setting such as a media used in the complex or if the flow reversal shall be allowed. [10]

Models in ClaRa library are designed to three principles. The first principle is a level of detail of the components that is described by the complexity, mathematical computation methods and thus possible application. This criterion answers questions like the purpose of the model and its applicability. Most of the models in the library are freely exchangeable in terms of their complexity. In fact, there are four levels of details [10]:

- **L1** – idealised model, that shows physical behaviour; the definition is derived either from the analytic solutions or from phenomenological considerations; applicability is limited by the simplification process, incorrect physical behaviour may occur
- **L2** – models are based on balance equations; equations are spatially averaged over the component and the model shows correct physics, unless the assumptions for the averaging process are violated
- **L3** – models are subdivided into a fixed number of spatial zones; spatial localisation can vary dynamically; for each zone, a set of balance equation is used; the model shows correct physics, unless the assumptions for the zonal subdivision and the averaging process are violated
- **L4** – models can be subdivided into number of control volumes; for each zone, a set of balance equations is used, that are averaged over the zone; the model shows the correct physics, unless the assumptions for the choice of the grid and the averaging process are violated

The other principle is the physical effect that is considered, which is reflected by the physical equations used in the model. Models chosen for certain application may differ by the simulation goal. As an example, in a pipe, it may be needed to solve spatial flow properties, but not to analyse sound waves and this approach is reflected in the complexity of the physics in the model. Even though the ClaRa library is designed for dynamic simulations, stationary behaviour is also applicable. Results from such simulations can be then transferred as initial values into the dynamic model. For such purposes, components at the same level of detail, but with different physics, are available in the **StaticCycle**s package. The last principle is a level of insight, which describes, how the physics is used, for example the pressure loss in a pipe may be modelled with nominal point or through correlation respecting the flow regime and fluid states. These assumptions are modelled in exchangeable models using predefined interfaces. [10]

Combination of ClaRa and Dymola is a very sophisticated and powerful combination. Nevertheless, due to the high sophistication, the complexity is also very high and thus, the use (result evaluation) can be difficult. Obtaining results is an iteration process, where according to the initial values, given to the component, the system is finding the right solution. The more components, the more equations and the more parameters are needed and so the computation takes more time. Evaluation process is composed of evaluating numerous set of values from different parts of each model (i.e.: for pipe, it is not only the resulting temperature and pressure, but also the heat flow along the component, the pressure difference, flow direction, heat generated in the component etc.).

6. Model components

In this part, the physical composition of all models together with their properties is discussed. Especially the pressurizer model is described in detail.

6.1. Pressurizer model

The attitude for computing the pressurizer behaviour is differing by the complexity of the model and desired results [11] [12]. Thus, the model can be divided into several regions, as described in [13]. To determine a response to a load change in a simple way, two principles can be introduced, these are a) an equilibrium single-region formulation or b) final equilibrium pressure conditions. When considering a), the whole pressurizer is taken as a single region at equilibrium state as shown in fig. 20. Where $\dot{Q}_h$ is a heat transfer to the system (by EHs), $(\dot{m}h)_{spray}$ is a mass and enthalpy flow from the spray system and $(\dot{m}h)_{surge}$ is a mass and enthalpy flow to or from the "hot leg" connection. [13]

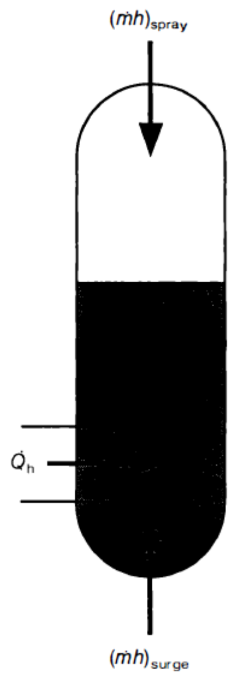

Figure 20 - One-region pressurizer - supplied mass flow rate, enthalpy and heat [13]

This approach is respecting the spray at inlet and the "hot leg" connection at the outlet. The whole system is perfectly insulated with no heat losses. There are 5 prescribed input parameters, these are inlet and outlet mass flow and enthalpy and heat flow from the electric heaters and 7 unknows, which are related to transient mass and energy equations and to fixed volume equation. This approach is sufficient for determination of unknowns for simple one-region equilibrium formulation during transient. [13]

When considering b), the problem becomes simpler and this approach can be used to determine the size of the pressurizer. In this case, the unknowns would be liquid and vapor masses and the heater power and equations would be those for continuity, energy conservation and volume constraint. The computation is done based on the initial state (fig. 21) and end states, that are either completely liquid-filled or vapor-filled vessel as shown in fig. 22. In the initial state (and always), electric heaters must be entirely liquid-covered and by this condition, the minimum coolant level is determined. In the fig. 21, the $(V_{g1})_{insurge}$ $(V_{f1})_{outsurge}$ are the initial state of vapour and liquid inside the body. In the fig. 22, the $(V_{f2})_{insurge}$ is a state of the liquid filled pressurizer and $(V_{f2})_{outsurge}$ is the minimal liquid level in the pressurizer, that is filled with vapour $(V_{g2})_{outsurge}$. [13]

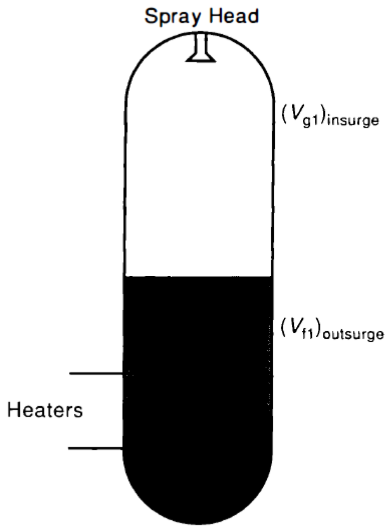

Figure 21 - Initial state of pressurizer [13]

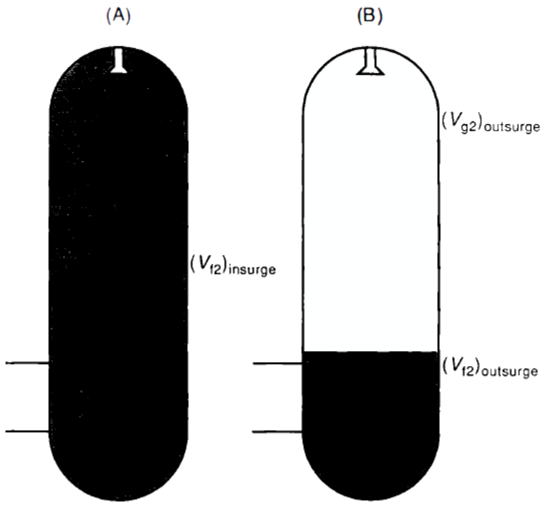

Figure 22 - Final states of pressurizer. A – insurge , B – outsurge [13]

More complex model describes transient behaviour either in c) nonequilibrium four-region formulation or in d) nonequilibrium two-region formulation. When considering c), in the upper region, there is a continuous vapor cushion, through which liquid drops fall and in the lower region, where is a continuous liquid volume, through which the vapor bubbles rise. So, the four regions are saturated vapor, saturated liquid and condensing vapor and evaporating liquid with properties as shown in the fig. 23. [13]

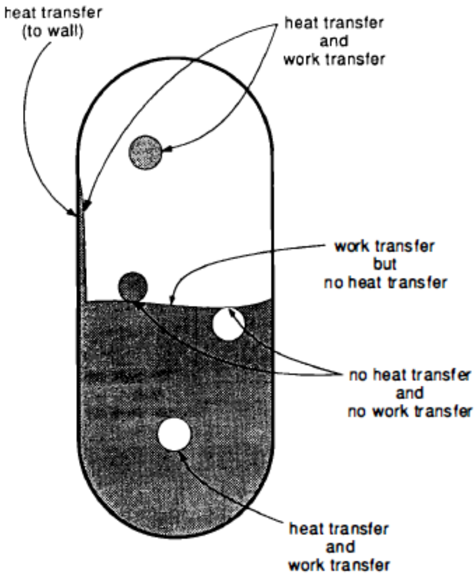

Figure 23 - Pressurizer with non-equilibrium four-region distribution [13]

The condensing vapor is divided into three forms: new drops (rainout), condensate film on spray drops, condensate on the pressurizer wall. The input parameters are the same is in a), there are 45 unknows and 37 equations in total, using the internal energy and pressure as the independent thermodynamic variables. This means, that to be able to solve this problem, other 8 constitutive equations must be added. These equations express the heat transfer between phases and to the wall and the relationship between the mass transfer of the vapor and liquid region, plus the droplet flow rate and the bubble flow rate. This is a very complex and sophisticated approach, which can be simplified into d). [13]

This simplification was made without loss of accuracy. As mentioned before, there are two regions operating at one pressure. These simplifications are, that the spray is reaching the liquid region together with the condensate from the upper region instantaneously. The vapor bubbles are also entering the vapor region instantaneously. The system is shown in fig. 24. The prescribed input parameters are the same as in the four-region formulation. This system however has 16 unknowns, and there are 13 equations in total and so only 3 other constitutive equations must be added to be able to solve this problem. These equations are the same as in the four-region formulation, but there is no need for droplet and bubble flow rate, since these were modified in the simplification. The mark, in fig. 24, W_{RO} represents condensation of vapour into new liquid drops, W_{FL} represents the flashing of liquid into vapour, W_{WC} represents condensed vapour on the wall, W_{SC} represents the condensed vapour on the spray drops, $\dot{m}_{spray}$ is a mass flow from the spray system and $\dot{m}_{surge}$ is a mass flow to or from the "hot leg" connection. [13]

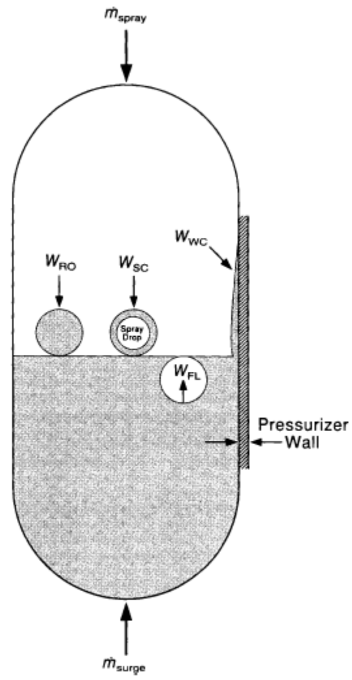

Figure 24 - Pressurizer with non-equilibrium two-region formulation [13]

The approach from the ClaRa library was compared with the approach of a functional model written in MATLAB [14]. The ClaRa model describes the physical behaviour similarly, but the assumptions are up to the user. In [14], the mass changed is caused only by the temperature change in the primary circuit, the influence of spray and the surge. The mass change caused by the phase transition is neglected, which is the main difference between the model used in [14] and model use in this work. The inputs for the model in [14] are average temperature of the primary circuit, the temperature of the "hot leg" and feedwater and surge influence. The measurable outputs are difference in the coolant level and the pressure in the pressurizer. The essential phenomena of mass and energy transfer is caused by the wall condensation, bubble rising and heat transfer. The equations for mass conservation are simplified version of mass conservation in ClaRa model.

As described before, the volume compensation system is composed of several components, where one of the most important one is the pressurizer. Model of the pressurizer used in this work is based on the ClaRa library model VLE_L3 (fig. 25), but it was slightly modified to fit requested needs. This model is frequently used, when two phases (vapour and liquid) are present and non-ideal phase interaction is expected.

Regarding the three principles described in the chapter 6, it has a level of detail L3, because the system is modelled with use of balance equations for two distinct zones (vapour and liquid). As for physical effects considered, following is offered in L3 model: the conservation of mass, simplified conservation of momentum, conservation of energy, reverse flow, heat transport due to convection, pressure loss due to friction and non-ideal phase separation and mixing based on phenomenological model ideas are used. And level of insight offers constant or ideal heat transfer, linear parallel or serial pressure loss or no friction and real separated or real mixing fluids. It has three physical connectors, namely inlet, outlet and heat. The inlet is the inlet of the spray system, outlet is a connection to the “hot leg” and heat connector represents power of electric heaters. For pressurizer purposes, following were chosen [10]:

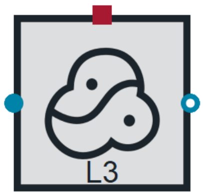

Figure 25 - ClaRa two-phase control volume L3 icon [10]

Level of insight and geometry:

Heat transfer	Constant HT, α_{nom} = {10,10} W/m^{2}K – liq,vap
Pressure loss	Nominal pressure loss coefficient, *dp* = 0,05 MPa
Phase border	Real separated zones, absorption inflow = 0,8
• τ_{cond}	2 s
• τ_{evap}	2 s
• α_{ph}	60 000 W/m^{2}K
• A_{heat_ph}	43 m^2
• *expHTph*	-7
• *equal_pressure*	true
Geometry type	Hollow cylinder, no interior, vertical
Dimensions	d_{inner} = 2,998 m
	d_{outer} = 3,348m
	L = 13,514 m
Material	stainless steel

The model structure is defined as in the fig. 26. Two distinct zones are considered (vapor and liquid). They can exchange mass and heat. Heat transfer to the material wall was chosen very small, so that the system behaves like being almost insulated. The pressure loss is considered due to friction at inlet only, with the nominal coefficient of dp = 0,05 MPa.

The allocation of the entering and outgoing enthalpy flows is considered with respect to the spatial distribution. The spatial distribution was decided to be real separated. This model assumes that the real separation process is not instantons. The incoming and outgoing mass flow should be allocated to one of the two zones present in the model. The mechanism of the zone allocation is defined by the real parameter *absorbInflow*, that is available in range 0 to 1. If the value is 1, it means, that the incoming and outgoing fluid is strictly allocated according to the filling level and the geometric position of ports. If the value is 0, it means, that the wet steam is ideally separated and dewing vapor fraction is allocated to the liquid zone and boiling liquid fraction is allocated to the vapor zone. [10] For this model, the incoming fluid is right after entering the vessel becoming a wet steam. The *absorbInflow* is set 0,8 and thus the inlet flow is partially separated into vapor and liquid and then added to the respective zones in the respective states.

Time constants for evaporation and condensation τ_{cond}/ τ_{evap} (described in the chapter 6.1.1) was chosen with respect to the physical behaviour of the condensation and evaporation process. This number was determined experimentally, however, only in a certain range (0,1 to 5 s) to preserve physical laws. The best results were obtained, when $\tau_{cond} = \tau_{evap}$ = 2 s (described in the fig. 49, fig. 54).

The heat transfer coefficient of the phase border α_{ph} was tested in range of (30 000 to 80 000 W/m2K) and the best results were obtained with α_{ph}= 60 000 W/m2K. The range was chosen based on the [4] and verbal agreement. The heat transfer between phases is however very complicated process and the coefficient depends on the conditions, so this determination is simplified. Related to the heat transfer coefficient, the heat transfer area at phase border A_{heat_ph} was determined. The area was calculated as the wall surface in the upper region and to this area, the surface of EHs was added. The heat is in fact transferred throughout the whole vapor region and also on the vapor bubbles surface inside the liquid zone so the surface A_{heat_ph} = 43 m^2 is another simplified assumption. The last coefficient related to the inter-phase heat transfer is exponent for volume dependency on the inter-phase heat transfer *expHTph*. This coefficient was tuned based on the obtained results. When simulating the spray or EHs operation (in chapter 8.2), the behaviour of the pressure and the coolant level was observed and if the gradient was changed in the opposite direction then expected, the coefficient was modified. The final value *expHTph* = -7 describes the process the most likely.

The geometry with all dimensions corresponds to reality. The material of the pressurizer in the real system is steel 10GN2MGA. Such material is not available in the ClaRa library of materials, so it was replaced by the stainless steel and this material was used in the whole primary circuit.

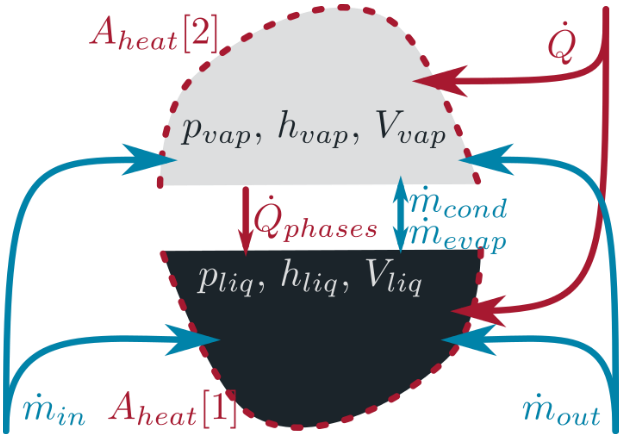

Figure 26 - ClaRa two-phase control volume general model structure [10]

6.1.1. Governing model equations

Conservation of mass

The mass balance of each zone considers evaporation and condensation mass flow rates (kg/s), volume changes (Δ m3) and mass flows (kg/s) through the inlet and outlet connectors. Since the real separated spatial distribution was set in the model, the mass flows in zones are allocated respectively [10]:

$$\frac{d\rho_{vap}}{dt}V_{vap} = \dot{m}_{in,vap} + \dot{m}_{out,vap} - \dot{m}_{cond} + \dot{m}_{evap} + \rho_{vap}\frac{dV_{vap}}{dt} \quad (7.1.1.1)$$

$$\frac{d\rho_{liq}}{dt}V_{liq} = \dot{m}_{in,liq} + \dot{m}_{out,liq} + \dot{m}_{cond} - \dot{m}_{evap} + \rho_{liq}\frac{dV_{liq}}{dt} \quad (7.1.1.2)$$

Conservation of momentum

The momentum balance respects the pressure losses (Pa) and because the model is simplified, so there is no pressure loss and thus the momentum flows through port can be neglected.

The three aspects considered are friction force (only at inlet), static pressure forces and gravity. [10]

$$p_{in} = p_{vap} + g\rho\Delta z + \Delta p_{fric} \quad (7.1.1.3)$$

$$p_{out} = p_{liq} + g\rho\Delta z \quad (7.1.1.4)$$

Conservation of energy

The energy balance is calculated with respect to entering and leaving enthalpy flow rates (kJ/kg) and energy transport due to mass and heat transfer between vapour and liquid (W). The mass flows (kg/s) are allocated to zones with respect to spatial distribution as mentioned before. In equations below, there are three terms that take the derivatives of volume (Δ m3), density (Δ kg/m^3), and pressure (Δ Pa) into account [10]:

$$\frac{dh_{vap}}{dt} = \frac{1}{m_{vap}}\left(\sum_{i=1}^{N_{in}} \dot{m}_{vap,in,i}\, h_{in,i} + \sum_{j=1}^{N_{out}} \dot{m}_{vap,out,j}\, h_{out,j} + \dot{m}_{evap}h_{dew} - \dot{m}_{cond}h_{bub} + p_{vap}\frac{dV_{vap}}{dt} + V_{vap}\frac{dp_{vap}}{dt} - h_{vap}\left(V_{vap}\frac{d\rho_{vap}}{dt} + \rho_{vap}\frac{dV_{vap}}{dt}\right) - \dot{Q}_{phases} + \dot{Q}_{vap}\right) \quad (7.1.1.5)$$

$$\frac{dh_{liq}}{dt} = \frac{1}{m_{liq}}\left(\sum_{i=1}^{N_{in}} \dot{m}_{liq,in,i}\, h_{in,i} + \sum_{j=1}^{N_{out}} \dot{m}_{liq,out,j}\, h_{out,j} - \dot{m}_{evap}h_{dew} + \dot{m}_{cond}h_{bub} + p_{liq}\frac{dV_{liq}}{dt} + V_{liq}\frac{dp_{liq}}{dt} - h_{liq}\left(V_{liq}\frac{d\rho_{liq}}{dt} + \rho_{liq}\frac{dV_{liq}}{dt}\right) + \dot{Q}_{phases} + \dot{Q}_{liq}\right) \quad (7.1.1.6)$$

The heat transferred (W) to each zone is determined according to the volume ratio of the zones [10]:

$$\dot{Q}_{liq} = heat.Q\,\frac{V_{liq}}{V_{tot}} \quad (7.1.1.7)$$

$$\dot{Q}_{vap} = heat.Q\,\frac{V_{vap}}{V_{tot}} \quad (7.1.1.8)$$

The model's density (Δ kg/m³) is taken as an explicit function of the states [10]:

$$\frac{d\rho_{liq}}{dt} = \frac{dp_{liq}}{dt}\frac{\partial\rho_{liq}}{\partial p}\bigg|_{h_{liq},\xi_{liq}} + \frac{dh_{liq}}{dt}\frac{\partial\rho_{liq}}{\partial h_{liq}}\bigg|_{p_{liq},\xi_{liq}} + \sum_{n=1}^{N_c}\frac{d\xi_{liq}}{dt}\frac{\partial\rho_{liq}}{\partial\xi_{liq}}\bigg|_{p_{liq},h_{liq}} \quad (7.1.1.9)$$

$$\frac{d\rho_{vap}}{dt} = \frac{dp_{vap}}{dt}\frac{\partial\rho_{vap}}{\partial p}\bigg|_{h_{vap},\xi_{vap}} + \frac{dh_{vap}}{dt}\frac{\partial\rho_{vap}}{\partial h_{vap}}\bigg|_{p_{vap},\xi_{vap}} + \sum_{n=1}^{N_c}\frac{d\xi_{vap}}{dt}\frac{\partial\rho_{vap}}{\partial\xi_{vap}}\bigg|_{p_{vap},h_{vap}} \quad (7.1.1.10)$$

Pressure states

The liquid and the vapour state are defined by the pressure (Pa) and enthalpy (kJ/kg) at the zone. Since the pressure of the liquid is equal to the pressure of the vapour, the following equation is true [10]:

$$p_{liq} = p_{vap} \quad (7.1.1.11)$$

Chemistry

Since, the two fluids in the volume can be mixed and during the process, the mass fraction is changed, the following equation determine the state of each mass fraction [10]:

$$\frac{d\xi_{vap}}{dt} = \frac{1}{m_{vap}}\left(\sum_{i=1}^{N_{in}}\dot{m}_{vap,in,i}\,\xi_{in,i} + \sum_{j=1}^{N_{out}}\dot{m}_{vap,out,j}\,\xi_{out,j} + \dot{m}_{evap}\xi_{dew} - \dot{m}_{cond}\xi_{bub} + \xi_{vap}\left(V_{vap}\frac{d\rho_{vap}}{dt} + \rho_{vap}\frac{dV_{vap}}{dt}\right)\right) \quad (7.1.1.12)$$

$$\frac{d\xi_{liq}}{dt} = \frac{1}{m_{liq}}\left(\sum_{i=1}^{N_{in}}\dot{m}_{liq,in,i}\,\xi_{in,i} + \sum_{j=1}^{N_{out}}\dot{m}_{liq,out,j}\,\xi_{out,j} - \dot{m}_{evap}\xi_{dew} + \dot{m}_{cond}\xi_{bub} + \xi_{liq}\left(V_{liq}\frac{d\rho_{liq}}{dt} + \rho_{liq}\frac{dV_{liq}}{dt}\right)\right) \quad (7.1.1.13)$$

Mass transfer between zones

The condensation and evaporation mass flow (kg/s) is determined by the vapour fraction (-) in the liquid zone and the liquid fraction (-) in the vapour zone (steam quality). This is defined by two time constants for evaporation and condensation.

These were modified so that the most real behaviour was obtained. Since q_{vap} and q_{liq} (vapor, liquid quality) change during the operation because of the load changes, EHs power input or sprays, governing equations, respecting this condition, can be seen below [10]:

$$\dot{m}_{cond} = (1 - q_{vap})\frac{m_{vap}}{\tau_{cond}} \tag{7.1.1.14}$$

$$\dot{m}_{evap} = q_{liq}\frac{m_{liq}}{\tau_{evap}} \tag{7.1.1.15}$$

Heat transfer between zones

The model for the inter-phase heat transfer assumes constant values for heat phase surface and heat transfer coefficient [10]:

$$\dot{Q}_{phases} = \alpha_{ph} \, . A_{heat\_ph}\left(\frac{V_{small}}{V_{large}}\right)^{expHTph}(T_{vap} - T_{liq}) \tag{7.1.1.16}$$

$$V_{large} = \max(V_{liq}, V_{vap})$$
$$V_{small} = \min(V_{liq}, V_{vap})$$

To be able to adequately describe the behaviour of the pressurizer with respect to the Dymola and ClaRa properties, several simplifications were made. Some were described in the governing model equation earlier, but to summarize them, following list was made:

a) The mass flow rate between zones is determined by the time constant of condensation and evaporation and steam quality
b) The vapour is at saturated state
c) The rising bubbles from the liquid escape at saturation state
d) The droplets from condensing vapour are entering the liquid region at saturated state
e) Both regions are of the same pressure of saturated vapour state
f) No boron acid is present in the whole system and the coolant has the same composition in the whole system
g) The losses are considered only at pressurizer inlet

6.2. Reactor and steam generator model

The model of the reactor is basically extended version of the pipe model, since it calculates with one phase only. The steam generator model was also chosen as pipe model since only primary side is taken into calculations. This simplification was made to simplify the primary circuit to only incoming heat to the reactor and outgoing heat from the steam generator. For this purpose, pipe model L4 was chosen. It assumes that density and enthalpy are spatially distributed, while it considers static momentum balance and neglecting kinetic energy terms. Physical effects considered are conservation of mass, conservation of energy, reverse flow, heat transport due to convection, pressure loss due to friction and respective spatial distribution of fluid. As for the level of insight, there are several options to choose from in heat transfer area, in pressure and geometry. For both models, it was decided to choose constant heat transfer with constant HT coefficient, linear pressure loss, and 4 element tube geometry. It has three physical connectors, namely inlet, outlet, and heat. For the reactor rsp. steam generator, the inlet is connected to the “cold leg” (rsp. “hot leg”), the outlet is connected to the “hot leg” (rsp. “cold leg”) and heat connector represents the power input (rsp. power output). The model is shown in the fig. 27. [10]

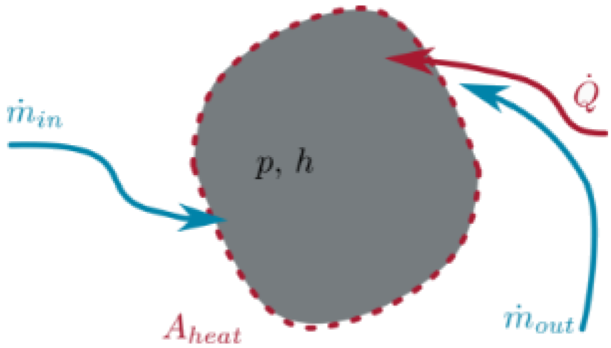

Figure 27 – ClaRa one-phase control volume general model structure [10]

To achieve required conditions in the primary circuit and maintain its properties, it was decided to model both, reactor and steam generator as tube bundle, example case shown in fig. 28. The original primary side composition of SG, i.e. 11 000 pipes, that are U shaped [3] was copied into the reactor, so that the amount of heat transfer is preserved. Even though in reality, the dimensions of the reactor and the steam generator are differing, with respect to simplification made in this thesis, both dimensions are equal. This was made because the purpose of both reactor and steam generator is only to deliver heat (inside and outside the primary circuit respectively).

Since this model is simplified and only one out of four loops is modelled, the respective mass flow rate and heat transfer has to be recalculated. The real reactor mass flow, when all four loops are in operation (all MCP are in operation) is between 83 000 and 88 000 m3/h (depending on reactor core fuel composition – Russian or American). Considering only one loop, it yields to ¼ of this mass flow, which is from approx. 20 500 to 22 000 m3/h. The model is only respecting unit of kg/s, so that this mass flow was recalculated with respect to the steady pressure and average temperature of 15,7 MPa and 305°C. The final mass flow then corresponds with the mass flow in one loop and in one SG, which is approx. 4400 kg/s. [15] [3]

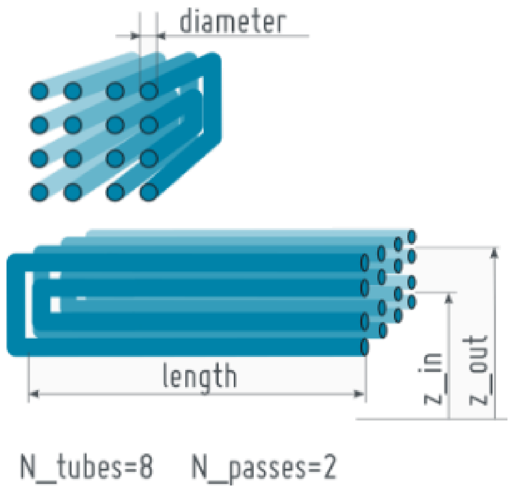

Figure 28 - Shape of a tube bundle - example [10]

The one loop simplification is also considered for the reactor power output. As described before, only ¼ of the real power (heat) is transferred into the reactor, and so if the real power is approx. 3000 MW_t, then in this model it is approx. 760 MW_t. In the system, there is pressure loss, that is replaced by the main circulation pump, but these pressure losses are transferred to heat, that increase the heat flow throughout the whole system. This extra heat generated in the system has to be removed from the system in the steam generator together with the heat generated in the reactor to keep the balance in the system. [15] [3]

Reactor level of insight and geometry:

Heat transfer	Constant HT, $\alpha = 20$ W/m²K
Pressure loss	Nominal pressure loss, dp = 0,37 MPa - reactor
	Nominal pressure loss, dp = 0,11 MPa – steam generator
Dimensions	d_{inner} = 0,016 m
	d_{outer} = 0,019 m
	z_{in} = 23,9 m
	z_{out} = 25,7 m
	L = 5,5 m (one pass)
	N_{tubes} = 11 000
	N_{passes} = 2
Material	Stainless steel

The heat transfer coefficient was chosen very low, so that the system behaves like almost insulated. All dimensions and pressure losses were chosen based on the [3] [15].

6.2.1. Governing model equations

Conservation of mass

The model considers one constant control volume (fluid). The mass balance considers the mass flow (kg/s) at inlet and outlet [10]:

$$\frac{d\rho}{dt}V = \dot{m}_{in} + \dot{m}_{out} \tag{7.2.1}$$

Conservation of momentum

The balance is composed of the pressure loss model, which considers [10]:

- Difference between the heights of the port
- Friction inside the control volume

Conservation of energy

The energy balance considers incoming and outgoing enthalpy flow rate (kJ/kg) and heat transport to the system (W). [10]

$$\frac{dh}{dt} = \frac{1}{m}\left(\dot{m}_{in}h_{in} + \dot{m}_{out}h_{out} + V\frac{dp}{dt} + \dot{Q}\right) \tag{7.2.2}$$

Chemistry

No chemical reaction is considered since there is only one fluid in one phase present.

6.3. Pipe system

The pipe system is composed of the pipe L4 simple model (fig. 29) and thin wall L4 connected to the pipe. The model pipe L4 simple can be used, if flow velocities are below the speed of sound and if the sound waves are negligible. The energy storage in the surrounding wall is considered via thin wall L4 connection. This model refers to the level of detail L4, because it is modelled with the use of balance equations. This model is derived from the fluid control volume L2, the extension is in the pressure, enthalpy and temperature being spatially distributed along the pipe. As for physical effects considered, conservation of mass, energy, reverse flow, heat transport due to convection and pressure loss due to friction. Constant heat transfer with constant HT coefficient was chosen and pressure loss was considered linear. Geometry corresponds with the real VVER 1000 primary circuit pipe geometry. This pipe model has 3 connectors, inlet, outlet and heat (connection to the thin wall L4). This pipe model was used in the whole model, for all piping except for the spray system and the replenishment system, where L2 model was used, for the time saving purposes during the computation. Also for the reason, that it was proved (in the primary circuit model), that values are not changed on the longitudinal dimension in the pipe. [10]

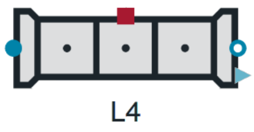

Figure 29 - ClaRa pipe L4 icon [10]

Thin wall L4 model (fig. 30) is a basic model of solid energy storage capacity with dynamic energy balance, taking heat conduction into account. This model could be used for energy storage of a flat thin wall neglecting heat conduction in longitudinal direction. The model is composed of one wall element only, no spatial discretisation is used. Physical effects considered are conductive heat transfer and energy storage. There are 2 connectors, 2 heat ports (for inner phase and outer phase). The outer phase is isolated. [10]

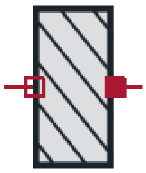

Figure 30 - ClaRa wall L4 icon [10]

On the pipeline, there are valves and fittings placed. The valve model VLE_L1 (fig. 31) can be used for introducing pressure loss effects and neglecting changes in the kinetic energy, it implies small density changes. It is modelled with level of detail L1, since it is modelled under phenomenological considerations that cause the pressure drop. Physical effects considered are compressible flow, adiabatic processes, conservation of mass, energy and nonlinear pressure drop due to friction. The pressure loss was chosen with linear nominal point. There are 2 connectors, inlet and outlet of the flow. The valve model can be used as check valve or control valve by changing the command "opening input is active". [10]

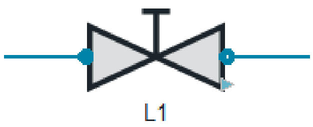

Figure 31 - ClaRa valve L1 icon [10]

The join model VLE_L2 (fig. 32) is and adiabatic junction model describing an ideally stirred fluid volume with dynamic energy and mass balance including pressure losses at each port. It is used, when mixing of two fluids (mass flows) with a constant volume of outlet mass flow are needed. Physical effects considered are conservation of mass, conservation of energy, reverse flow and pressure losses. The level of insight provides several options for pressure loss model for inlets and outlet. It was decided to choose no friction in all connectors, since the pressure loss is respected in the connected pipeline. It has three physical connectors, as mentioned before, two inlets and one outlet that respect mass flow rate, pressure and specific enthalpy. [10]

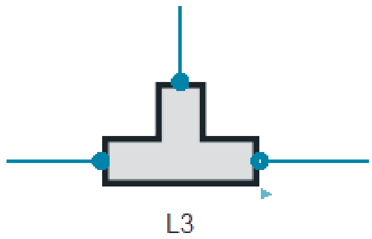

Figure 32 - ClaRa join L2 icone [10]

To be able to transport the fluid through the system, the pump is needed. In this case it is called the main circulation pump and the model (fig. 33) used for this pump was chosen with the level of detail L1. This model is suitable for applications, where time behaviour of the flow rate and outlet states depending on the power input and pressure differences is to be determined. This model calculates with the conservation of mass and energy (in steady state) and considers a mechanical and hydraulic efficiency. The fluid, that is pumped is assumed to be incompressible, but this simplification is not significant for this simulation and results obtained. If needed, more sophisticated model (pump L1 affinity) can used. This pipe model has 3 connectors, inlet, outlet and power input of the pump. Usually a real expression relates to the power in watts. [10]

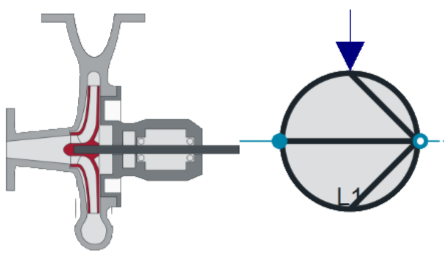

Figure 33 - ClaRa pump simple icon

Pipe level of insight and geometry:

Cold and "hot leg"

Heat transfer	Constant HT, $\alpha = 20\ W/m^2K$
Pressure loss	Nominal pressure loss value
	dp "cold leg" = 0,065 MPa
	dp "hot leg" = 0,0405 MPa
Dimensions	d_{inner} = 0,85 m
	d_{outer} = 0,995 m
	$z_{in} = z_{in}$ reactor
	$z_{out} = z_{out}$ reactor
	L_{hot} = 10 m L_{cold} = 26 m
	N_{tubes}[3] = 1
	$N_{cv} = N_{ax}$[4] = 4

Connection between pressurizer and "hot leg"

Heat transfer	Constant HT, $\alpha = 20\ W/m^2K$
Pressure loss	Nominal pressure loss value
	dp = 0,01 MPa
Dimensions	d_{inner} = 0,426 m
	d_{outer} = 0,466 m
	z_{in} = 22,6 m
	z_{out} = 25,7 m
	L = 10 m
	N_{tubes} = 1
	$N_{cv} = N_{ax}$ = 4

Spray pipeline

Heat transfer	Constant HT, $\alpha = 20\ W/m^2K$
Pressure loss	Nominal pressure loss value
	dp = 0,06 MPa each branch

[3] N_tubes is a number of parallel tubes.
[4] N_cv is a number of elements, from which the pipe is composed. N_ax is a number of a elements of the wall composition.

Dimensions	$d_{innerYP11,12}$ = 0,181 m $d_{outerYP11,12}$ = 0,219 m
	$d_{innerYP13}$ = 0,105 m $d_{outerYP13}$ = 0,133 m
	z_{in} = 23,9 m
	z_{out} = 30,3 m
	$L_{YP11,12,13}$ = 38 m (total)

The pressure loss coefficient of spray system was determined based on the simple calculation of Bernoulli's equation. The pressure at spray outlet should be slightly higher, than the nominal pressure in the pressurizer:

$$\rho_{in} = \rho_{out} = f(p_{in}; T_{in}) = f(16{,}1\ MPa; 298\ °C)^5 = 749{,}12\ \frac{kg}{m^3} \quad (7.3.1)$$

$$g = 9{,}81 \frac{m}{s^2}$$

$$z_{in} = 23{,}9\ m;\ z_{out} = 30{,}3\ m$$

$$d_{inner_{spray_{common}}} = 0{,}223\ m$$

$$v_{in} = 0 \frac{m}{s}$$

$$\dot{m} = 10 \frac{kg}{s}$$

$$p_{out} = 15{,}8\ MPa$$

$$v_{in} = \frac{Q}{S\ .\ \rho_{in}} = \frac{10}{\pi .\frac{0{,}223^2}{4}\ .749{,}12} = 0{,}349\ \frac{m}{s} \quad (7.3.2)$$

$$\frac{1}{2}\rho_{in}v_{in}^2 + p_{in} + \rho_{in} g z_{in} = \frac{1}{2}\rho_{out}v_{out}^2 + p_{out} + \rho_{out} g z_{out} + Z_p \quad (7.3.3)$$

$$Z_p = \frac{1}{2}\rho_{in}(v_{in}^2 - v_{out}^2) + (p_{in} - p_{out}) + \rho_{in} g (z_{in} - z_{out}) = 0{,}3\ MPa \quad (7.3.4)$$

Where index *in* represents the values at the spray inlet (on the MCP outlet) and index *out* represents the values at the spray system nozzle. The parameter $d_{inner_{spray_{common}}}$ represents the inner diameter of the common pipe of all spray branches. The final value 0,3 MPa thus express the pressure loss of all spray branches and since there are 3 branches plus common inlet and outlet, it yields **0,06 MPa** per **each branch**.

TK replenishment system

Heat transfer	Constant HT, α = 20 W/m^{2}K
Pressure loss	Nominal pressure loss value
	dp = 0,02 MPa

[5] The resulting values of „cold leg" temperature and pressure behind the MCP in the model (see chapter 8). The pressure loss is calculated with respect to these values.

Dimensions	d_{inner}= 0,110 m
	d_{outer} = 0,136 m
	z_{in} = 18 m
	z_{out} = 23,9 m
	L= 7 m
	N_tubes = 1
	N_cv = N_ax = 4

Valve level of insight and geometry:

Pressure loss	Nominal pressure loss value
	dp = 0,01 MPa
	ρ_{nom}= with respect to the incoming fluid
Dimensions	$\dot{m}$ = with respect to pipe connection
	dimensions fit the diameter of the connected pipe

Join level of insight and geometry:

Pressure loss	No pressure loss (pressure loss is respected in pipeline)
Dimensions	The volume is calculated as a sum of 0,5 m of each of the connected pipe multiplied by the flow cross section

Pump level of insight and geometry:

P_drive	5 MW
Mechanical efficiency	98 %
Dimensions	dimensions fit the diameter of the connected pipe

The heat transfer coefficient was chosen very low, so that the system behaves like almost insulated, which was verified on the wall temperature as shown in chapter 8. in the fig. 43. All dimensions, pressure losses and data not commented above were chosen based on the [3] [15].

6.3.1. Governing equations

Pipe

Governing equations are derived from the VLE_L2. See chapter 6.2.1 .

Wall

The temperature and substance properties are spatially averaged over the whole component as shown in the fig. 34. [10]

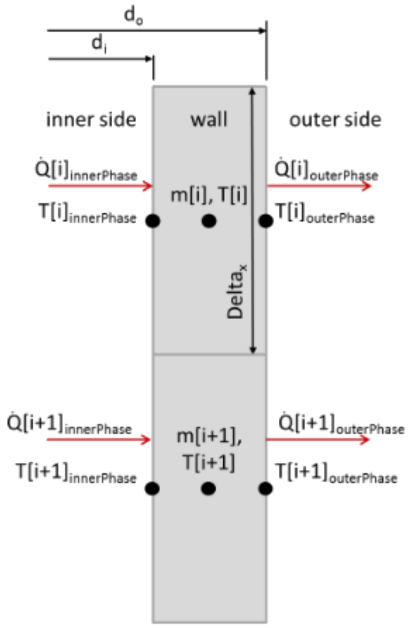

Figure 34 - Wall L4 general model structure [10]

Energy conservation

The inner energy (J) of the storage material is calculated with specific heat capacity (J/kgK), diameters (m), density of storage material (kg/m^3) and temperature of storage material (K) as follows [10]:

$$U = T\,.\,\rho\,.\frac{\pi}{4}\left(d_{out}^4 - d_{in}^4\right).\,delta_x\,.\,c_p \quad (7.3.1.1)$$

With energy balance of the wall, the change of the inner energy with the in- and outflowing heat (W) is calculated [10]:

$$\frac{dU}{dt} = \dot{Q}_{inner\ phase} + \dot{Q}_{outer\ phase} \quad (7.3.1.2)$$

Depending on the chosen state location, the surface temperatures (K) of the wall material are calculated. It was chosen, that the state is located at the inner phase, so the calculation deals with the heat conductivity of the storage material (W/mK) and its correction factors (-) [10]:

$$T_{inner\ phase} = T \qquad (7.3.1.3)$$

$$T_{outer\ phase} = \frac{\dot{Q}_{outer\ phase} \ . \ log\left(\frac{d_{out}}{d_{in}}\right)}{2\,\pi \ . \ delta_x \ . \ \lambda \ . \ CF_\lambda \ . \ N_{tubes}} + T \qquad (7.3.1.4)$$

Valve

The governing equations consider mainly isenthalpic throttling process without energy losses. Depending on the opening percentage of the inlet port, the throttling is performed. This regulation process is considered only for the YP13S0, that is controlled continuously, all other valves are controlled discretely.

Energy balance

The energy balance respects the isenthalpic process. Due to incompressible fluid entering and leaving the valve and equal inlet and outlet cross section, constant flow velocities are guaranteed and so the following equation of enthalpy balance (kJ/kg) is taken [10]:

$$h_{in} = h_{out} \qquad (7.3.1.5)$$

Mass balance

For steady state neglecting mass storage (kg/s) [10]:

$$\dot{m}_{in} + \dot{m}_{out} = 0 \qquad (7.3.1.6)$$

Chemistry

No chemical reactions are taking place.

Join

The model describes an ideally stirred volume with two inlets and one outlet.

Conservation of mass

The mass balance (kg/s) is respecting both inlets and outlet [10]:

$$\frac{d\rho}{dt}V = \dot{m}_{in,1} + \dot{m}_{in,2} + \dot{m}_{out} \tag{7.3.1.7}$$

Conservation of energy

The energy balance computes with incoming and outgoing enthalpy flow rates (kJ/kg) and incoming and outgoing mass rates (kg/s). The heat transported to the system in the flow is an integrated part of the pipe model, that must be connected. [10]

$$\frac{dh}{dt} = \frac{1}{m}\left(\dot{m}_{in,1}h_{in,1} + \dot{m}_{in,2}\, h_{in,2} + \dot{m}_{out}h_{out} + V\frac{dp}{dt}\right) \tag{7.3.1.8}$$

Chemistry

No chemical reaction is considered.

Pump

The model considers the balance of mass, energy and momentum. Mechanical and hydraulic efficiency are integrated as well.

Conservation of mass

The constant fluid mass flow (kg/s) is assumed, so [10]:

$$0 = \dot{m}_{in} + \dot{m}_{out} \tag{7.3.1.9}$$

Conservation of energy

The constant energy balance of the pump computes with the incoming enthalpy (kJ/kg) and hydraulic power (W) of the shaft, composed of the mechanical and hydraulic efficiency (-) [10]:

$$h_{out} = h_{in} + \frac{P_{hyd}}{\eta_{hyd}} = h_{in} + \frac{(P_{drive}\,.\eta_{mech}\cdot\eta_{hyd})}{\eta_{hyd}} = h_{in} + P_{drive}\,.\eta_{mech} \tag{7.3.1.10}$$

Conservation of momentum

The conservation of momentum is used for pressure changes (Δ Pa) in the model [10]:

$$\Delta p = p_{out} - p_{in} \tag{7.3.1.11}$$

Hydraulics

The volume flow (m3/s) in the model is calculated with the numerical factor for stability (p_{eps}). The density is assumed constant in the model. [10]

$$\dot{V} = \frac{P_{hyd}}{\Delta p + \Delta p_{eps}} \qquad (7.3.1.12)$$

Chemistry

No chemical reaction is considered.

6.4. Integration of the pressuriser

The pressurizer model itself is a developed model that can be connected to the primary circuit without any difficulties. To the simplified primary circuit model created in this work, it was connected via the connection subjects described in chapter 6.3. Verification of functionality of the model was performed during normal operation conditions[6]. On the connection to the "hot leg", there is a valve 2 (shown in fig. 35) with properties that represent the pressure loss between the components, which is crucial for the successful integration. This valve is still opened and the pressure loss is very small, but the model would not be able to initialize without this component. This composition problem was probably caused by the Clara and Dymola integration, because if the valve was replaced by the pipe, as it is in the real system, the calculation failed during the initialization. Considering the fact, that the pipe also represents the pressure loss, it should not have been a problem. However even after consulting this issue, the specific cause was not revealed. The valve 1 (shown in fig. 35) in front of the pressurizer (on the spray system) is also still opened and serves the same purpose as the valve on the "hot leg" connection.

The dimensions of the pressurizer can be changed in the "geometry" section. It is important to make sure, that inlet and outlet highs are set correctly with respect to the connecting pipeline and the body dimensions itself. Together with the dimensions, the initial coolant level can be changed in the "initial values", but EHs must always be liquid covered. It is important to connect the spray system at inlet and "hot leg" connection at outlet because of pressure losses and the gravity as well.

[6] The pressure in the primary circuit is 15,7±0,2 MPa and the temperature in the "cold leg" rsp "hot leg" is aprox. 289°C rsp. 321°C. No transient is expected and all conditions are steady.

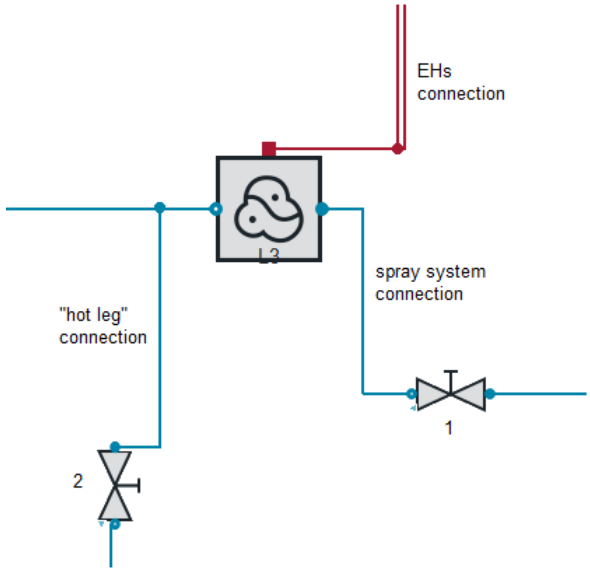

Figure 35 - Pressurizer connection detail

The mass flow through the spray system can be tuned with respect to the system properties by changing the flow rate in all branches. The power of electric heaters can also be tuned by setting different power in the heat flow connectors.

If this model is to be used during the start-up (with Nitrogen cushion), the properties and the regulation regimes should be changed. The regulation system is simplified only to the properties of the "P" regime and so if the "T" regime is to be used, the regulation regime must be more complex.

To be able to integrate this pressurizer model to another potential primary circuit model, following conditions should be abide:

- both models should be done in Dymola (with ClaRa library)
- valves on the "hot leg" connection and on the spray system outlet must be opened
- pressurizer inlet must be connected to the spray system, outlet must be connected to the "hot leg" connection
- to use this model in simulation of other PWR type, parameters should be changed with respect to the whole system
- to use this model during the start-up (with Nitrogen cushion), parameters and the regulation regime should be changed

7. Control models

In this chapter, the final control models and its function are described, where in the next chapter, these models are implemented into the primary circuit and verification tests are made. The simple primary circuit is shown in the fig.36. The regulation is indicated by arrows and the main components of the primary circuit are described in the figure. This figure serves only for the indication of composition of the system. The whole system with regulation parts is shown in the Attachment 1.

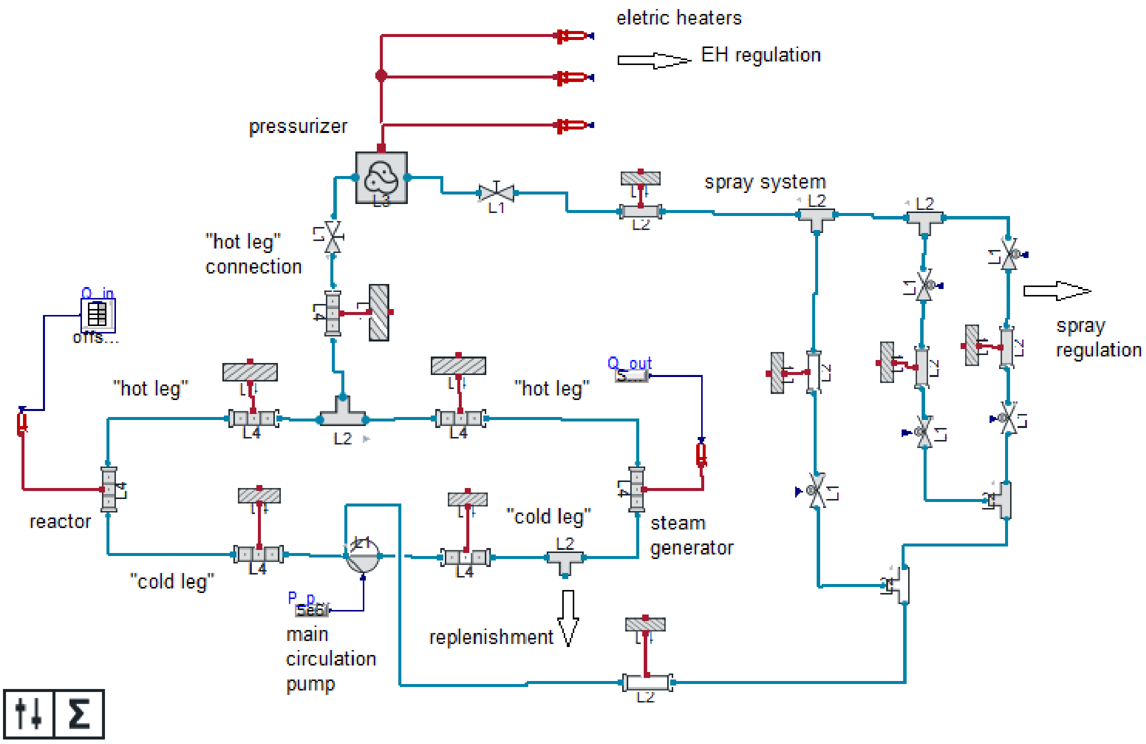

Figure 36 - Simple primary circuit

7.1. Pressure and temperature control model

The control model originates from the real control system on the NPP. This real model was modified with respect to the normal operational conditions and transient modelled. This specifically means, that the control is performed in the "P" regime, because the T_{max} in the "hot leg" is higher than 230°. And in the "P" regime with pressure in the primary circuit being higher than 14 MPa the pressure measurement is performed in the pressurizer [6]. Both "P" and "T" regimes have their own PID regulator, but due to the setting, the derivation constant is equal to zero, so it makes both regulator PI in fact. The output from both regulators is connected to the common regulation part via the switch. This common regulation part is ensuring sending commands to specific actuators.

Neither the valve nor the EH can be controlled via several signals, i.e. the input does not accept several different signals, but this is nevertheless not a problem. The signals controlling the valve or the EH are connected to the "RS flip flop" that decides between several values based on the prescription in the comparing blocks ("less threshold", "greater threshold") in front of it. The upper value is set if the conditions of the upper input are fulfilled and reset to the lower value is they are violated (fulfilled the conditions of the lower input). The resulting signal from this "RS flip flop" leads to the blocks, that converts Boolean input to real input. In case of valves it is opening/closing them, in case of EHs, it is turning them on or off.

Assuming the conditions being in the range of the "P" regime, the continuous regulation of EH I. and II. group as well as the valve YP13S02 is performed via PI regulator PPPC102 with gain k = 1 and integrational constant T_i = 2000 s [6]. These values determine how fast and accurate the regulation is. The output from this regulator enters the functional generator PPPY102 (behaviour described in chapter 4.3) in case of the EHs and functional generator PPPY103 (behaviour described in chapter 4.3) in case of the valve.

In the fig. 37, the spray part of the pressure control system is shown. As mentioned before, it is composed of the continuous regulation (red coloured) and discrete regulation (dark blue, pink, green). The spray system consists of 3 branches, where on the very left one, there is an YP13S02 continuously controlled by the PI regulator PPPC102 and the functional generator PPPY103. The PI regulator has two inputs, the setpoint, on its left, and the measurement, leading from the sensor on the bottom of the figure. In the middle branch and the right branch, valves YP12S01,S02 and YP11S01,S02 are placed respectively. These are controlled by the "greater threshold" and "less threshold" blocks (dark blue connection), that are connected to the measurement and to the "RS flip flop" (pink connection). This block sends the signal to the converter from Boolean to real value and the output from the converter is connected (green connection) to each of the four valves. Valves YP11,12S01 are controlled only the superior signals and YP11,12S02 are controlled by superior signals and by the difference of the pressure between measurement and setpoint (described in chapter 4.3).

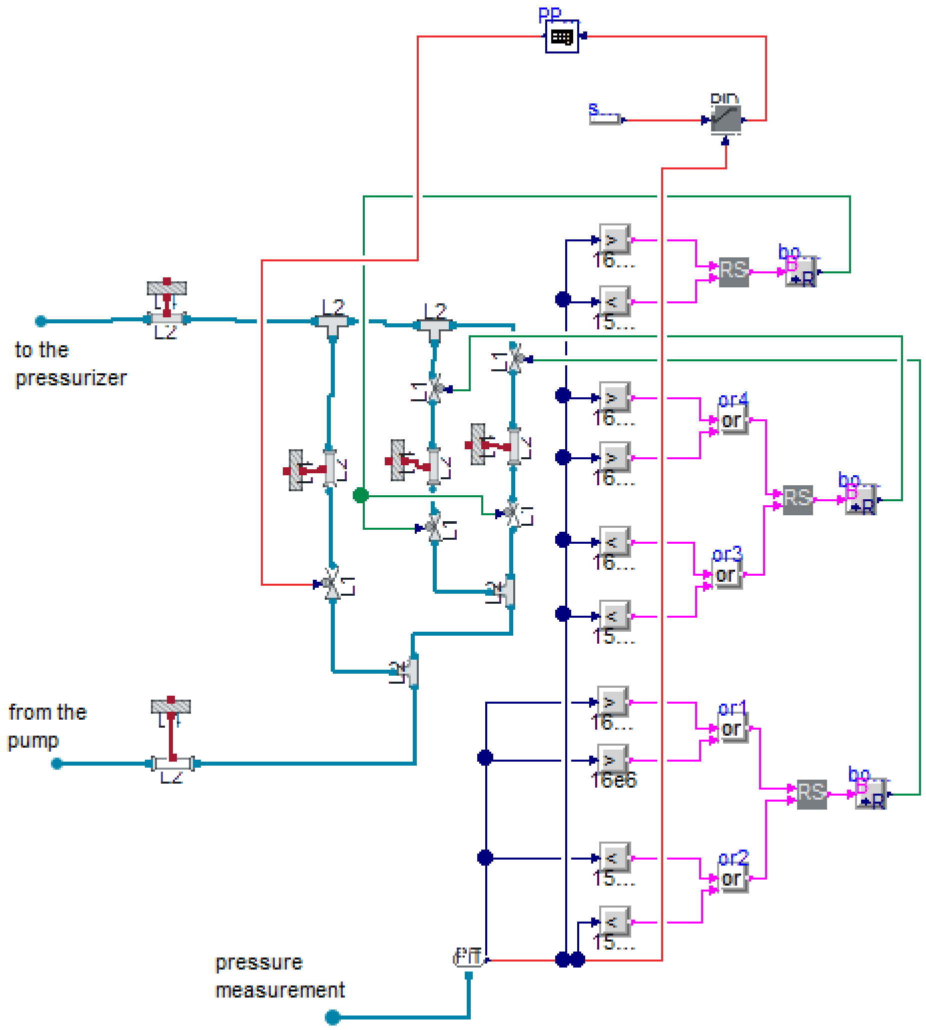

Figure 37 – Pressure control - spray system

In the fig. 38, the part with the EHs is shown. As well as the spray regulation, the EH regulation is composed of the continuous regulation (red coloured) and discrete regulation (dark blue, pink, green). The spray system is composed of 3 branches, the bottom electric heat flow connector (EHFC) is a merge[7] of YP10W01 and YP10W02, that are continuously controlled by the PI regulator PPPC102 and the functional generator PPPY102. The PI regulator has two inputs, the setpoint, on its left, and the measurement, leading from the sensor on the bottom of the picture. Remaining two EHFCs are controlled by the pressure difference. The control is performed by the “greater threshold” and “less threshold” blocks (dark blue connection), that are connected to the measurement and to the “RS flip flop” (pink connection). This block sends the signal to the converter from Boolean to real value and the output from the converter is connected (green

[7] The power input of each two EHs controlled by the same signal was merged into one power output.

connection) to remaining EHFCs. The middle EHFC is a merge of YP10W04, W06 and the upper one is a merge of YP10W03, W05.

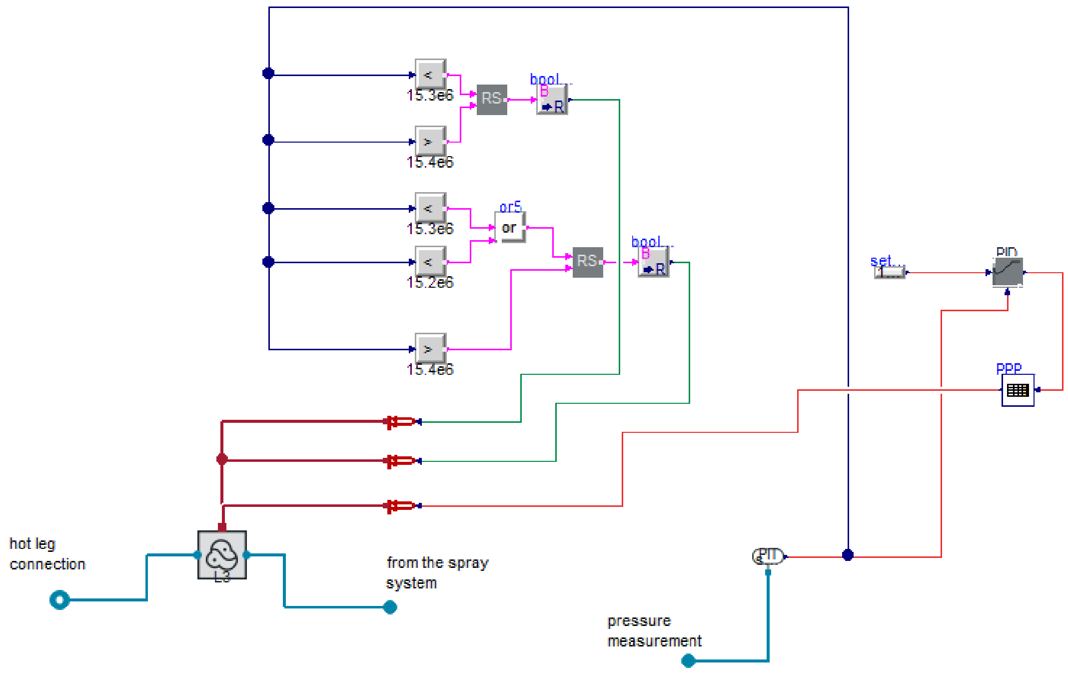

Figure 38 - Pressure control - electric heaters system

7.2. Coolant level control

Since the coolant level control is quite complicated and many elements enter the calculation and the regulation itself, only simplified system is designed for this work. These are composed of the measured level and setpoint (simplification without the correction = average from the cold and "hot leg") entering the sum block. The outlet from this block controls the TK31,32S01 closing valves and also enters directly the PPFC203 regulator with gain k = 0,01 – 10% of flow rate (m3/h) and integrational time constant T_i = 0,1 – 300 s [6] (PPLC202 is skipped because the level correction is not calculated). The outlet from this regulator controls through functional generators PPFY204,205 and PPFY206,207 (behaviour described in chapter 4.3) the TK31,32S02 regulation valve in the cascade regime (described in the in chapter 4.3.). Due to the simplification made in this system, the TK system pumps are replaced by the simple flow source.

The fig. 39 shows the coolant level control system. The setpoint and the measurement enter the sum block, that attributes the setpoint value and subtracts the measurement value. The output leads to the PI regulator PPFC203 and to the "greater threshold" and "less threshold" blocks (working as the superior values). The signal from these block proceeds as in the EH case and controls the TK31,32S01 valves. The output from the PI regulator enters the functional generators PPFY204, that is set as a main one and PPFY207, that is set in the cascade (described in the in chapter 4.3.).

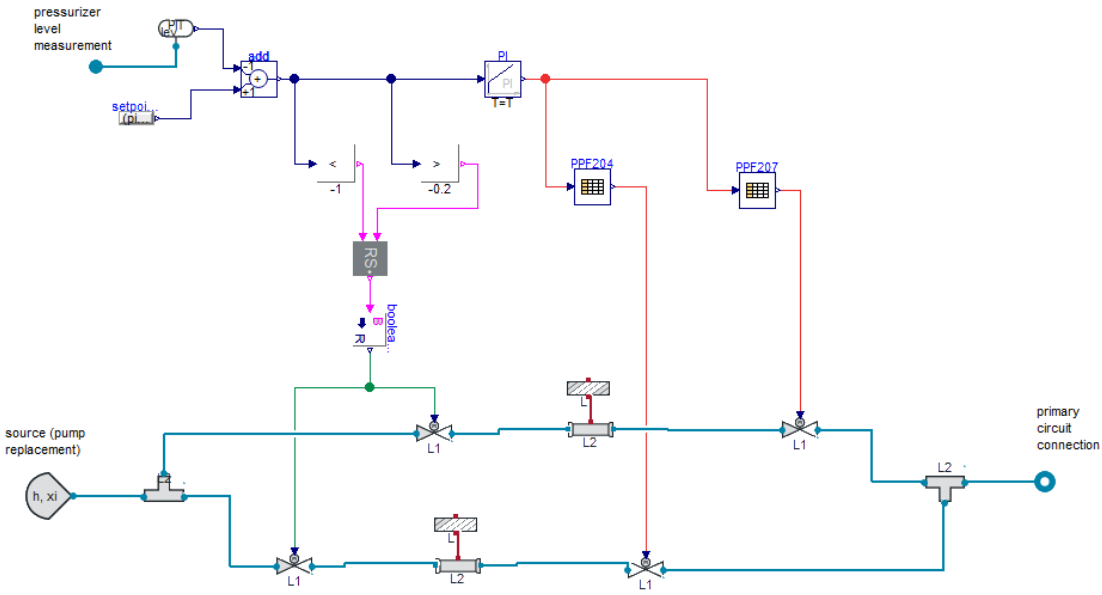

Figure 39 - Pressurizer level control

As mentioned before in the chapter 5., several different methods for the computation are available. All methods were tested on one of the final models and most of them either failed during the initialization or during the process. However, RADAU IIA, ESDIRK, SDIRK and DASSL were successful. The RADAU method was the slowest during the initialization. ESDIRK, SDIRK and DASSL had the best computing time and results. Since DASSL, designed to integrate stiff systems using a BDF-method, is usually used, this method was chosen for further calculations.

8. Model evaluation

This chapter deals with the whole model evaluation based on results obtained from simulation of several transient. These results are compared with the data obtained from [16].

8.1. Primary circuit evaluation

The functionality of the complex model (Attachment 1) was verified by a simple simulation, with the constant reactor power output. Properties of the model and components behaviour were observed and evaluated in following figures. During these simulations, the replenishment system is not in operation. In fig. 40, the reactor power output during the simulation is shown. The power change is almost negligible (max 1 MW during 200 s). This behaviour was taken from the spray system simulation (fig. 46), because the reactor power is simulating normal operation conditions, which is desired for these purposes. The fluid flowing in the system has properties taken from IAPWS95.

All simulations were performed with following initial values:

Pressure in the pressurizer	15,7 MPa
Coolant level in the pressurizer	8,175 m
Properties of the “cold leg”	
- between SG and MCP	h = {1280;1320} kJ/kg
	p = {15;15,1} MPa
- between MCP and Reactor	h = {1280;1320} kJ/kg
	p = {15,5;15,6} MPa
Properties of the “hot leg”	
- between Reactor and join	h = {1450;1480} kJ/kg
	p = {15,55;15,6} MPa
- between join and SG	h = {1460;1490} kJ/kg
	p = {15,5;15,55} MPa

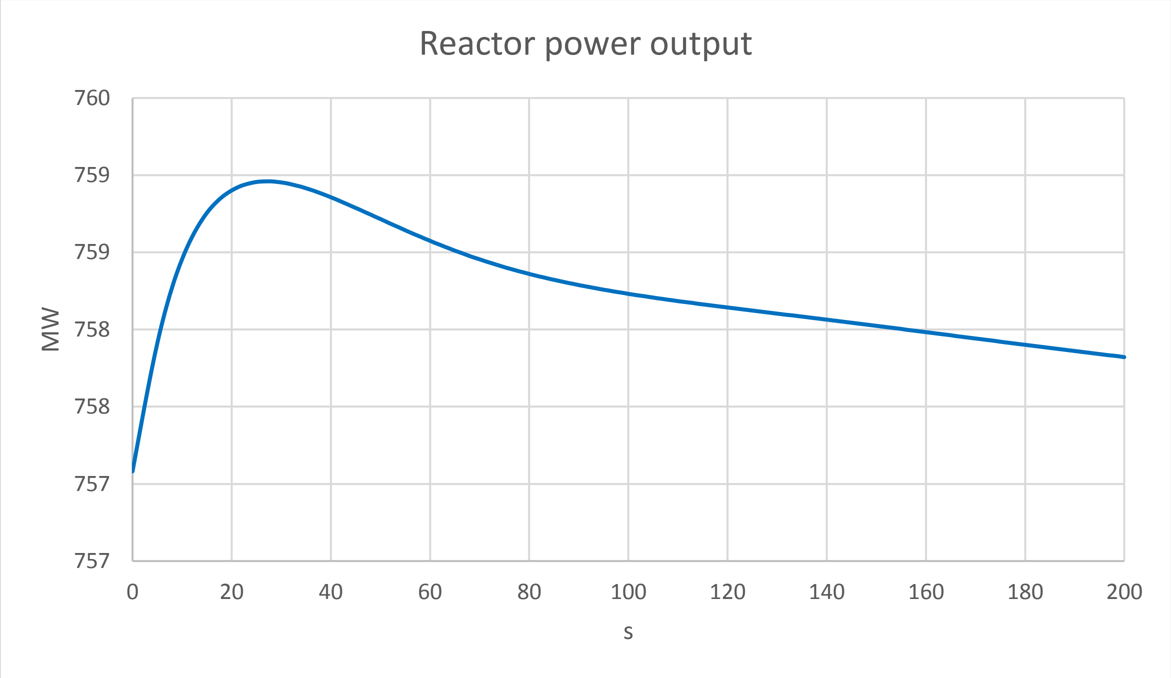

Figure 40 - Reactor power output

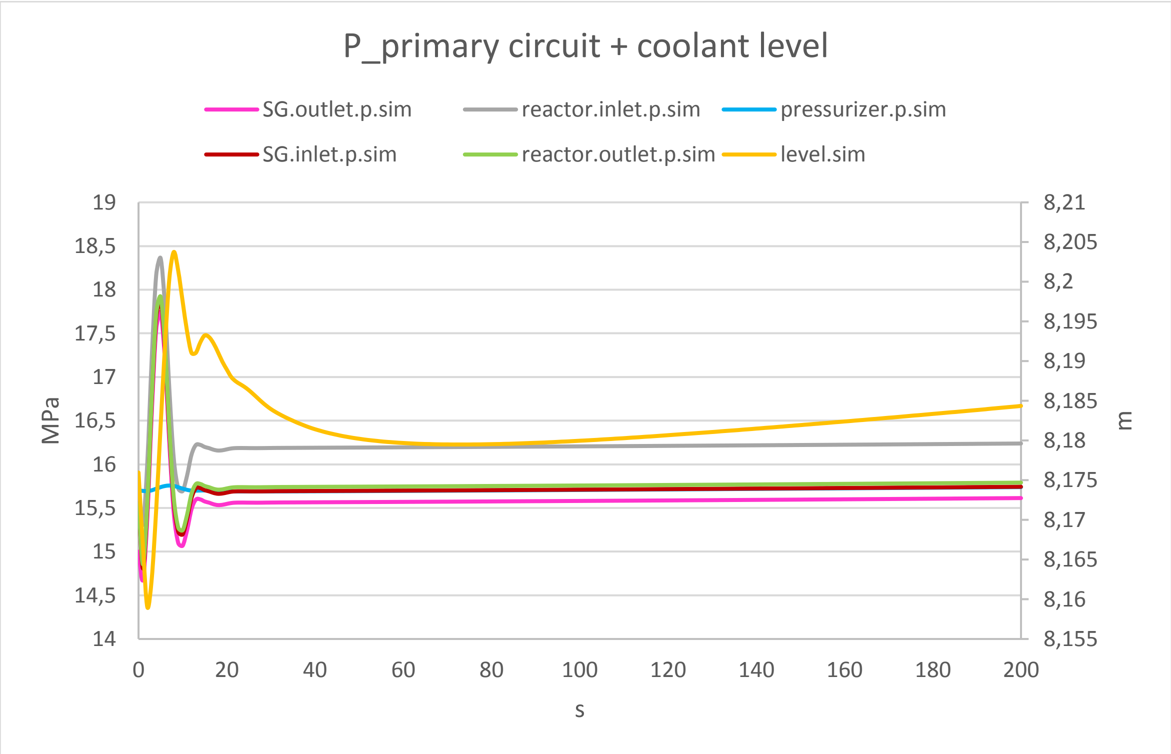

Figure 41 - Pressure in the primary circuit + coolant level

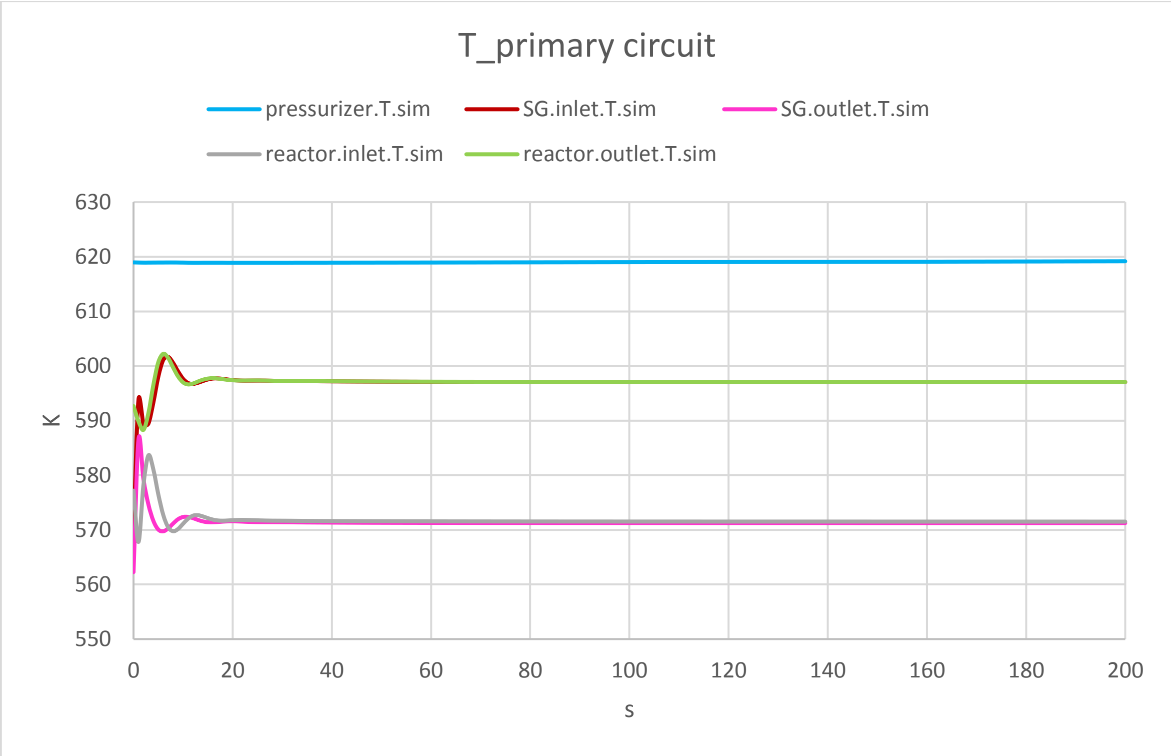

Figure 42 - Temperature in the reactor, steam generator and pressurizer

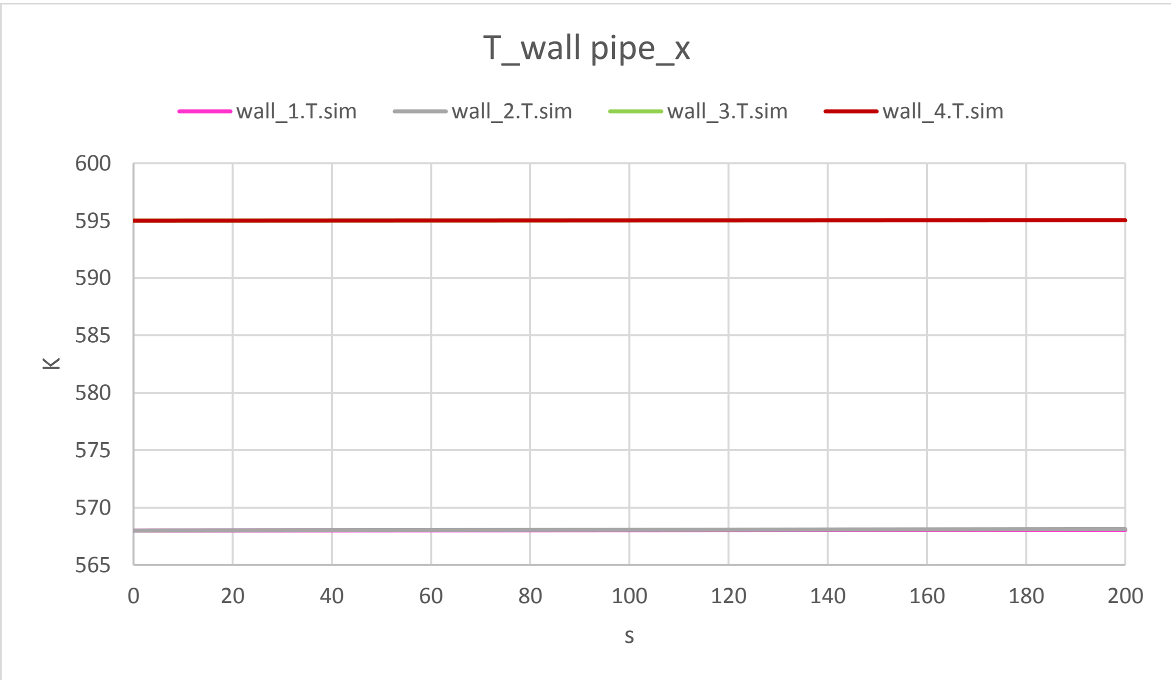

Figure 43 - Wall temperature in the primary circuit

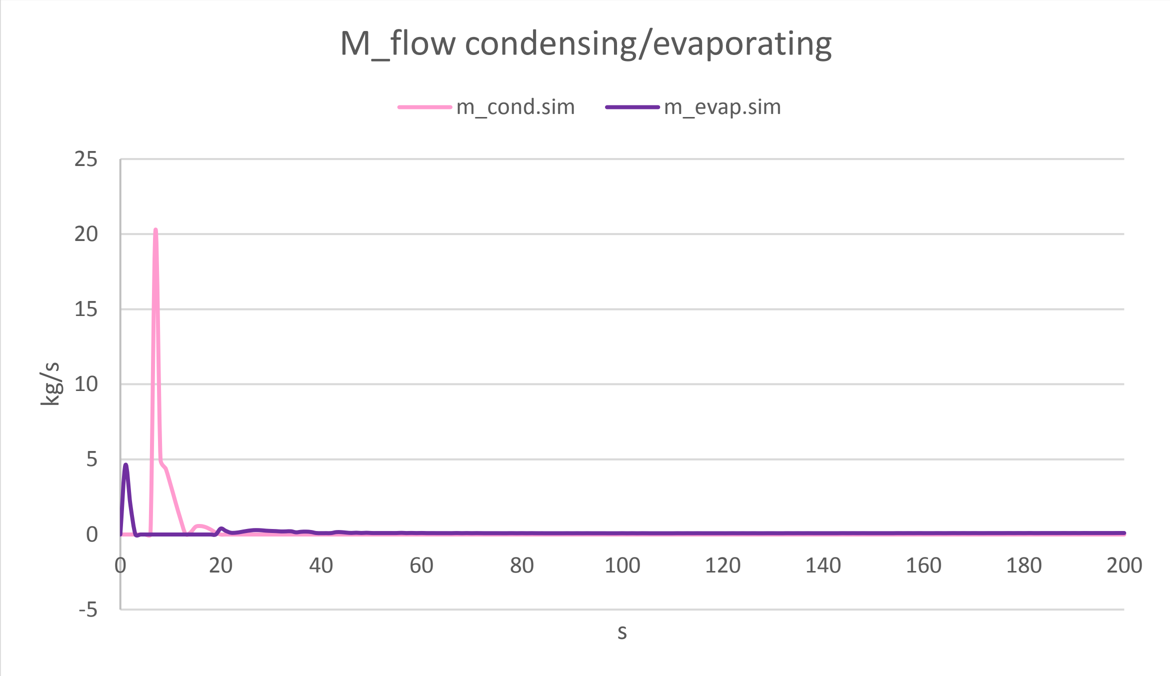

Figure 44 – Condensing/evaporating mass flow

From the results of the basic simulation, the behaviour of the system can be described. It is important to note, that during the first 20s, the system stabilizes and so the results should be evaluated in range from 20 s to 200 s. This stabilization process is caused by the initial values setting and the initialization itself.

In fig. 41, the pressure properties of the primary circuit and the coolant level are shown. The pressure at the reactor inlet is the highest value of all, because it is basically the pressure behind the MCP, which replaces all the pressure losses. The pressure loss of the reactor affects the pressure at reactor outlet, which is 15,7 ± 0,02 MPa throughout the whole simulation. Pressure at the inlet and outlet of the steam generator also corresponds with the pressure loss in the body itself and the pressure loss in the "hot leg". In total, the primary circuit behaviour in terms of pressure is very accurate.

The pressurizer remains at 15,7 MPa, which is the nominal pressure. Since there are no significant changes in the system, there are no changes in the pressurizer. The last curve is a coolant level in the pressurizer. As described before, the data should be evaluated, when the system is stabilized enough and so first 20 s are not taken into evaluation. This value is connected to the secondary axis, so the range of the coolant behaviour is between 8,18 and 8,188 m. This means, that the coolant level can be assumed stable throughout the whole simulation.

The fig. 42 describes the temperature at the inlet and outlet from the reactor and steam generator. The temperature of the pressurizer is also shown in the figure. The temperature of the "cold leg" is approx. 572 K, which is approx. 298 °C and so the temperature in the model is higher by 9 °C. This difference influences the model behaviour as shown in the forgoing evaluation. This difference is probably caused by some extra heat accumulated in the system or by the insufficient settings. The temperature of the “hot leg” is approx. 597 K, which is approx. 323 °C and so this temperature differs from the real value by only 2 °C. The average temperature is then 311 °C, which is 6 °C more that in the real system. The temperature in the pressurizer corresponds to the 346 °C, which is the real temperature in the pressurizer. Despite some temperature differences between the “cold leg” and the “hot leg”, the system’s behaviour is very close to the reality.

As mentioned before, the system behaves like almost insulated, and the temperature of all walls is almost constant. Initial temperature of each wall was chosen 2 °C below the fluid temperature flowing in the pipe and as shown in the fig. 43. This temperature remains still during the whole simulation. Index of walls corresponds to the index of pipes (i.e. 1 – between steam generator and MCP, 2 – between MCP and reactor, 3 – between reactor and pressurizer connection, 4 – between the pressurizer connection and steam generator).

The last figure 44 shows the condensing and evaporating mass flow, which is almost zero due to no load change and no other actuators being in operation. No vapor is condensing and no liquid is evaporating during normal operation in the model. Even though in the real system, the spray system is constantly heated by 1 m^3/h flow rate (chapter 4.2), this was neglected in this simulated model.

8.2. Pressurizer response test

In this chapter, the response of the pressurizer to the spray system (fig. 45) or EHs system (fig. 50) in operation is verified. The reactor power output is shown in the fig. 46 (the same behaviour as in the simple simulation case). The pressurizer model connected to the primary circuit was tested in terms of the behaviour when either all spray branches were in operation or all EHs were in operation. Having results from the [16], it was possible to compare the behaviour of the model to the real data. All initial values are preserved (as in the previous simulations), except for the reactor power, that is the engine for all transient performed. The fluid flowing in the system is liquid and vapor with properties taken from IAPWS95. Since only one loop is modelled, the amount of coolant flowing in the spray is ¼ of the real flow, so instead of 44 kg/s, it is 11 kg/s (in all branches are involved). This is based on the assumption, that the amount of original coolant would decrease the pressure too much, when considering the one loop only. This assumption was verified in the model, where both mass flow rates were tested and as expected, the results with lower flow rates were correct.

1. Spray system in operation

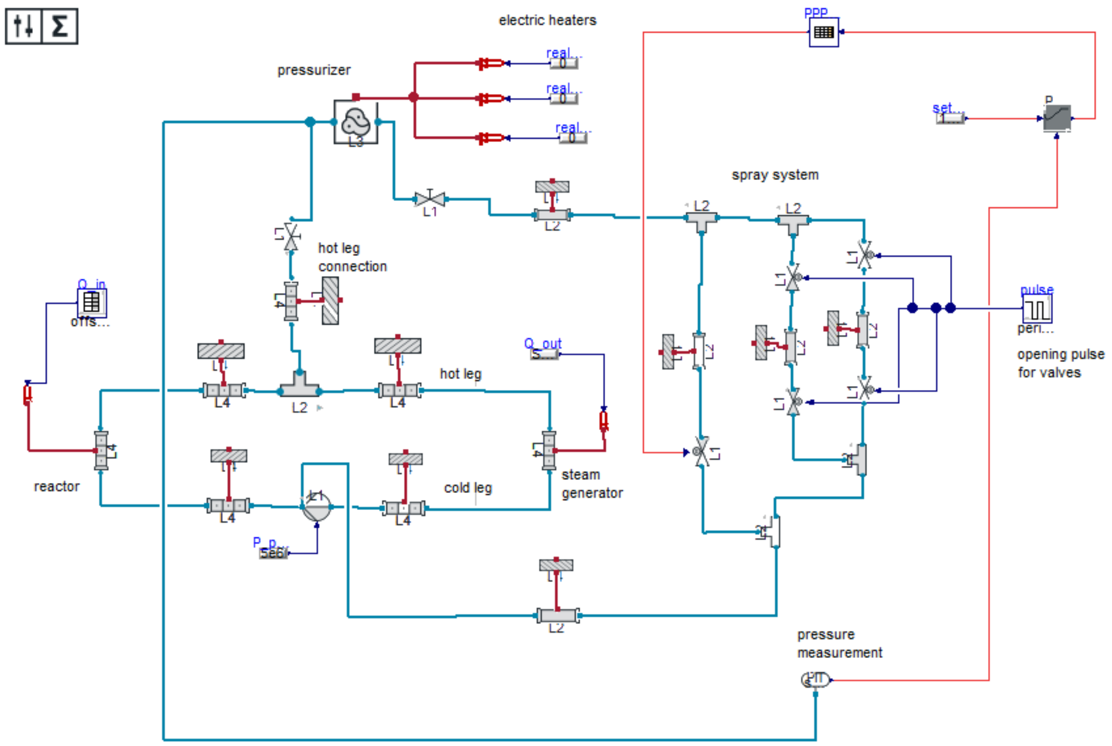

Figure 45 - Control circuit - spray system in operation

From the results of this basic simulation with spray system in operation, the response of the system can be described. It is important to note, that during the first 20s, the system stabilizes and so the results should be evaluated in range from 20 s to 200 s. This stabilization process is caused by the initial values setting and the initialization itself. The reactor power output is shown in the fig. 46 (the same behaviour as in the simple simulation case). The load change is negligible (max. 1 MW in 200 s), so it is assumed almost constant.

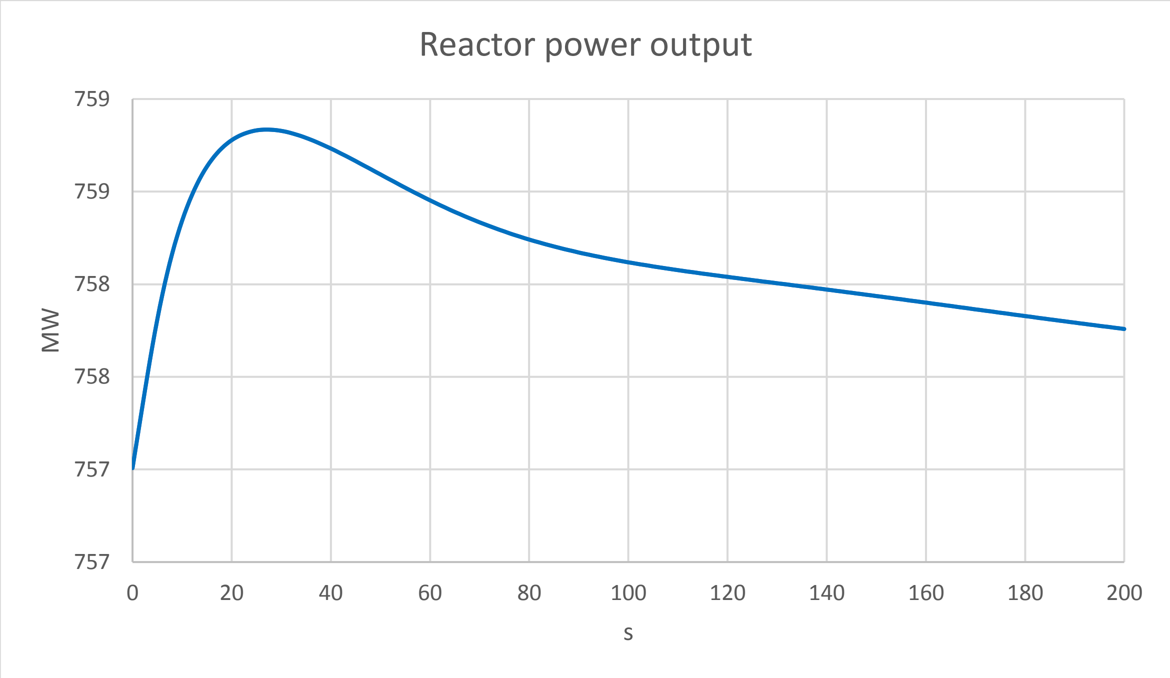

Figure 46 – Spray system in operation - reactor power output

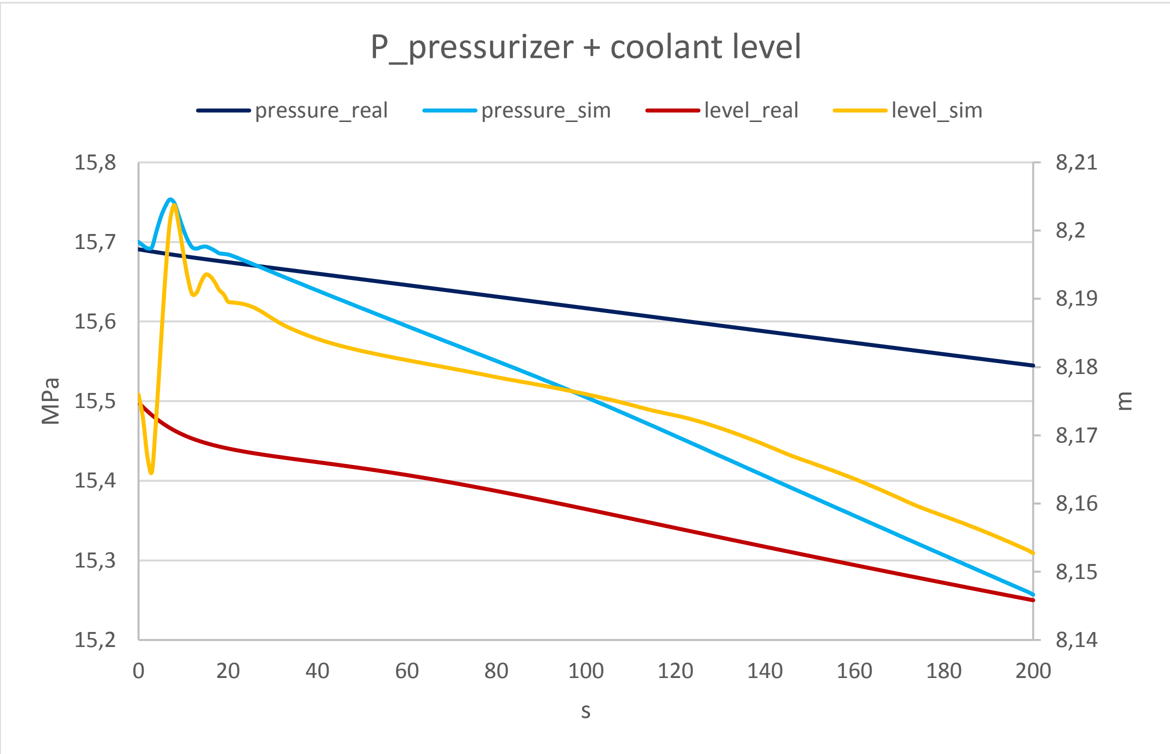

Figure 47 – Spray system in operation - pressure and level in the pressurizer

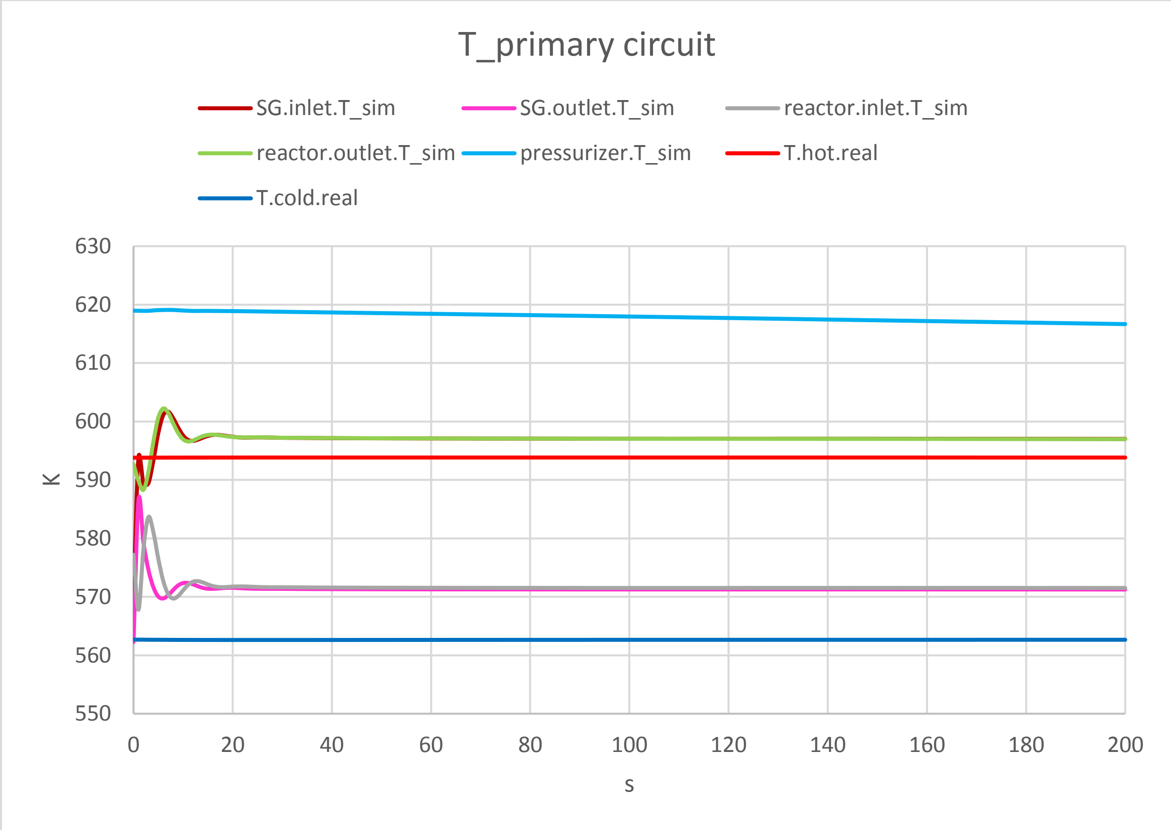

Figure 48 - Spray system in operation - Temperature in the primary circuit

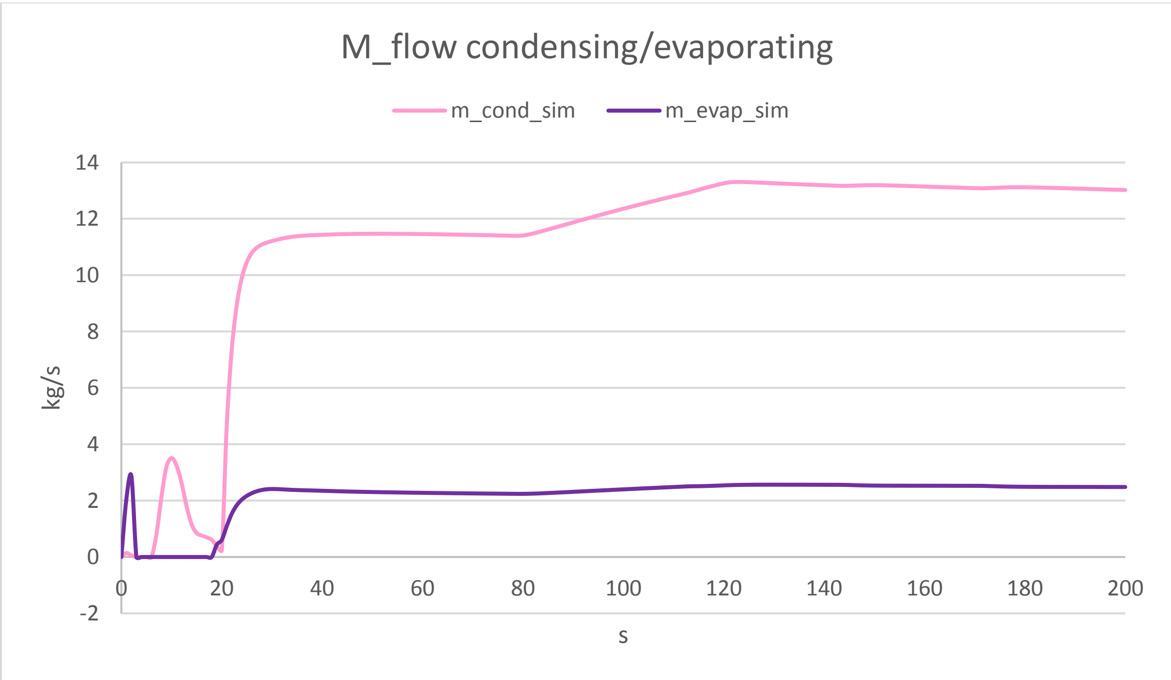

Figure 49 - Spray system in operation - Condensing/evaporating mass flow

This simulation was performed in order to determine the pressurizer response to injection of the coolant. As mentioned before, the spray system is connected behind the pump outlet, so the temperature in spray pipeline is the “cold leg” temperature. In the fig. 47 the real and simulated pressure in the pressurizer are compared together with the real and simulated coolant level. As it can be seen, the real pressure decreases with higher gradient and so reaches lower level (15,27 MPa), than in the real system (15,54 MPa). When comparing the results from the next simulation (EHs in operation), the pressure is increased for 0,3 MPa. When assuming, that the efficiency of the spray system and the EHs system should be even, the result from the simulation seems to more realistic even though the pressure drop is slightly more (difference is 0,4 MPa). The initial coolant level in the model is higher than in the real system and so the final value is higher, but the gradient in first 100 s is very similar. After reaching 100 s, the gradient of the simulation coolant level is increase and also more mass flow is condensing in the system, as shown in the fig. 48.

The difference between the real “cold leg” and “hot leg” temperature was discussed in the previous simulation and this difference remains the same. The behaviour of the simulated temperature (fig. 48) is stable and constant, with the temperature in the pressurizer decreasing, which is expected, because of the condensation process inside the body. The temperature decrease is however not very significant, only 2 – 3 °C, which is accurate.

In the fig. 49, it is shown, that the evaporation occurs together with the condensation. The behaviour of this phenomena is strongly influenced by the time constant of condensation and evaporation (τ_{cond}, τ_{evap}), discussed in the chapter 7.1. These processes are divided by the zone allocation. The final liquid mass is increased and the vapor mass is decrease.

2. Electric heaters in operation

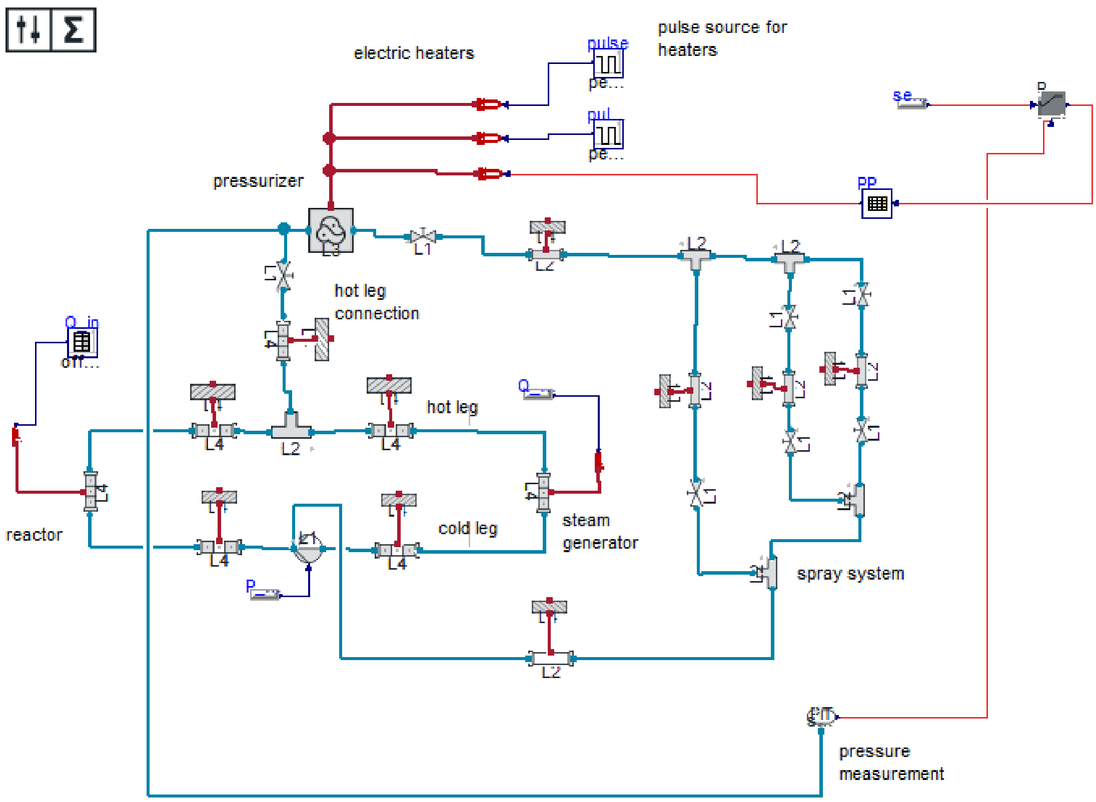

Figure 50 - Control circuit - electric heaters in operation

All EHs are turned on after 20 s of the operation (when the system is stabilized) and remain on for 200 s, all valves are closed. The data obtained from the [16] show the real power in the fig. 51. Note, that time 0 in the graph is time 20 s in the simulation. This simulation was performed in order to determine the pressurizer response to EHs. All initial values are preserved (as in the previous simulations), except for the reactor power, that is the engine for all transient performed. The fluid flowing in the system is liquid and vapor with properties taken from IAPWS95.

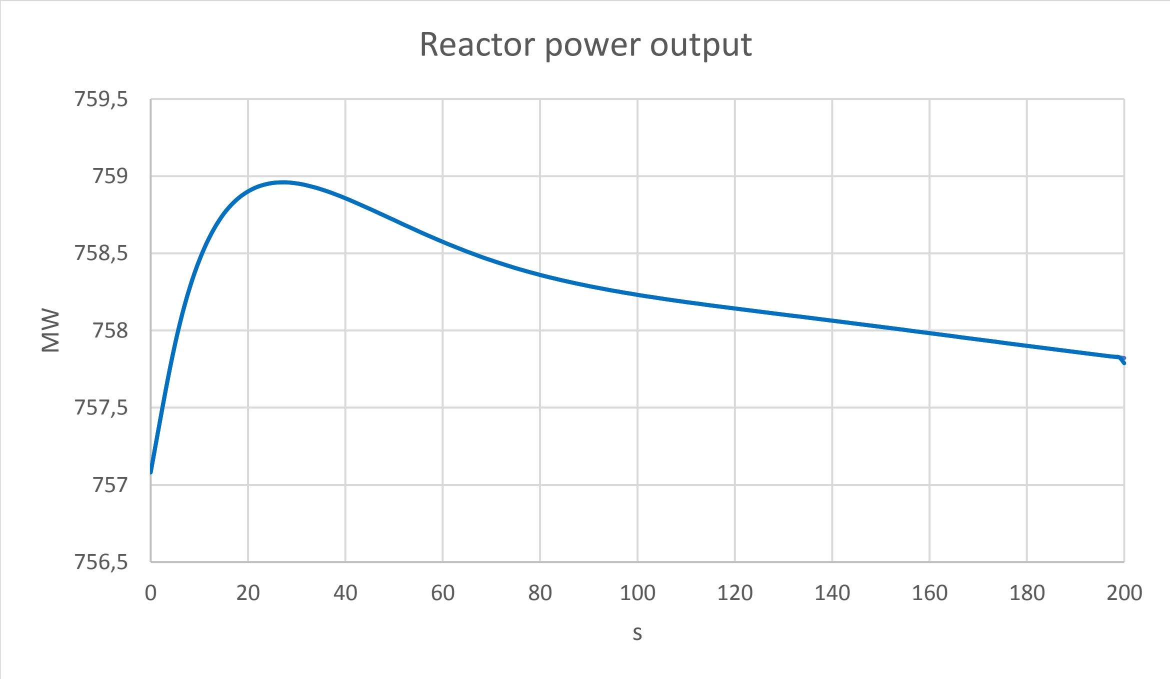

Figure 51 – Electric heaters in operation - reactor power output

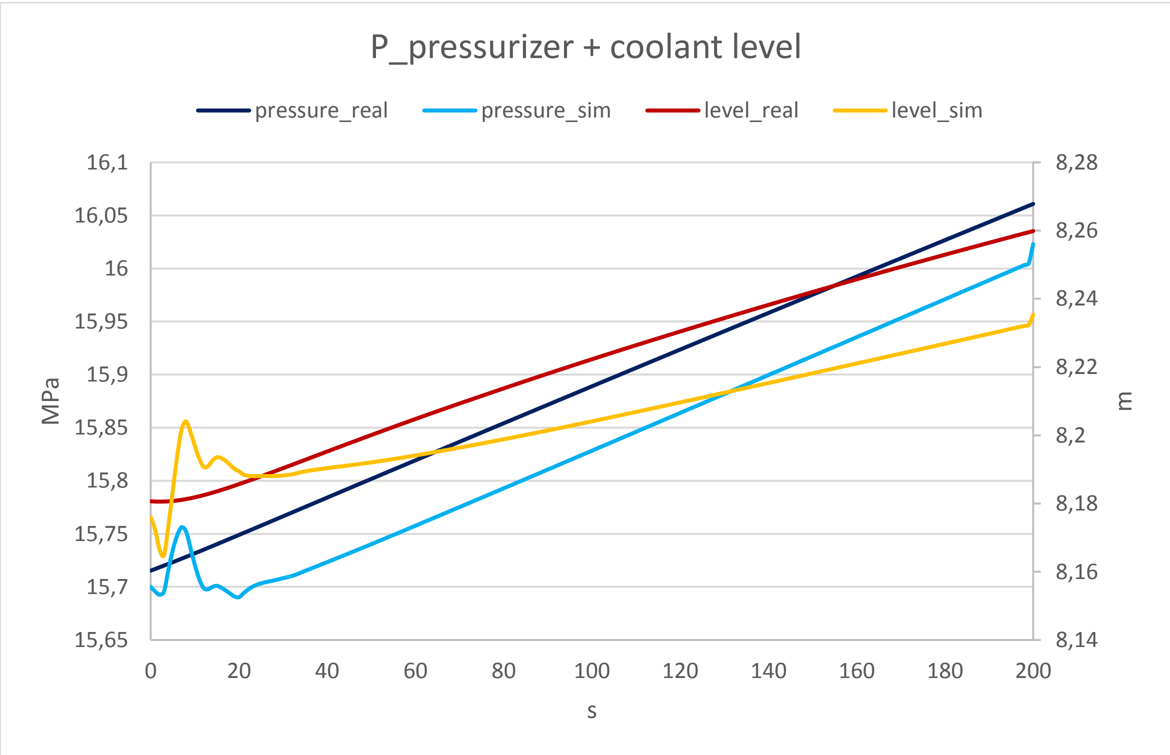

Figure 52 - Electric heaters in operation - pressure and level in the pressurizer

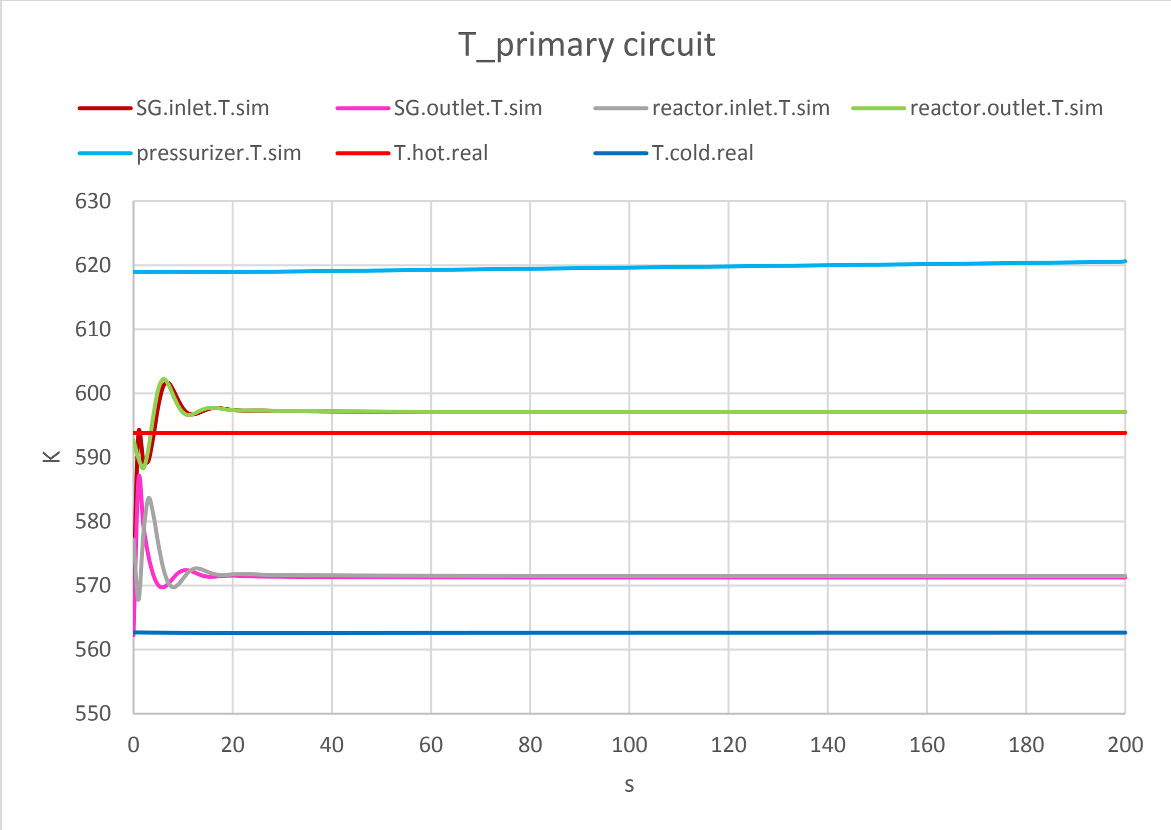

Figure 53 - Electric heaters in operation - Temperature in the primary circuit

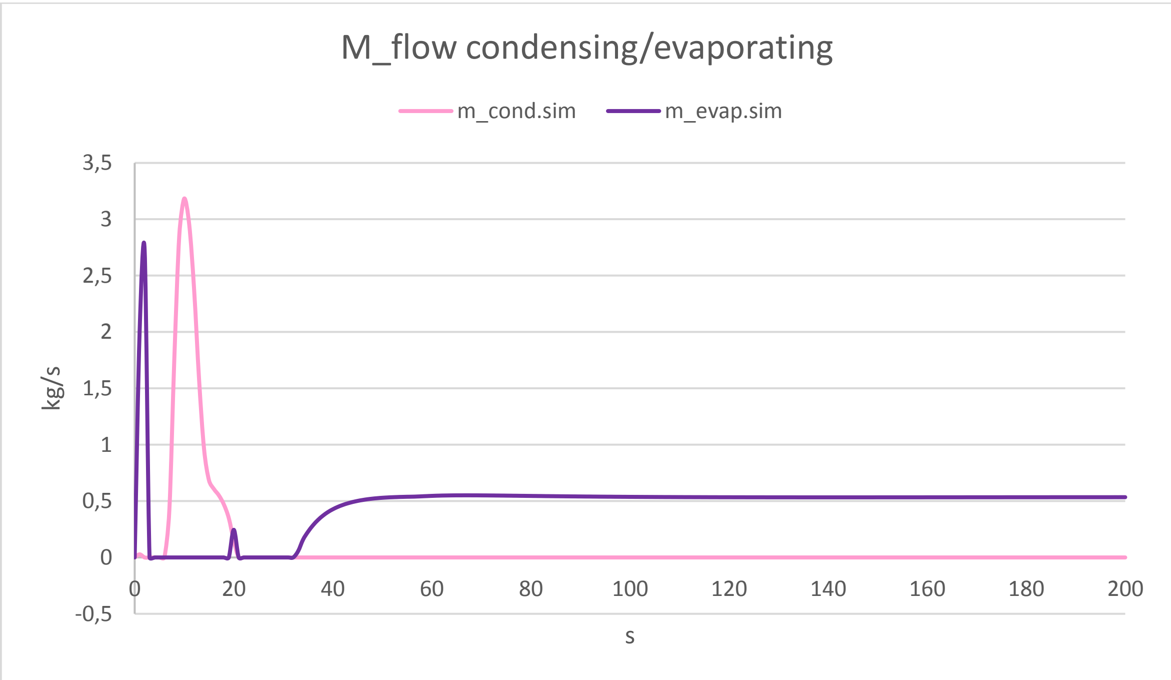

Figure 54 - Electric heaters in operation - Condensing/evaporating mass flow

In the fig. 52 the real and simulated pressure and coolant level are compared. As it can be seen, that the real pressure increases with almost the same gradient and so reaches to similar level (16,04 MPa), then in the real system (16,06 MPa). The coolant level increases with the smaller gradient and so reaches lower level (8,26 m in the real system and 8,235 in the simulation). The final coolant difference is very close to the difference observed in the previous simulation. So, considering both, this is a supporting claim, that the system's behaviour is very accurate. The fluctuations at the beginning of the simulation are caused by the system instability (system is finding the right solution) are then after 20 s, it is stabilized.

The difference between the real "cold leg" and "hot leg" temperature was discussed in the previous simulation and this difference remains the same. The behaviour of the simulated temperature (fig. 53) is stable and constant, with the temperature in the pressurizer increasing, which is expected, because of the evaporation process increasing the temperature inside the body.

The last figure 54, shows the condensing and evaporating mass flow. The vapor mass still increase, which is an expected behaviour. Since only EHs are in operation and no coolant is being injected (or outsurged), only evaporation occurs. The behaviour of this phenomena is strongly influenced by the time constant of evaporation (τ_{evap}), discussed in the chapter 6.1.

8.3. System response test to transient

The response of the pressurizer in the simulation is compared to the real data. The primary circuit temperature is compared to the not affected loop. All initial values are preserved (as in the previous simulations), except for the reactor power, that is the engine for all transients performed. During these simulation, the replenishment system is not in operation. The fluid flowing in the system has properties taken from IAPWS95.

1. **Failure of one main circulation pump**

The first transient simulated was the failure of one MCP in the whole system. When there is a failure of one MCP, the mass flow rate through the affected loop is rapidly decreased and so is the average temperature of the coolant in this loop. The other loops respond by the increasing the flow rate, but due to this, the average temperature of these loops is decreased. The reactor power is at the beginning rapidly decreased to 55% and then it stabilizes on 50% after 200 s as shown in the fig. 55.

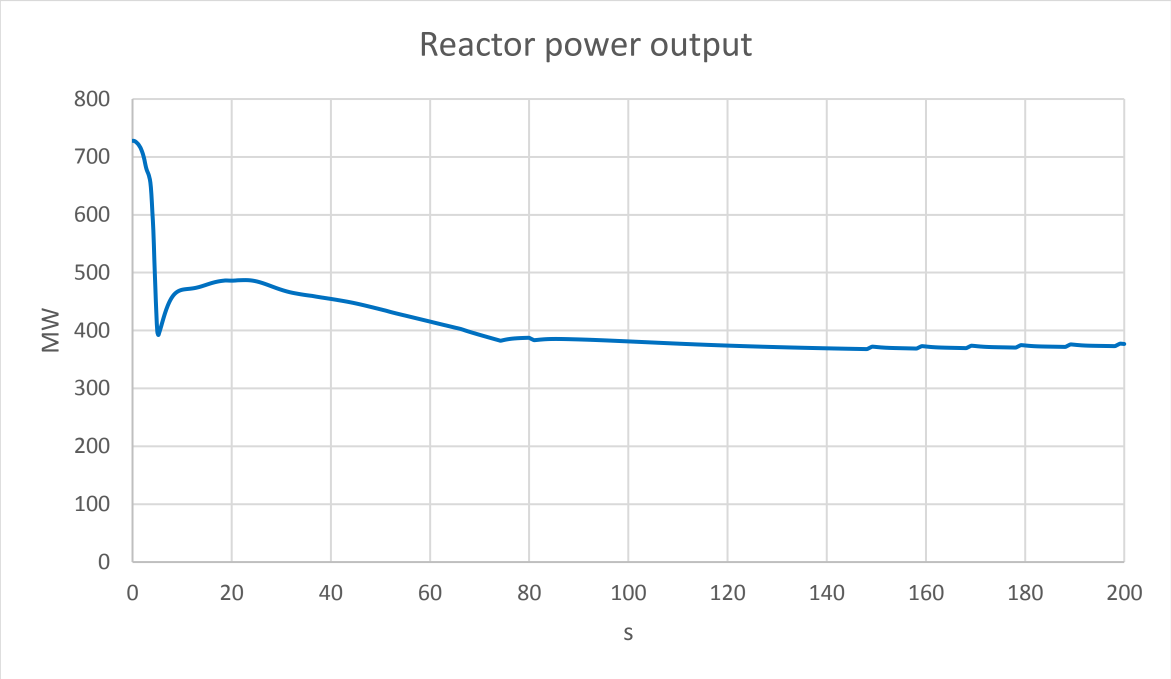

Figure 55 - Transient 1 - reactor power output

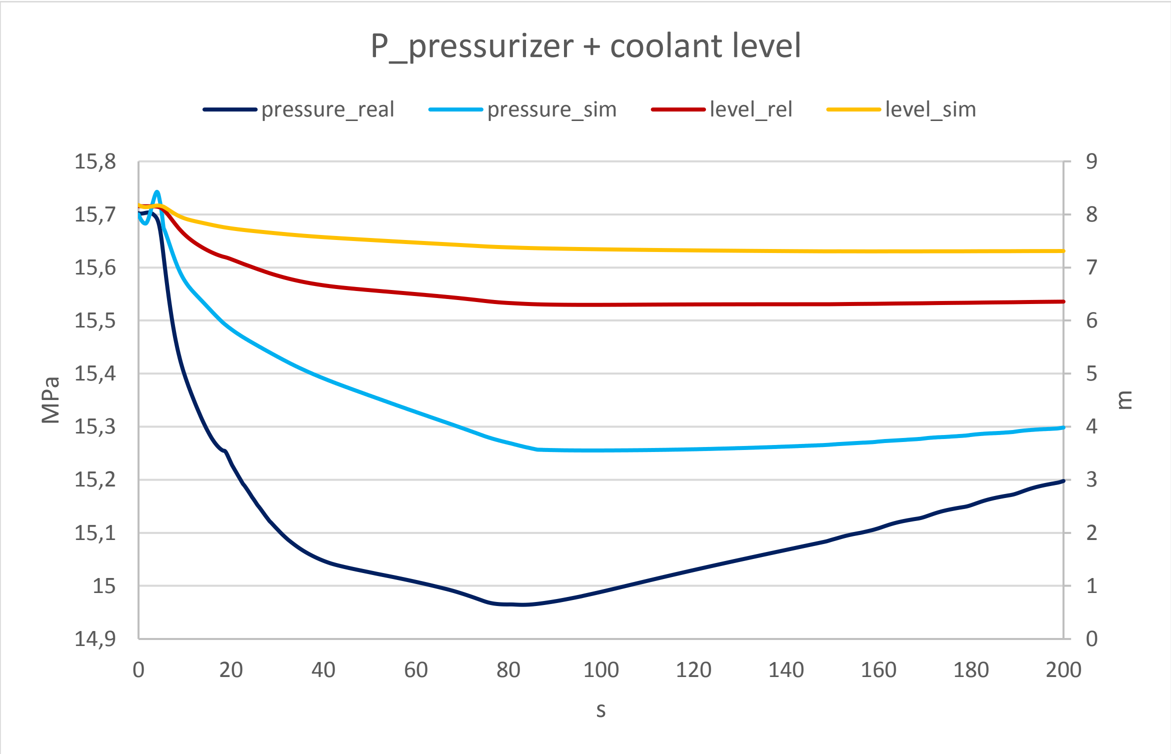

Figure 56 - Transient 1 - pressure and level in the pressurizer

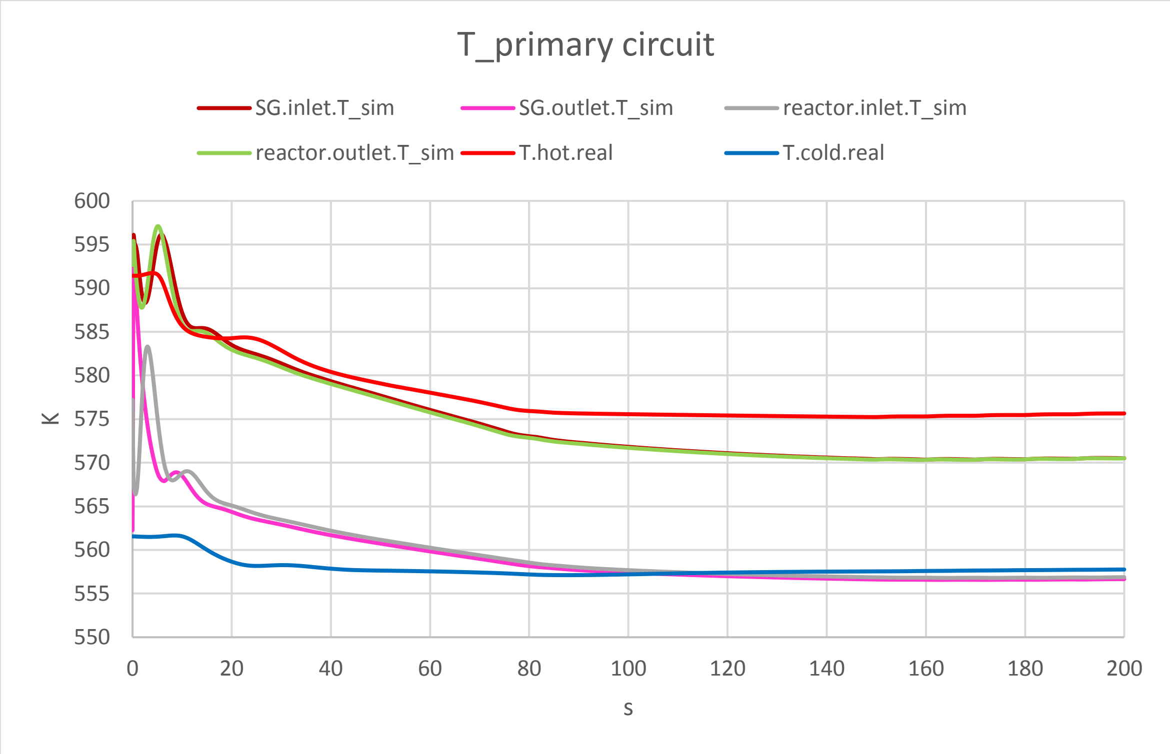

Figure 57 – Transient 1 - Temperature in the primary circuit

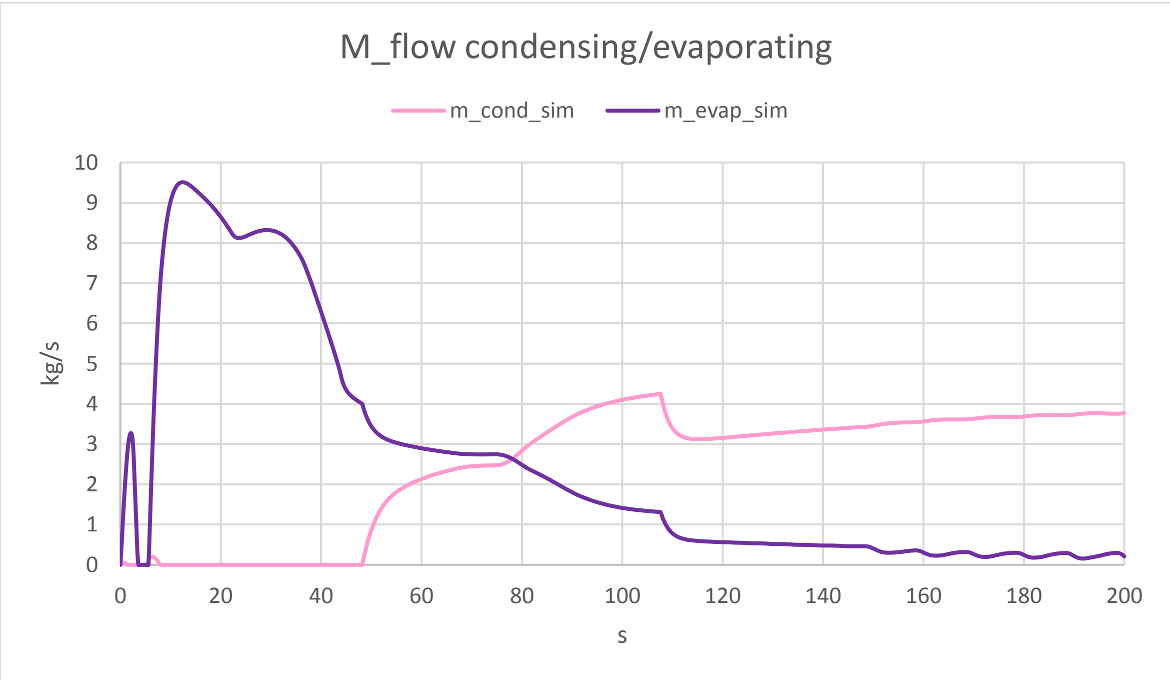

Figure 58 – Transient 1 – Condensing/evaporating mass flow

The pressure and coolant level results are shown in the fig. 56. The coolant level decreases by the similar gradient, but there is the difference between the final real and simulated value (approx. 1m). This difference is expected based on the previous simulation.

The pressure decreases as it does in the reality, but the gradient is not that big and so the minimal value (at 80 s) reaches only 15,25 MPa. However, the behaviour of the simulated temperature in the primary circuit is very close to the real behaviour. So, the reason for the difference is most likely caused by the fact, that temperature in the “hot leg” is decreased more (fig. 57) and so the pressure, that has to be compensated is not that big.

In the last figure (fig. 58), the condensing and evaporating mass flow is shown. Since the system is composed of two zones, different processes occur in each zone throughout the simulation and as mentioned before, the behaviour of this phenomena is strongly dependent on the $\tau_{cond}$and τ_{evap}. The pressurizer tries to deal with the load change. The final vapor mass is increased and the final liquid mass is decreased. Both values are steady at the end of the simulation.

2. Transfer to the self-consumption mode

The second transient simulated was the transfer of the unit to the self-consumption mode. During the loss of power, the unit is transferred into the self-consumption mode. The reason is, that the generator is phased out from the grid. When this happens, the reactor power output is decreased almost immediately to 55% and it is going through the stabilization process until it is stabilized around 40%, after 200 s, as shown in the fig. 59. The average temperature of all loops is decreased and the flow rate is increased.

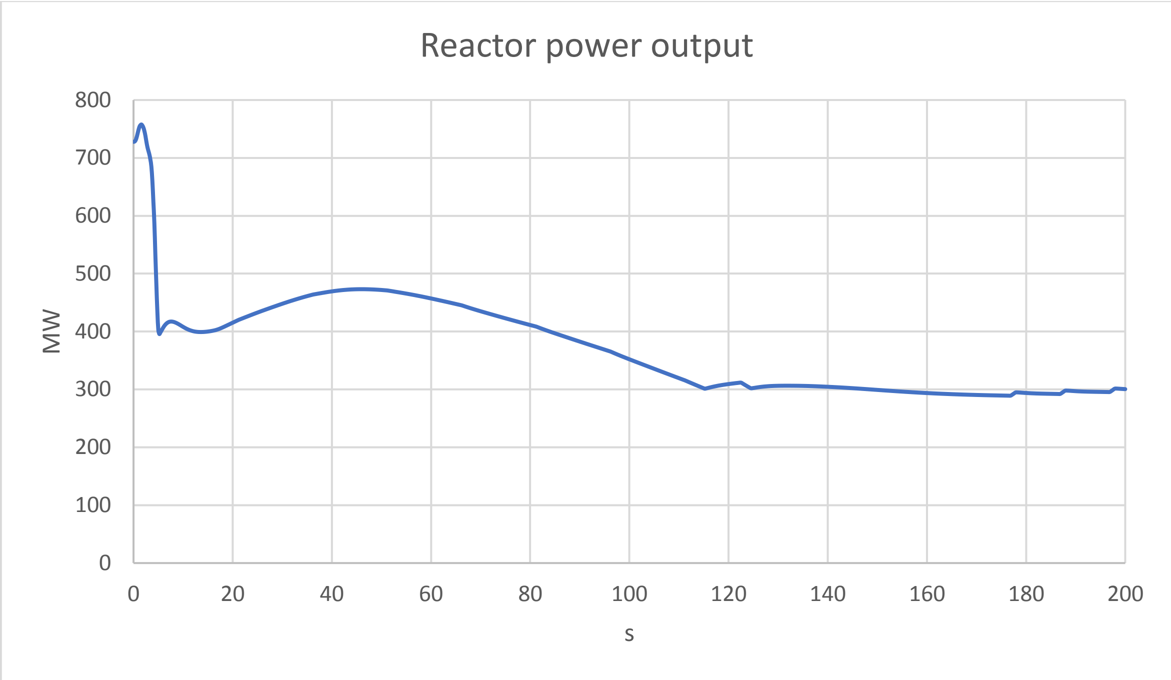

Figure 59 - Transient 2 - reactor power output

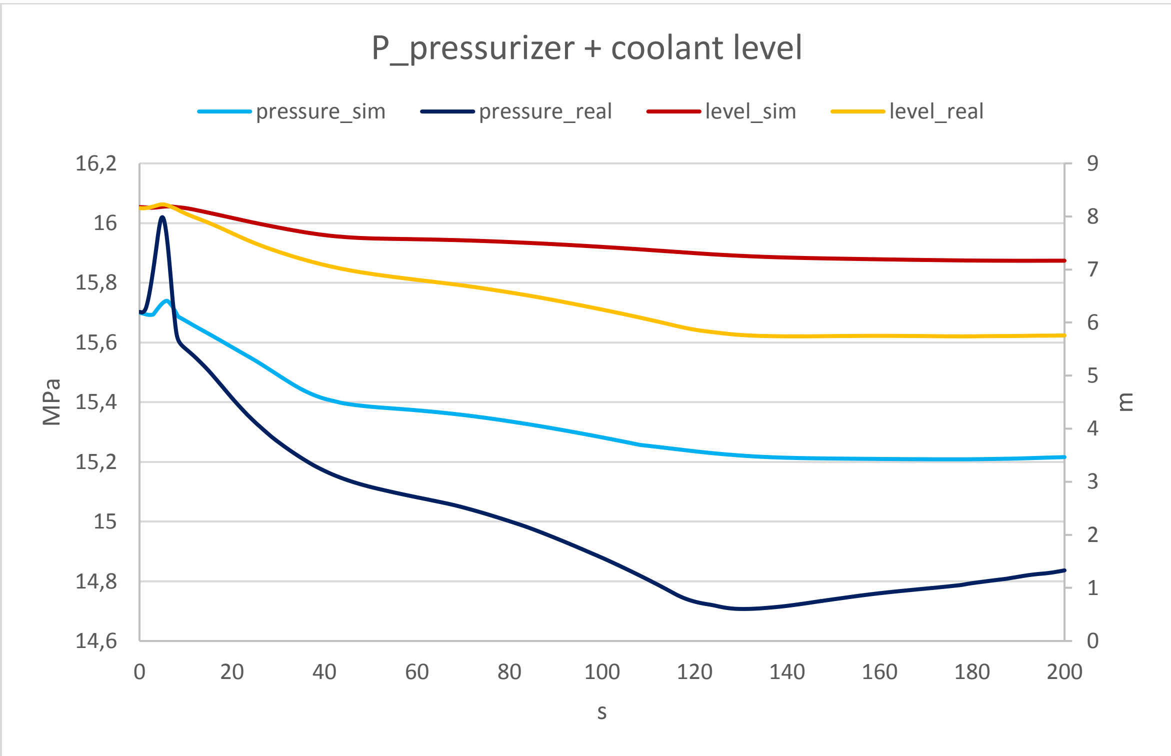

Figure 60 - Transient 2 - pressure and level in the pressurizer

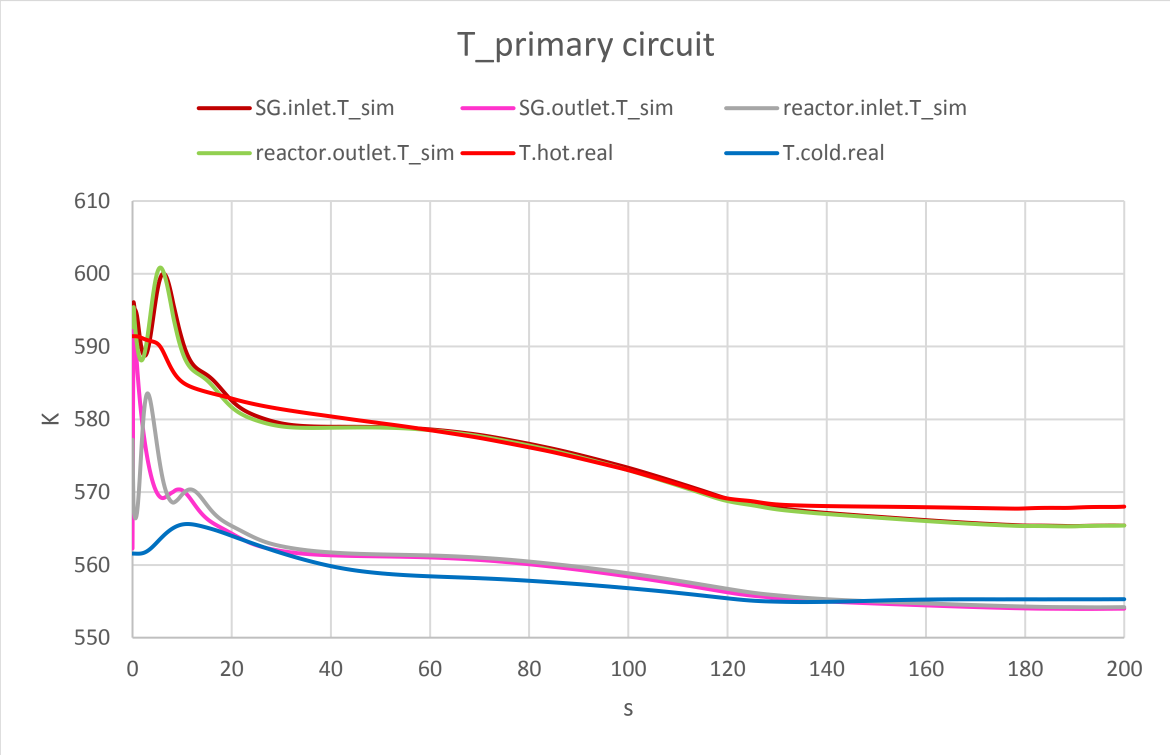

Figure 61 - Transient 2 – temperature in the primary circuit

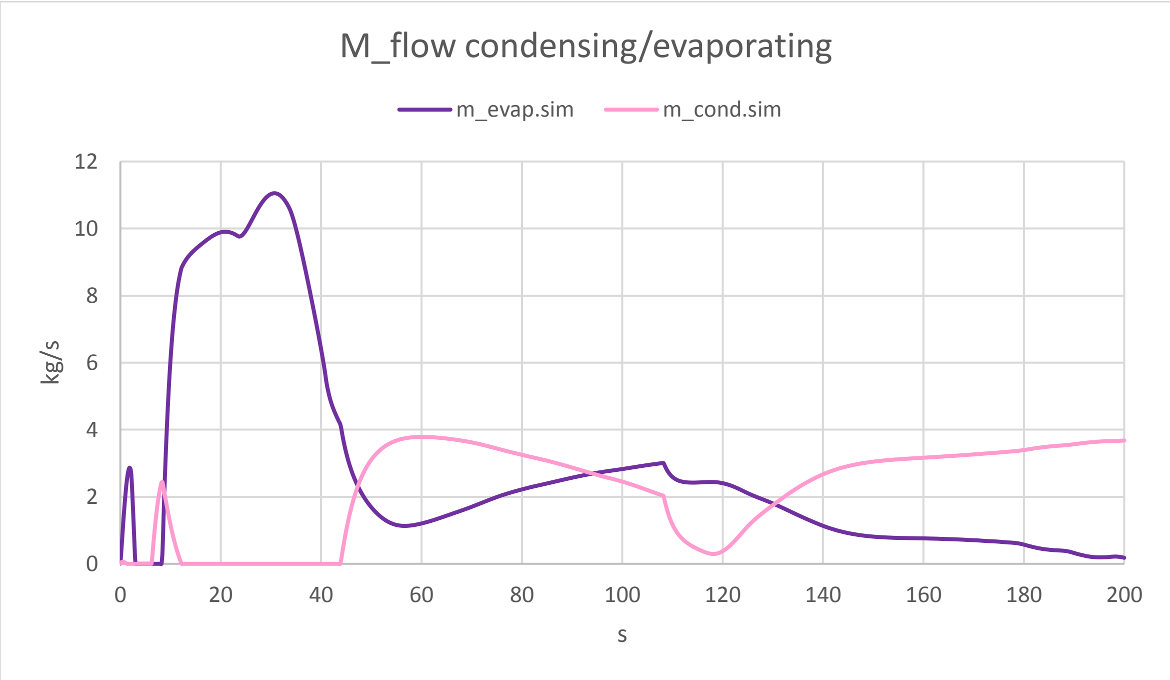

Figure 62 - Transient 2 - condensation/evaporation in the pressurizer

The results of the pressure and coolant level are shown in the fig. 60. The pressure decreases as it does in the reality, but the gradient is not that big and so the final value does not reach 14,7 MPa. The lowest pressure is 15,19 MPa and resulting pressure differences in this and in the previous transient is approx. 0,4 MPa. The coolant level decreases with the similar gradient and the final difference between the real and simulated coolant level is again approx. 1m. This is very close to the result in the previous transient, which is supporting claim, that the system is working accurately, with respect to its setting.

The fig. 61 shows real and simulated temperatures. that are almost identical, but at the end of the simulation, the difference between these values is evident. The reactor power is stabilized on the lower power then in the previous simulation and so the final temperature difference is not that significant.

In the last figure 62, the condensing and evaporating mass flow is shown. At the beginning of the simulation more coolant is evaporated and this amount decreases with the time. The amount of condensing coolant is lower at the beginning (the same as in the previous simulation), and is decreased, when the evaporation increased, but after this change, it is still or slightly increasing.

9. Conclusion

The aim of this thesis was, first, to describe the attitude to the pressure and coolant level control in the pressurizer of VVER 1000 ETE and to describe the Dymola and ClaRa library. This was accomplished at the beginning of this work. Quite complex description of the pressurizer, its behaviour during several operations and the regulation algorithms of the whole system were described.

Second task of this thesis was to describe the physical behaviour of the pressurizer in order to be able to use it in the Dymola software. Detailed description of the pressurizer physical behaviour and the attitudes to the numerical solution were provided. The final model with all assumptions is based on the ClaRa library and properties of this model were modified for purposes of this thesis. The process of the modification was explained together with the description of every modified value. Used equations were described together with components description of all properties in each model. Third task was to provide with the instructions on implementing the pressurizer to the primary circuit. The pressurizer model interface and integration to a simplified (as in this thesis) or a more sophisticated primary circuit were described and assumptions for successful integration was provided.

The fourth and the final task was to verify the pressurizer model implemented in the simplified primary circuit. The model properties and its parts were described and a simple verification by nominal operation parameters was performed. The results were commented in detail in the chapter 8.2. Then the test of the pressurizer response to the spray system and electric heaters being in operation was performed. The final verification was made by two transients and result from the simulation were compared with the provided data [16].

From the data comparison it was discovered, that the pressuriser model used in this work, even though being simplified, is quite accurate. The differences in the behaviour between the real and simulated system were most likely caused by the differences present in the simplified primary circuit. Since the pressurizer model was implemented and tested on this model, the final results were affected by these differences. The results from all simulations are very promising and by improving the assumptions or by using different approach in terms of simplifications, the accuracy may be improved. This model can be implemented in more sophisticated primary circuit model and the differences may be lower. The combination of Dymola and ClaRa is a very promising and powerful combination that may be used in the commercial sphere when modelling the real simulation for nuclear power plants.

10. References

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List of equations:

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