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LEAKAGES EFFECT CHARACTERISATION OF AN ITER COOLING SYSTEM THROUGH THE DEVELOPMENT OF A 1-D HYDRAULIC MODEL IN OPENMODELICA

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Abstract

Il seguente elaborato è il risultato di 6 mesi di stage svolti presso NIER Ingegneria S.p.A. nell'ambito della modellazione idraulica dell'Ex-Vessel cooling system (EVCS) dell'Electron Cyclotron Upper Launcher (EC UL), un sottosistema di ITER (il reattore sperimentale a fusione nucleare in costruzione a Cadarache), tramite l'utilizzo del software OpenModelica. I temi trattati riguardano la modellazione del sistema in condizioni nominali e in condizioni di off-design (in presenza di ostruzioni o di rotture).

Per quanto riguarda il primo argomento, il sistema (in condizioni nominali) è stato modellato tramite OpenModelica, verificandone il design e appurando che le portate si distribuissero all'interno del sistema come desiderato.

Per quanto riguarda il secondo argomento, il sistema (in condizioni di off-design) è stato modellato in presenza di ostruzioni o di rotture. Nel caso di perdite di rotture sono stati considerati due scenari: piccole perdite e doppia ghigliottina. Per ciascun branch si sono considerate tre diversi posizioni della perdita: inizio, metà e fine del beam interessato dalla leak. Nel caso di piccole perdite si è considerato il beam collegato ad ambiente tramite una resistenza, mentre nel caso di doppia ghigliottina il beam era direttamente collegato ad ambiente. Per rendere più semplice il post-processing nello studio del sistema in condizioni di off-design è stato utilizzato OMPython. Gli obiettivi sono stati verificare che le variazioni di portata fossero rilevate dai misuratori di portata, presenti in mandata e ritorno di ogni branch. Inoltre, si è dovuto provare che la portata minima fosse garantita in ciascun componente per motivi di sicurezza. Tramite i vari modelli implementati con OpenModelica e simulati con OMPython si è potuto verificare che il design dell'EVCS soddisfa i requisiti definiti.

Abstract

The following dissertation is the result of a 6 months stage conducted at NIER Ingegneria S.p.A. in the hydraulic modelling of the Ex-Vessel cooling system (EVCS) of the Electron Cyclotron Upper Launcher (EC UL), a subsystem of ITER (the experimental fusion nuclear reactor under construction in Cadarache), through the use of the OpenModelica software. The topics discussed concern the modelling of the system in nominal operating conditions and in off-normal operating conditions (in presence of obstructions or leakage).

With regard to the first topic, the system (in nominal operating conditions) was modelled through the use of the OpenModelica software, proving the design and checking that the mass flow rates were distributed as desired within the system.

In off-normal operating conditions the system was modelled in presence of obstructions or leakage. In the case of leakages, two scenarios were considered: small breaks and double ended guillotine. Three different locations of the leak were assessed for each branch: start, middle and end of the beam affected by the leak.

In the case of small breaks, the beam was connected to ambient through a resistance, whereas in the case of double ended guillotine the beam was directly connected to ambient. OMPython was used to make the post-processing easier.

The objectives were to verify that flow rate variations could be detected by the mass flow rate meters, placed both in the feed and in the return of each branch. Moreover, it was needed to check that the minimum mass flow rate was provided in each component for safety purposes. Through various models implemented with OpenModelica and simulated with OMPython, it could be assessed that the EVCS design fulfils the defined requirements.

1 INTRODUCTION

This thesis is focused on the hydraulic modelling of the Ex-Vessel Cooling System (EVCS) of the Electron Cyclotron Upper Launcher (EC UL), a subsystem of ITER (the experimental fusion nuclear reactor under construction in Cadarache). The work was done at NIER Ingegneria S.p.A., a company that works in many sectors of engineering consulting, which is in charge of the EVCS design.
In the first part of the essay, the EC Upper Launcher configuration and its cooling system, and then the EC UL EVCS design and its layout (specifically on the main functions required) will be described. In the second part the hydraulic model of the EVCS in normal operating conditions will be presented, and its modelling through the use of the "OpenModelica" software [6] will be discussed.
After the analysis of the system in normal operating conditions, the hydraulic model in off-normal operating conditions will be introduced, such as the presence of obstructions or leakages. These studies are carried out by adopting OMPython [8], the OpenModelica Python Interface, implemented in Python; this software helped make the post-processing easier. Then the attention will be focused on the redistribution of flow rates through the various sections of the circuit and on the effects that these off-normal conditions can have on the cooling performance.

1.1 Objectives

The thesis is focused on the verification of two main requirements of the EVCS design:

- the ability to provide a minimum mass flow rate to all the different actively cooled components it serves;
- the ability to detect, through the use of mass flow meters, if the mass flow rate in one of the EVCS components decrease below its minimum.

The modelling of the system in nominal conditions was focused on the validation of the EVCS design, whose object is to provide the minimum mass flow rate in each component. The nominal model was implemented to assess that the pressure drop assigned to the orifice was adequate to achieve the desired distribution of flow rate in the system. In fact, given the design realised by NIER, given the total mass flow rate and the pressure budget available, the system was modelled by using OpenModelica and proving that the flow rates were actually redistributed through the various sections of the system as shown in Figure 3.2.
Regarding the system in off-normal conditions, the obstruction and the leakage were modelled with an orifice. A beam for every branch was perturbed each time by using the same input data of the nominal model. The aim was to find the pressure drop to assign to the orifice in order that the minimum mass flow rate was provided in the component. Once the pressure drop which provided the minimum flow rate in the component was found, a check has been carried out; in particular, if the instrumentation system of the EC UL EVCS (based on Venturi Flowmeters) was able to detect flow rate variations and if the mass flow rate dropped below the minimum

value in a component. Two different leakages scenario were evaluated: small break and double ended guillotine. Three different locations were considered for each leak: start, middle and end of the beam. The objectives for small breaks were to find which was the pressure drop to assign to the orifice that provided the minimum mass flow rate in the component following the leak and if the mass flow rate meters (placed both in the feed and in the return of each branch) could detect mass flow rate variations. As regards double ended guillotine, it was analysed how the flow rates were distributed within the system and where a flow reversal occurred.

1.2 Electron Cyclotron Upper Launcher

This chapter provides the description of the Electron Cyclotron Upper Launcher, its configuration and its cooling system.

1.2.1 Electron Cyclotron Heating and Current Drive

ECH&CD provides 170 GHz high power microwave beams for plasma heating and current drive applications. ECH&CD consists of four main subsystems: high voltage power supply (HVPS), radio frequency source (RF), transmission line (TL) and launchers.

ECH&CD includes two types of launchers that transfer power to the plasma:

- a launcher is located in the equatorial port (Equatorial Launcher, EL), used for concentrated storage of power, and has the function of decoupling heat from the current driving function;
- four launchers are located in the four upper ports (Upper Launchers, UL), used to deposit power in the outer half of the plasma cross-section to control magnetohydrodynamic instabilities.

1.2.2 Cooling System Configuration

As shown in Figure 1.1, the composition of each EC Upper Launcher is as follows:

- the "First Confinement System" (FCS), which is the assembly of components extending the first confinement barrier of the Vacuum Vessel volume, installed “ex-Vessel” (i.e. in the port cell and interspace)
- the "Upper Launcher" which is the assembly of structural, optical and shielding components, installed “in-Vessel” (i.e. within the Vacuum Vessel boundary)

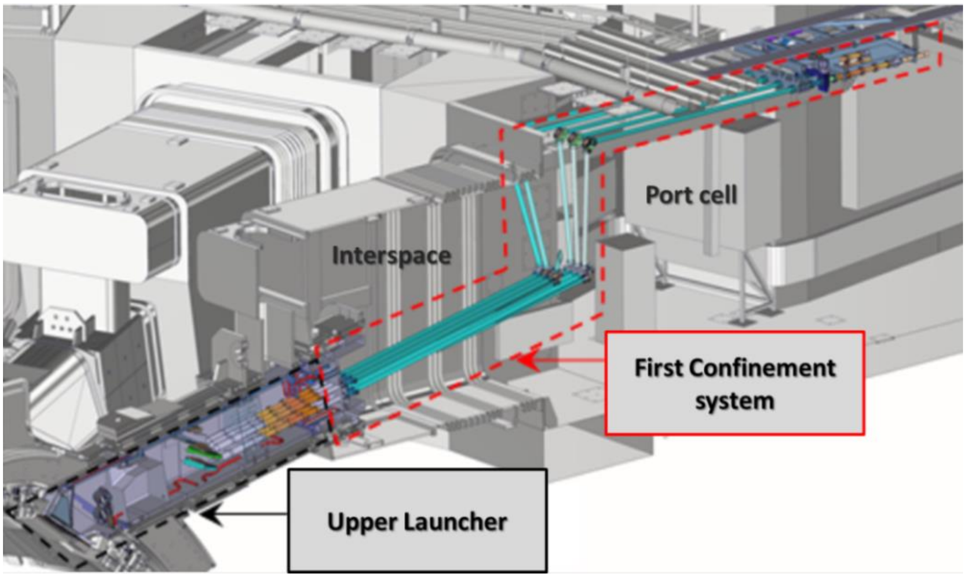


Figure 1.1 – EC Upper Launcher configuration

1.2.3 Configuration

The EC Upper Launcher cooling system consists of two independent distribution systems:

- The EC UL Ex-Vessel cooling system can provide fresh water to the EC FCS components;
- The EC UL In-vessel cooling system can provide fresh water and gas (nitrogen for maintenance) to the EC UL components.

The EC UL Ex-Vessel and In-Vessel cooling system must meet different requirements, due to the different components to be cooled, functions required and environmental and loading conditions experienced during operations, testing and maintenance, incidents and accidents. The design of the EC UL EVCS is clearly related to the design of the EC UL FCS. Figure 1.2 and Figure 1.3 show the different components of the EC UL FCS that are cooled by the EVCS:

- Thermal Insulation - Closure Plate Sub Plate (TI-CPSP);
- Waveguides in Port Cell, in Interspace (WGs-PC, WGs-IS);
- Waveguide Counter Flanges in Port Cell, in Interspace (WGs CF-PC, WGs CF-IS);
- Mono Block Mitre Bend body (MBMB-b) and mirror (MBMB-m);
- Mitre Bend body (MB-b) and mirror (MB-m);
- Isolation Valve (IV);
- Diamond Window Unit (DWU).

The boundary between the Upper Launcher and the Transmission Line is realized by the EU-US Adapters, just prior to the DWU (on Gyrotron side).

The DWU includes a (~1.1 mm thick) disk made by low RF power loss and higher thermal conductivity material. Cooper cuffs with relatively thin copper walls (~1 mm) are brazed to the diamond disk and can be indirectly cooled. The IV is an all-metal valve which must be closed to advance the first confinement system from the DWU, in the event of vacuum volume overpressure (i.e. in the event of coolant leakage).

The ex-vessel WGs and optical components (MB and MBMB) are connected (from the CPSP up to the IV) through flange couplings with Double Metal Seal (DMS) and online leak monitoring of the seals interspace.

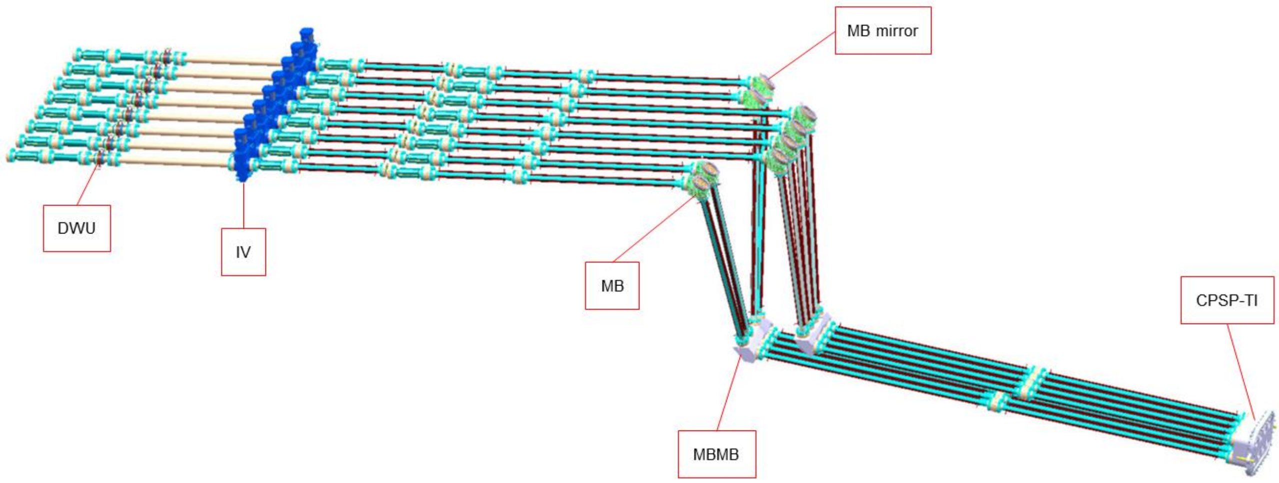


Figure 1.2 – EC UL FCS assembly

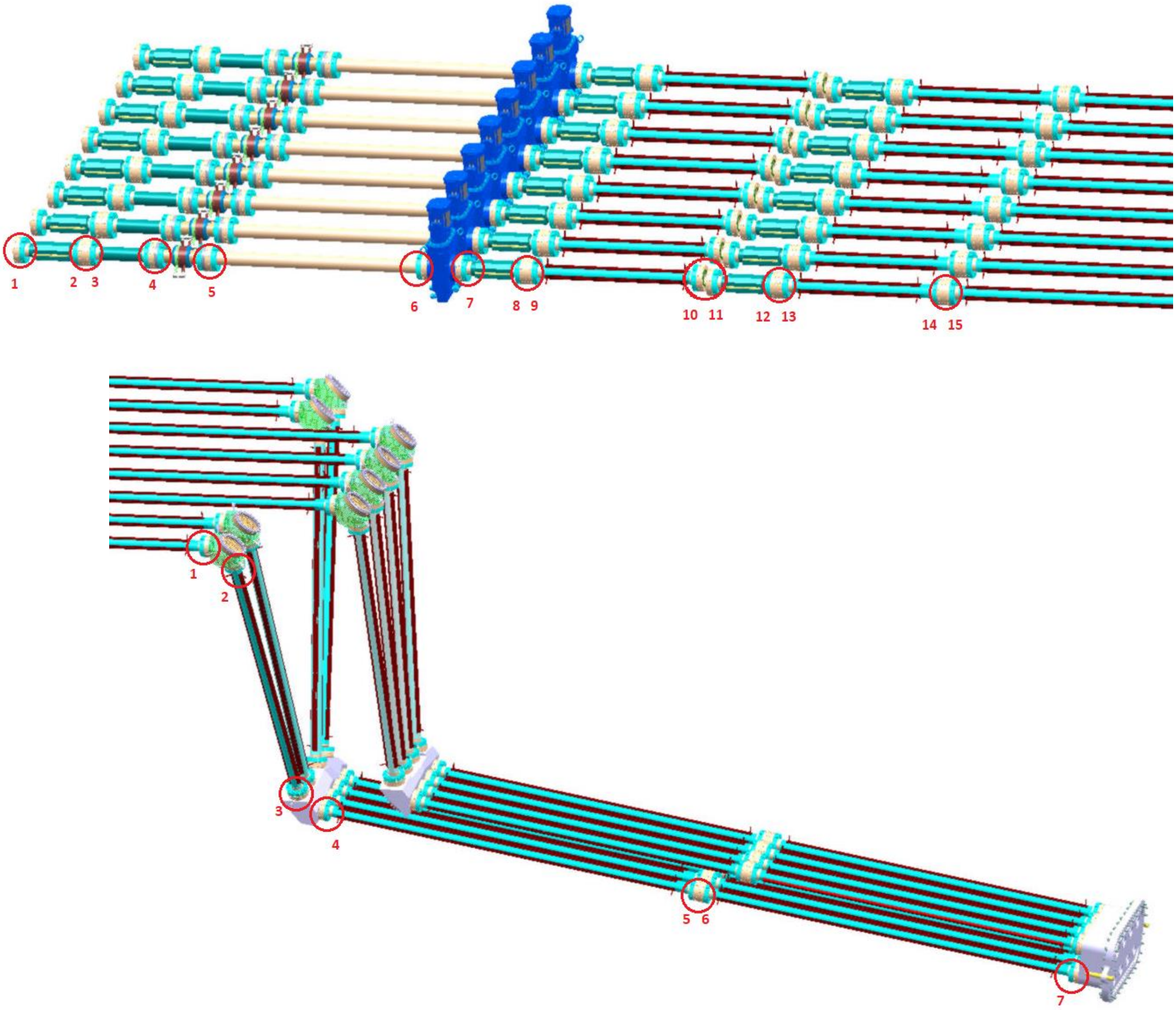


Figure 1.3 – EC UL Waveguides Counter Flanges

1.2.4 Electron Cyclotron Upper Launcher Ex-Vessel Cooling System

1.2.4.1 Main Function

The main functions required to the EC UL EVCS are to:

- provide water to and retrieve it from the EC UL Ex-Vessel (and TL) components internal cooling in order to make possible the heat removal from the EC UL Ex-Vessel (and TL) components (subjected to thermal power due to ohmic losses during mm-wave propagation);
- detect "loss of cooling" conditions;
- reduce the risks associated with applicable hazards, ensuring the possibility of accidents is minimized, and the consequences are limited by the design basis conditions considered.

It requires the capability of the system:

- to balance the pressure drops through FCS components;
- to regulate the coolant flows through FCS components;
- to isolate the circuit in case of failure and for maintenance purposes;
- to monitor the coolant parameters and specifically;
- to detect loss of cooling condition to protect FCS components;
- to interface with the internal cooling circuits of the FCS cooled components;
- to interface with the Port Cell and Interspace building, with the penetration in the Bio-Shield that delimits them, with the CCWS-1, with the Cable Trays (for the sensors) and with the Gallery TL and Shutter Valve;
- to ensure the required structural stiffness and mechanical stability against dynamic loads acting on the launcher during ITER operations (e.g. forces and moments due to plasma disruptions) and external events (e.g. seismic);
- to allow and facilitate manual assembly, welding, screwing and inspection.

1.2.5 Location

According to the physical location of the components, two parts of EC UL EVCS are defined, as shown in Figure 1.4:

- PCC (Port Cell Components) including all components hosted in the Port Cell;
- ISC-CCWS (InterSpace Components belonging to CCWS) including all components in the Interspace.

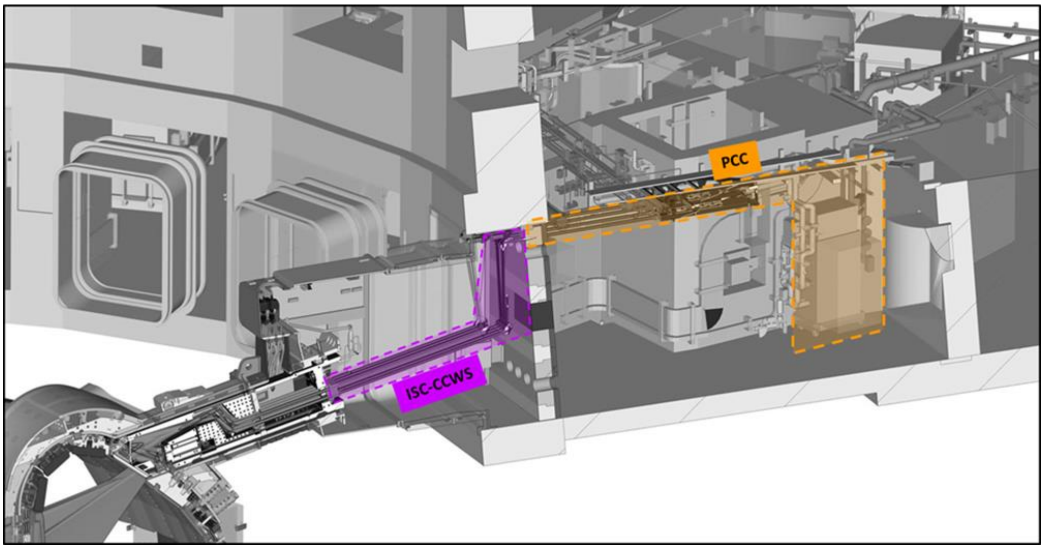


Figure 1.4 – EC UL EVCS, Cooling System

1.2.6 Technical Solution

1.2.6.1 Instrumentation for Monitoring

The system is equipped with the instrumentation (measurement sensors) required to:

- monitor coolant temperature to facilitate fault localization by coolant temperature measurements;
- monitor coolant pressure at the inlet line by coolant pressure and differential pressure measurements;
- detect coolant losses by flow measurements;
- detect flow obstructions by flow measurements.

Temperature measurements have been set to provide data as follows:

- Inlet temperature – upstream of inlet manifold;
- Component outlet temperatures – downstream of component or group of components;
- Mixing temperatures – downstream of coolant mixing points ;
- Outlet temperature – downstream of outlet manifold .

Pressure gauge sensors have to be installed at the inlet of the circuit.
Differential pressure sensors have to be installed between inlet and outlet of the circuit.
Flow measurement devices have to be installed at the inlet and outlet of branches A1, A2, B1, B2, C1, C2, E1, E2, E3, E4, E5, E6, E7, E8 and F.
The focus in this thesis was to assess the detection of flow in case of obstruction or leakage.

1.3 Abbreviations

The general list of ITER acronyms used for the present document is reported below.

CCWS	Component Cooling Water System
DMS	Double Metal Seal
DN	Nominal Diameter
DWU	Diamond Window Unit
EC	Electron Cyclotron
EV	Ex-Vessel
EVCS	Ex-Vessel Cooling System
FCS	First Confinement System
ISV	Isolation Shutter Valve
IV	Isolation Valve

MB	Mitre Bend
MBMB	Mitre Bend MonoBlock
MFR	Mass Flow Rate
PC	Port cell
TI-CPSP	Thermal Isolation Closure Plate SubPlate
TL	Transmission Lines
UL	Upper Launcher
WG	WaveGuide
WGCF	WaveGuide Counter Flange

2 METHODOLOGY

Tools and software used are presented below. OpenModelica was adopted for creating models, by using components within the Fluid section. OMPython was used for simulating models, because it made the post-processing easier, and for creating iterative cycle for finding the pressure drop that provided the minimum mass flow rate in the component affected by the obstruction or the leakage.

2.1 OpenModelica

OpenModelica is an open source Modelica-based modelling and simulation environment intended for industrial and academic usage; in particular, it was used OMEdit [7], an open-source graphical interface for creating, editing and simulating Modelica models in textual and graphical modes. OMEdit communicates with OMC through an interactive API, requesting model information and creating models/connection diagrams based on the Modelica annotations.

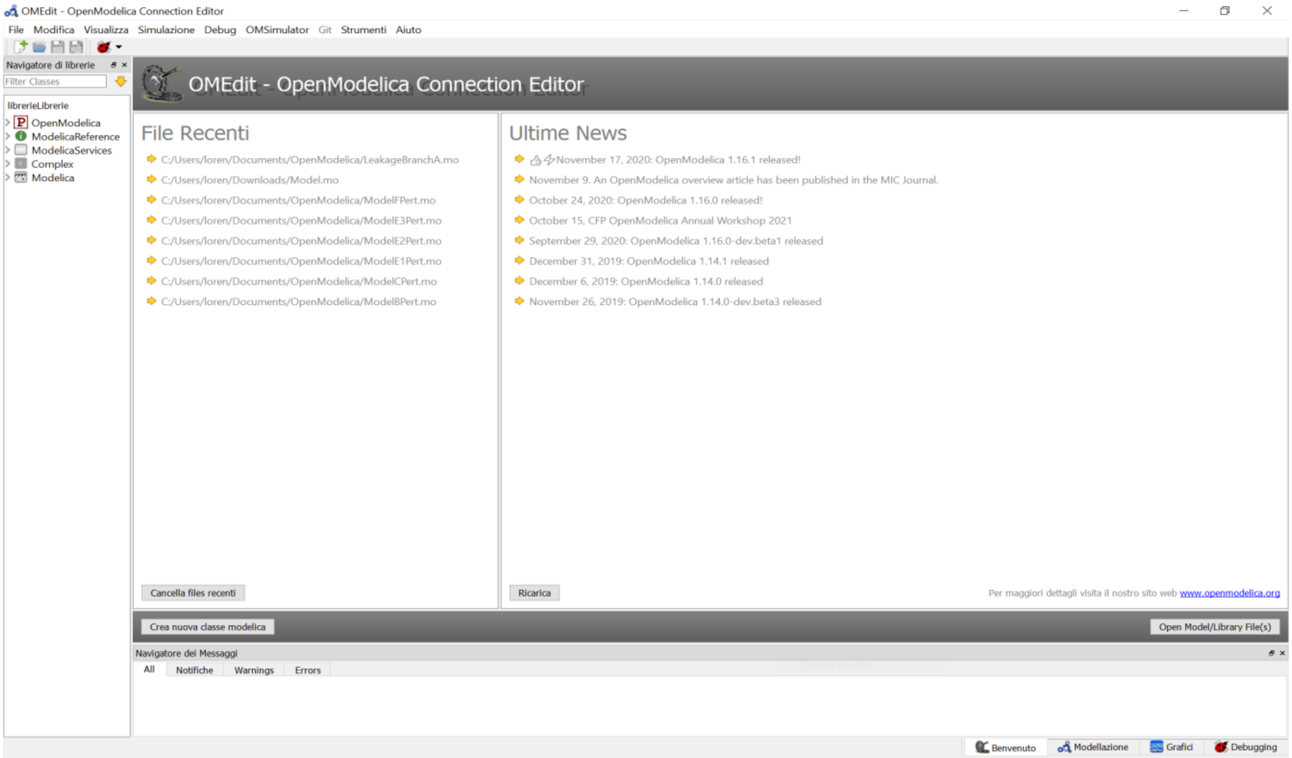


Figure 2.1 – OMEdit

The section dedicated to Fluid within the Modelica environment was specifically used. Among the packages listed in Figure 2.2, were used:

- Pipes
- Fittings
- Sources
- Sensors

The components were selected from respective packages and then dragged to the modelling ambient, in order to add them in the model. Every time a component was added in the model, it was registered in the text view with its parameters.

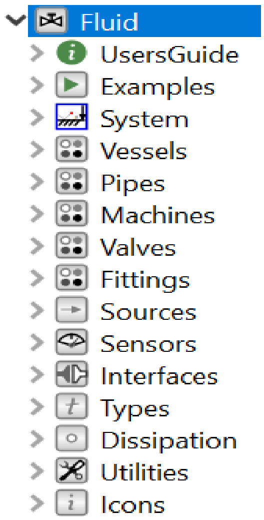


Figure 2.2 - Packages

The compilation of the model required that the fluid that flowed in each element was specifically defined. The Ex-Vessel Cooling System is fully crossed by water. There were a lot of packages for the definition of the carrier fluid: air, compressible and incompressible fluids, ideal gas and R134a. A specific one was created, called 'MyWater', starting from the 'ConstantPropertyLiquidWater' package available on OpenModelica: by using this package, the density, specific heat capacity (at constant pressure and constant volume) and the dynamic viscosity could be set as constants (equal to the values in the hydraulic model, respectively 994.752 [kg/m^3], 4176.904 [J/Kg K] and 0.000734 [Pa s]). The following expression must be used in the text view for each component: redeclare package Medium = MyWater.

2.2 OMPython

OMPython is the OpenModelica Python Interface implemented in Python. It is a free, open source, highly portable Python based interactive session handler for Modelica scripting. It provides the modeler with the components needed to create a complete Modelica modelling, compilation and simulation environment and it is designed to combine both the solving strategy and model building. The obstruction and the leakage model were simulated through OMPython. It was used Jupyter notebook, an open-source web application, and Spyder, a free and open-source scientific environment written in Python, to creating the script.

2.2.1 Test Commands

First, the OMPython library was imported from Python. OMPython provides two classes of communication with OpenModelica: OMCSession and OMCSessionZMQ. Both classes had the same interface and the OMCSessionZMQ was used, because it is recommended on the OpenModelica website [6]. An

OMCSessionZMQ object was created to test the command outputs by importing it from the OMPython library within Python interpreter. This module allowed to interactively send commands to the OpenModelica server and display their output. A Modelica System object was then introduced; the object constructor requires a minimum of 2 input arguments which are strings:

- The first input argument must be a string with the file name of the Modelica code, with Modelica file extension '.mo'. if the Modelica file is not in the current directory of Python, then the file path must also be included.
- The second input argument must be a string with the name of the Modelica model.

```
import OMPython #importing the OMPython library from Python
from OMPython import OMCSessionZMQ #importing the OMCSessionZMQ from OMPYthon
from OMPython import ModelicaSystem #importing the Modelica System from OMPython

omc = OMCSessionZMQ() #creating a OMCSessionZMQ
mod = ModelicaSystem("model_path + file_name.mo", "file_name") #creating a Modelica System
```

Figure 2.3 – OMPython test commands

The 'simulate' method was then adopted, which simulates model according to the simulation options:

```
mod.simulate() #simulation of the model
```

Figure 2.4 – Simulate Method

The data for the post-processing had to be obtained, by using this procedure:

```
Data = mod.getSolutions(["Data_File_name"])
#getting the value which I was interest in
```

Figure 2.5 – GetSolutions Method

'Data_File_name' represents the name of the component in the model, depending on whether the mass flow rate or the pressure of the component was needed and indicated if it concerned the input or the output. The getSolutions method returns a list of numpy arrays. It can be called with a list of quantities name (or a single quantity name) in string format as argument; it returns the simulation results of the corresponding names in the same order.

One element from the numpy array must be extracted, through the following statement:

```
Data = Data.flat[0]
```

Figure 2.6 – Extraction from a numpy array

Moreover, 'Data' could be defined with any expression.

The a) 'getParameters' and b) 'setParameters' method were applied:

```
Get = mod.getParameters(["Parameter_name"])
```

Figure 2.7 – getParameters Method

The argument is the parameter's name used in the OpenModelica model, and it returns the corresponding parameter value. In this way it could be checked if the variable was equal to the one applied in the model.

```
Set = mod.setParameters(["Parameter_name = x"])
```

Figure 2.8 – setParameters Method

This is used to set parameters values. It can be called with a sequence of parameter name and assigning corresponding value as argument. For example, the pressure drop or the nominal mass flow rate of a component could be changed and start a new simulation.

The Mass Flow Rate Meters have been neglected in the following simulations implemented through OMPython because they would have been useful only if there had been a feedback control on the mass flow rate within the system.

3 HYDRAULIC MODELLING OF EC UL EVCS

3.1 System Layout

A representative diagram is provided in Figure 3.1.

Each Launcher cooling circuit has been divided in six branches arranged in parallel, namely:

Branch A serving the TL components in the Port Cell including the Isolation Shutter Valve (ISV) and the WGs in Port Cell.

Branch B serving the WGCF in Port Cell.

Branch C serving the DWUs and the IVs.

Branch D dedicated to the TL components in the Gallery.

Branch E serving the components in the Interspace, i.e. MBMB Mirror and Body, MB Mirror and Body, WGs and their WGCFs.

Branch F dedicated to the TI-CPSP in the Interspace.

The 6 branches are connected to the CCWS-1A through a couple of manifolds (supply and return).

The branches A, B and C have the same layout: the main branch splits in two sub-branches, each connected to a manifold which distributes the flow among 4 Lines, one per beam. The flow is collected downstream by 2 manifolds, one per each sub-branch, prior to join again in the branch return line.

The branch D, for the purpose of the present activity, is treated as a black box, provided that the required mass flow rate is supplied by the EVCS.

The branch E, dedicated to the components in the Interspace, is the only one adopting a “per-beam” structure. The branch supply is connected to a manifold which distributes the flow among 8 sub-branches, one per beam. Each sub-branch is then directed towards a manifold, which distributes the flow among 3 lines based on the components to be cooled as follows:

Line En1 serving the WGCFs.

Line En2 serving the MBMB Mirror and the MB Mirror.

Line En3 serving the MBMB Body, the MB Body and the WGs.

Downstream the components, a two-stage manifold similar to the supply layout is used, so the flow can be recollected.

Branch F directs the flow directly through the TI-CPSP.

For branches E and F, valves, sensors and orifices have been placed outside the bioshield (i.e. in the Port Cell), to ensure higher radiation protection and better accessibility for maintenance during the nuclear phase.

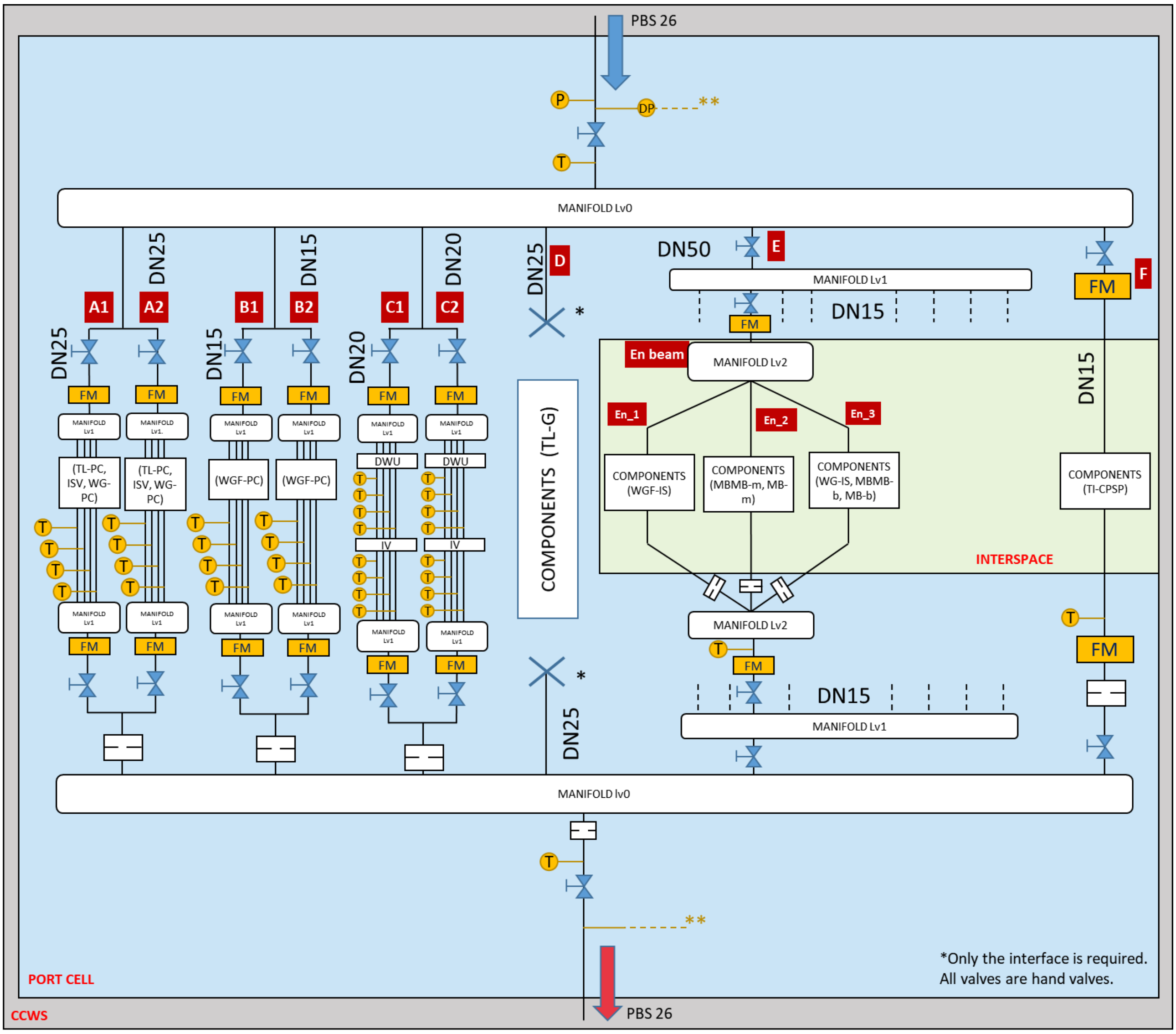


Figure 3.1 - EC UL EVCS, Layout

3.2 Cooling Data for EVCS Circuit

Each of the EVCS circuits is provided with appropriate coolant mass flowrate to remove the thermal load of the components it cools while keeping the outlet temperature within prescribed limits. In Table 3.1 the mass flow rate into each cooling line, branch and sub-branch is defined.

Cooling Section			Component	MFR	MFR	MFR
Branch	**Sub-Branch**	**Line**	**ID**	**[kg/s]**	**[kg/s]**	**[kg/s]**
A	A1	A1n (x4)	TL-PC, ISV, WG-PC	0.297	1.188	2.376
	A2	A2n (x4)	TL-PC, ISV, WG-PC	0.297	1.188	

B	B1	B1n (x4)	WGF-PC	0.023		0.092		0.184	
	B2	B2n (x4)	WGF-PC	0.023		0.092			
C	C1	C1n (x4)	DWU, IV	0.106		0.424		0.848	
	C2	C2n (x4)	DWU, IV	0.106		0.424			
D	-	-	TL-G	-		-		2.376	
E	En (x8)	En1	WGF-IS	0.030		0.426		3.408	
		En2	MBMB-m, MB-m	0.106					
		En3	WG-IS, MBMB-b, MB-b	0.290					
F	-	-	TI-CPSP	-		-		0.233	

Table 3.1 – Cooling Data for EC UL EVCS

PIPING					
NAME	**MFR [Kg/s]**	**L [m]**	**DN**	**D [m]**	**v [m/s]**
Inlet-Outlet	9.425	20.6	65	6.69E-02	2.69540743
Branch A	2.376	2	25	2.79E-02	3.90690928
Branch A-1	1.188	30.7	25	2.79E-02	1.95345464
Branch A-2	1.188	30.7	25	2.79E-02	1.95345464
Branch B	0.184	2	15	1.71E-02	0.8054172
Branch B-1	0.092	27.2	15	1.71E-02	0.4027086
Branch B-2	0.092	27.2	15	1.71E-02	0.4027086
Branch C	0.848	2	20	2.25E-02	2.14400658
Branch C-1	0.424	28.2	20	2.25E-02	1.07200329
Branch C-2	0.424	28.2	20	2.25E-02	1.07200329
Branch E	3.408	2	50	5.48E-02	1.45255895
Branch E-0	0.426	28.5	15	1.71E-02	1.86471591
Branch E-1	0.03	12.8	10	1.38E-02	0.2016315
Branch E-2	0.106	12.8	10	1.38E-02	0.7124313
Branch E-3	0.29	12.8	10	1.38E-02	1.94910449
Branch D	2.376	2	32	3.67E-02	2.25792549
Branch F	0.233	54.6	15	1.71E-02	1.0199033

Table 3.2 – Pipes Data

COMPONENTS PRESSURE DROP			
Description	**Branch**	**Component**	**DP [Pa]**
Transmission Lines in Gallery	D	TL-G	6.29E+04
Transmission Lines in PC + Shutting Valves	A-1	TL-PC+ISV	6.29E+04

Waveguides in Port Cell	A-1	WG-PC	3.13E+04
Waveguides Flanges in Port Cell	B-1	WGF-PC	1.20E+05
Diamond Window Unit	C-1	DWU	5.70E+03
Isolation Valve	C-1	IV	1.60E+04
Transmission Lines in PC + Shutting Valves	A-2	TL-PC+ISV	6.29E+04
Waveguides in Port Cell	A-2	WG-PC	3.13E+04
Waveguides Flanges in Port Cell	B-2	WGF-PC	1.20E+05
Diamond Window Unit	C-2	DWU	5.70E+03
Isolation Valve	C-2	IV	1.60E+04
DMS Miter Bend Mirror	E-2	MB-m	1.50E+04
DMS Miter Bend Body	E-3	MB-b	1.93E+04
DMS Mono Block Miter Bend Mirror (each)	E-2	MBMB-m	1.50E+04
DMS Mono Block Miter Bend Body (each)	E-3	MBMB-b	1.93E+04
Waveguides in Interspace	E-3	WG-IS	3.28E+04
Waveguides Flanges in Interspace	E-1	WGF-IS	9.53E+04
Thermal Isolation Closure Plate SubPlate	F	TI-CPSP	6.00E+04
Flowmeter A-1	A-1	FM	1.00E+05
Flowmeter A-2	A-2	FM	1.00E+05
Flowmeter B-1	B-1	FM	1.00E+05
Flowmeter B-2	B-2	FM	1.00E+05
Flowmeter C-1	C-1	FM	1.00E+05
Flowmeter C-2	C-2	FM	1.00E+05
Flowmeter E-0	E-0	FM	1.00E+05
Flowmeter F	F	FM	1.00E+05

Table 3.3 – Pressure Drop Data

ORIFICES	
LINE	**ΔP [Pa]**
Branch A	**207832.7512042193**
Branch B	**284221.3997869775**
Branch C	**357707.11236831703**
Branch D	**394832.67754760385**
Sub-Branch E_1	**239270.17538552155**
Sub-Branch E_2	**297951.92807152064**
Sub-Branch E_3	**216606.1702615875**

Branch F	303852.04572093795
Inlet-Outlet	20084.0

Table 3.4 – Orifices Data

	Nominal Global Cooling				
	LINE	MFR [Kg/s]	K*	ΔP [Pa]	Check K*
	Global Cooling	9,425	1,24E+04	5,50E+05	0,00E+00
	Main client losses	9,425	8,98E+02	3,99E+04	-
Branches level	Branch A	2,376	1,81E+05	5,10E+05	0,00E+00
	Branch B	0,184	3,01E+07	5,10E+05	0,00E+00
	Branch C	0,848	1,42E+06	5,10E+05	0,00E+00
	Branch D	2,376	1,81E+05	5,10E+05	-
	Branch E	3,408	8,78E+04	5,10E+05	-
	Branch F	0,233	1,88E+07	5,10E+05	-

	Nominal E branch				
	LINE	MFR [Kg/s]	K*	ΔP [Pa]	Check K*
	Client tot	3,408	8,78E+04	5,10E+05	*0,00E+00*
Client level	Client piping	3,408	1,32E+02	7,64E+02	-
	Beam n	0,426	5,61E+06	5,09E+05	*0,00E+00*
En Beam sub-branches level	Beam i/o	0,426	1,92E+06	1,74E+05	-
	En_1	0,03	7,45E+08	3,35E+05	-
	En_2	0,106	5,97E+07	3,35E+05	-
	En_3	0,29	7,98E+06	3,35E+05	-

	Other Nominal Branches				
	LINE	MFR [Kg/s]	K*	ΔP [Pa]	Check K*
Branch Level	Client A losses	2,376	7,77E+04	2,19E+05	-
	Client B losses	0,184	1,69E+07	2,85E+05	-
	Client C losses	0,848	1,01E+06	3,62E+05	-
Sub-Branch level	Branch An losses	1,188	2,08E+05	1,47E+05	-
	Branch Bn losses	0,092	2,46E+07	1,04E+05	-
	Branch Cn losses	0,424	1,32E+06	1,19E+05	-
Beam Level	N-th Beam An	0,297	3,26E+06	1,44E+05	-
	N-th Beam Bn	0,023	4,56E+08	1,21E+05	-
	N-th Beam Cn	0,106	5,18E+06	2,91E+04	-

Figure 3.2 – Data of the Nominal Hydraulic Model

The model was realized in the form of a MS Excel spreadsheet by NIER, through which the hydraulic model of the EC UL EVCS was implemented, and consisted of the following 7 sections:

1. Definition of reference input data.
2. Pressure losses from CFD analysis.
3. Piping data.
4. Characterization of combined pressure losses.
5. Derivation of Equivalent Pressure Loss Coefficients (EPLCs).
6. Summary of Orifices and Valves.
7. Summary of pressure losses.
8. Orifice first-guess sizing.

The data reported in the previous Figures and Tables was accessible in an Excel file [3] which has been made available for the modelling of the system through OpenModelica.

3.3 Components

- **Mass Flow Source**

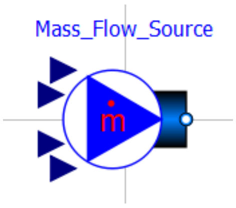


Figure 3.3 – Mass Flow Source

It represented the main source of the system. Only one parameter could be set, the mass flow rate, which is equal to 9.425 kg/s, as shown in Table 3.2 (inlet-outlet).

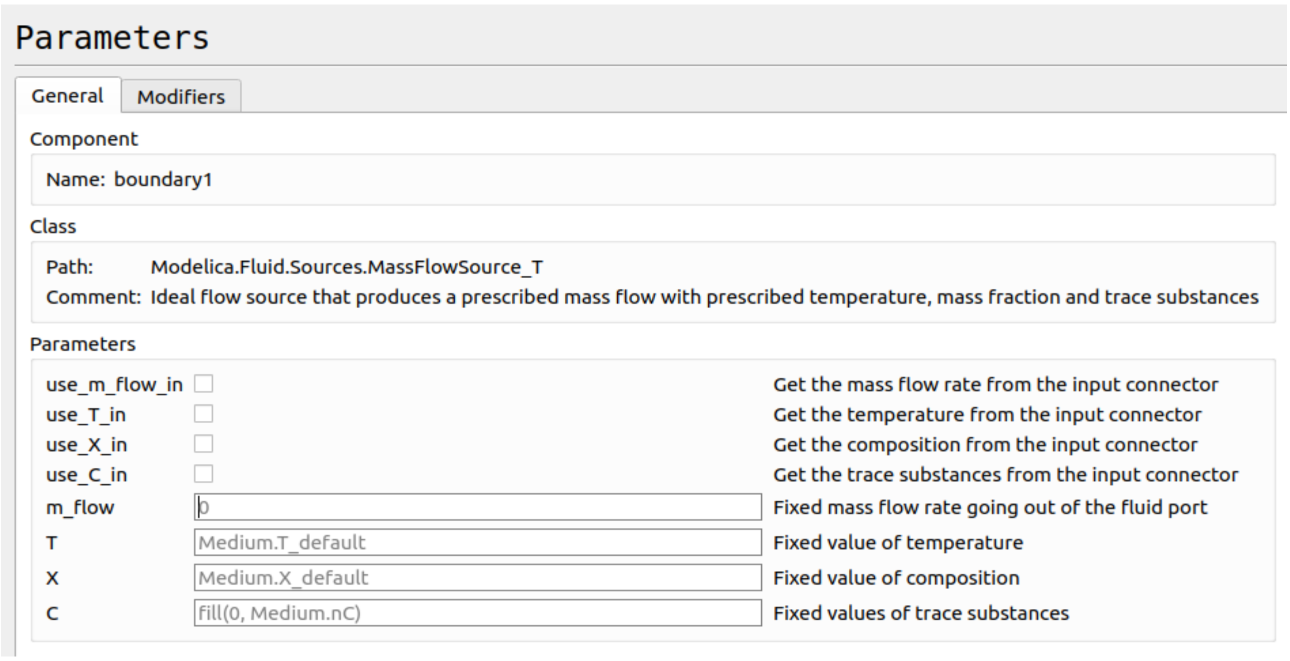


Figure 3.4 – Mass Flow Source Parameters

- **Mass Flow Rate Meter**

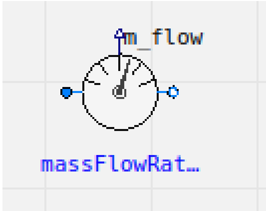


Figure 3.5 – Mass Flow Rate Meter

Mass Flow Rate Meters were used to verify the correct repartition of flow within the system. The modelled system through OpenModelica has validated the location of the Mass Flow Rate meter**;** instead of locating a mass flow rate meter in each beam (configuration not acceptable for lack of space), it was placed upstream and downstream of the beam, proving the correct distribution of flow.

- **Pipe**

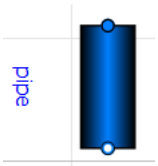


Figure 3.6 - Pipe

Pipes were used to define the length of the different branches and of the piping in the beam. The parameters that had to be set were length and diameter, which are shown in Table 3.2. Starting from these parameters, the software evaluated fluid's pressure at inlet (port_a) and at outlet (port_b) of pipes.

For pipes with circular cross section the pressure drop is computed as [9]:

$$dp = \lambda(\mathrm{Re},\mathrm{D}) \cdot \left(\frac{\mathrm{L}}{\mathrm{D}}\right) \cdot \rho \cdot \mathrm{v} \cdot \frac{|\mathrm{v}|}{2}$$

$$= \lambda(\mathrm{Re},\mathrm{D}) \cdot 8 \cdot \frac{\mathrm{L}}{\pi^2 \cdot \mathrm{D}^5 \cdot \rho} \cdot \mathrm{m}_{\mathrm{flow}} \cdot |\mathrm{m}_{\mathrm{flow}}|$$

$$= \lambda_2(\mathrm{Re},\mathrm{D}) \cdot \mathrm{k}_2 \cdot \mathrm{sign}(\mathrm{m}_{\mathrm{flow}});$$

Equation 3.1 – Computation of the pressure drop in a pipe

with

$$Re = |\mathrm{v}| \cdot \mathrm{D} \cdot \rho/\mu$$

$$= \mathrm{m\_flow}| \cdot 4/(\pi \cdot \mathrm{D} \cdot \mu)$$

$$m_{flow} = A \cdot v \cdot \rho$$

$$A = \pi \cdot (\mathrm{D}/2)^2$$

$$\lambda_2 = \lambda \cdot Re^2$$

$$k_2 = L \cdot \mu^2/(2 \cdot D^3 \cdot \rho)$$

where:

- L is the length of the pipe.
- D is the diameter of the pipe. If the pipe has not a circular cross section, $D = 4 \cdot A/P$, where A is the cross section area and P is the wetted perimeter.
- $\lambda = \lambda(Re, D)$ is the "usual" wall friction coefficient.
- $\lambda_2 = \lambda \cdot Re^2$ is the used friction coefficient to get a numerically well-posed formulation.
- $Re = |v| \cdot D \cdot \rho/\mu$ is the Reynolds number.
- D = d/D is the relative roughness where "d" is the absolute "roughness", i.e., the averaged height of asperities in the pipe (d may change over time due to growth of surface asperities during service).
- ρ is the upstream density.
- μ is the upstream dynamic viscosity.
- v is the mean velocity.

The first form with λ is used:

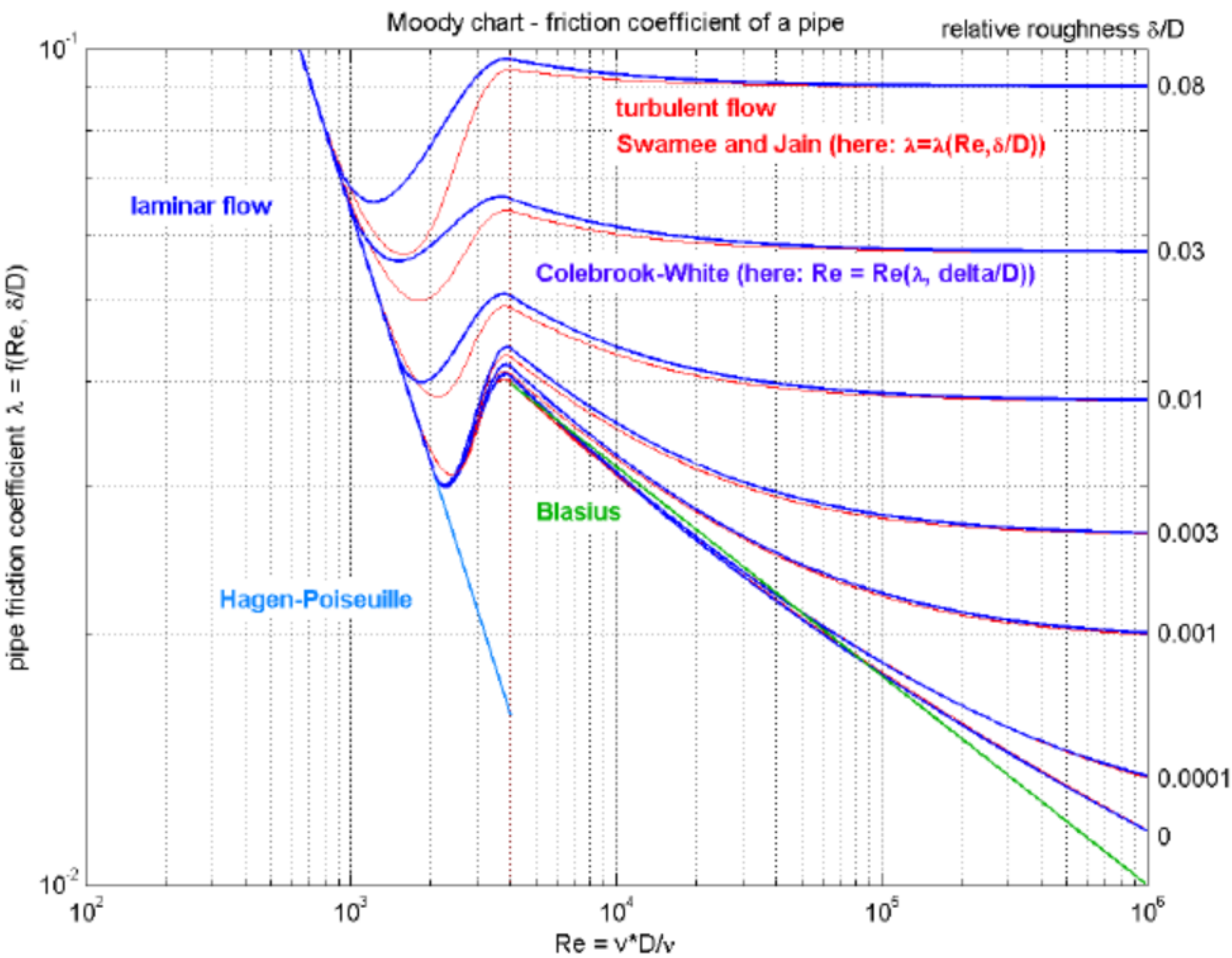


Figure 3.7 – Moody chart

This form is not suited for a simulation program since λ = 64/Re if Re < 2000, i.e., a division by zero occurs for zero mass flow rate because Re = 0 in this case. More useful for a simulation model is the friction coefficient $\lambda_2 = \lambda \cdot Re^2$, because $\lambda_2 = 64 \cdot Re$ if Re < 2000 and therefore no problems for zero mass flow rate occur. The characteristic of λ_2 is shown in the next figure and is used in Modelica.Fluid:

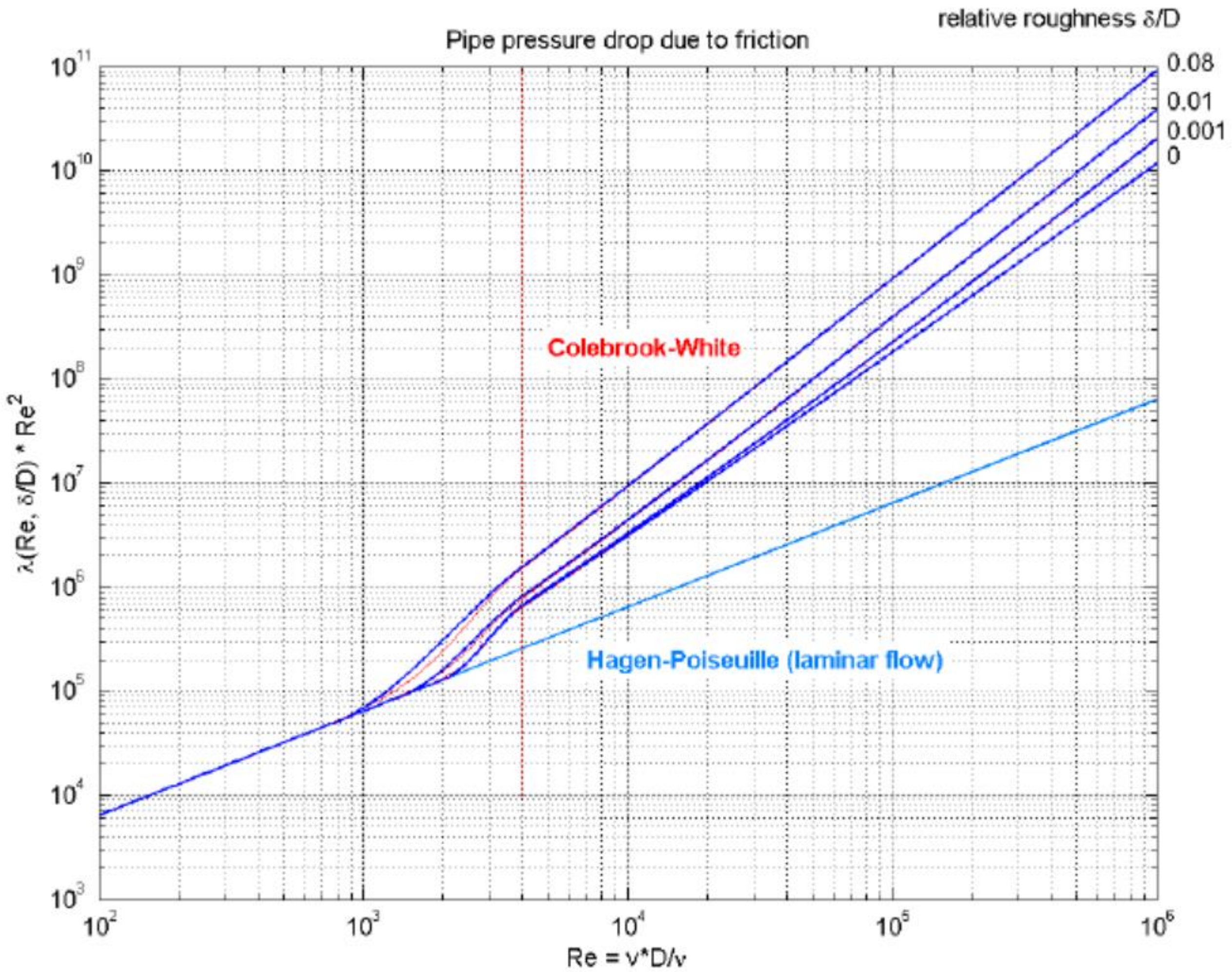


Figure 3.8 – Pipe Pressure Drop due to Friction

In the system we have Re ≥ 4000 so the flow is turbulent, and the following statement is used to evaluate the pressure drop in pipes:

if the pressure drop dp is assumed to be known, $\lambda_2 = |dp|/k_2$. The Colebrook-White equation:

$$1/\sqrt{\lambda} = -2 \cdot \log_{10}(2.51/(Re \cdot \sqrt{\lambda}) + 0.27 \cdot D)$$

gives an implicit relationship between Re and λ. Inserting $\lambda_2 = \lambda * Re^2$ allows to solve this equation analytically for Re:

$$Re = -2 \cdot \sqrt{\lambda_2} \cdot \log_{10}(2.51/\sqrt{\lambda_2} + 0.27 \cdot D)$$

Finally, the mass flow rate m_flow is computed from Re via $m\_flow = Re \cdot \pi \cdot D \cdot \mu/4 \cdot sign(dp)$.

If the mass flow rate is assumed known (and therefore implicitly also the Reynolds number), then λ_2 is computed by an approximation of the inverse of the Colebrook-White equation adapted to λ_2:

$$\lambda_2 = 0.25 \cdot (Re/\log_{10}(D/3.7 + 5.74/Re^{0.9}))^2$$

The pressure drop is then computed as $dp = k_2 \cdot \lambda_2 \cdot sign(m\_flow)$.

A pipe was added for each beam, with length equal to 12.8 m and diameter equal to 13.8e^{-3}m. The value proposed by OpenModelica for the roughness (2.5e^{-5} m) was adopted.

Two pipes for the modelling of branches (**A, B, C, E, F**) and sub-branches (**A_n, B_n, C_n, E_0**) were used, to which I assigned a length equal to the half of the length shown in Table 3.2. For example, Branch A has a length of 2 m, so two pipes of 1 m each were used.

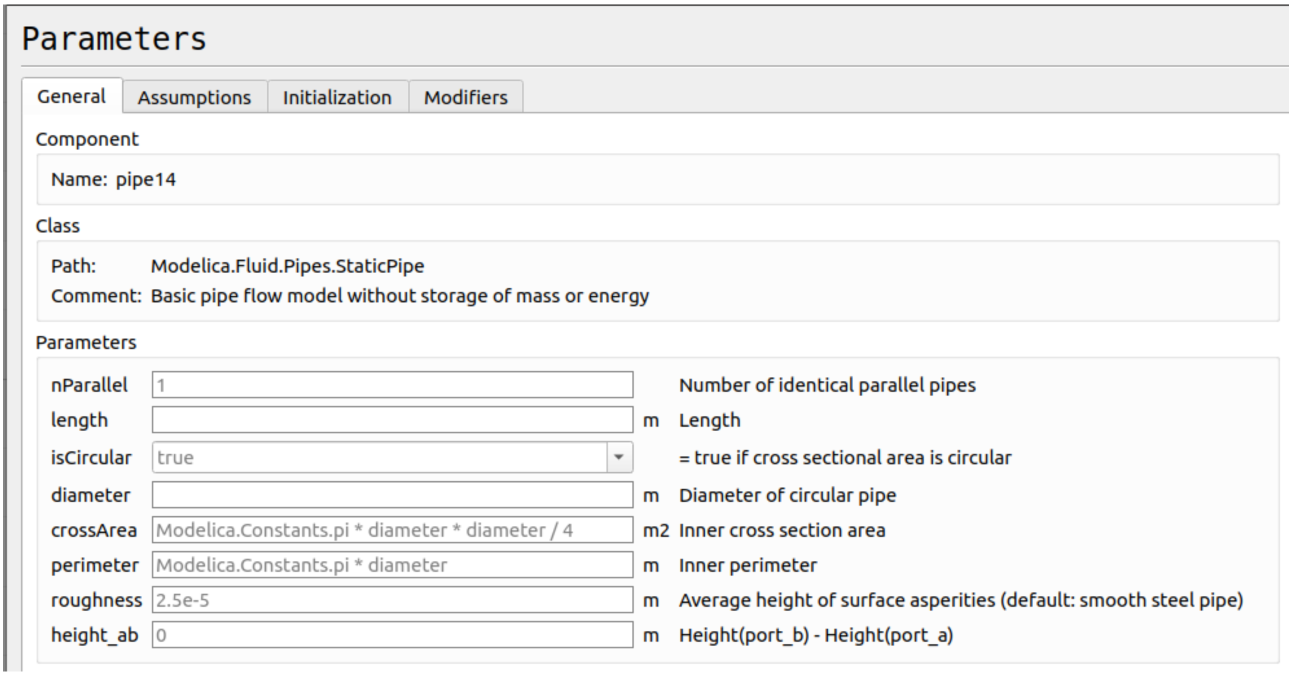


Figure 3.9 – Pipe Parameters

After the simulation it was possible to:

- verify if the flow crossed the pipe correctly, checking that the mass flow rate in port_a was equal to the one in port_b.
- calculate the pressure drop in the pipe, as the difference between the pressure in port_a, and the one in port_b.

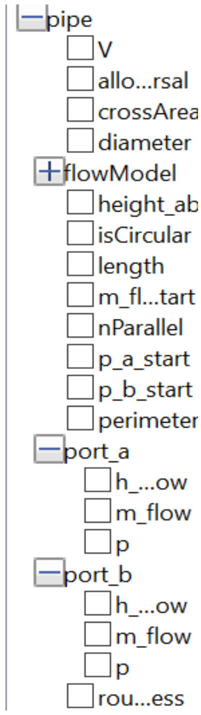


Figure 3.10 – Results for Pipes

- **Orifices**

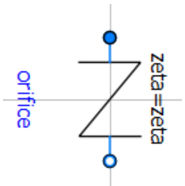


Figure 3.11 – Orifice

Orifices were used **a)** to model the components present in the system and **b)** as real orifices, because of their presence in each branch (as shown in Table 3.2). Regarding the components' modelling, given their pressure drop (as reported in Table 3.3), **1)** a nominal flow equal to the one that crossed a particular component in a specific branch and **2)** a nominal pressure drop equal to the one indicated in Table 3.3 were assigned to the orifice.

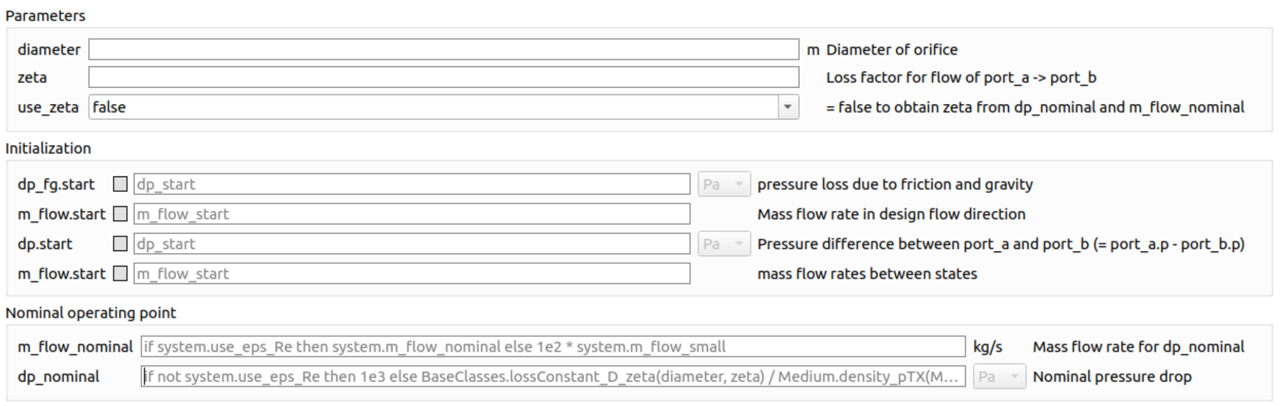


Figure 3.12 – Orifice Parameters

In general, depending on the location of the component, the mass flow of the branch or of the beam was used as m_flow_nominal (Table 3.2), and the pressure drop of the component (Table 3.3) as dp_nominal. Each time there was more than one component in a branch, a single orifice was added in the model with a nominal pressure drop equal to the sum of the pressure drops of the components. An orifice was adopted for the modelling of the pressure drop linked with the Mass Flow Rate meters of each sub-branch, giving a nominal loss equal to the half of the value represented in Table 3.3. Moreover, the values of the pressure drop shown in Table 3.4 were used for the modelling of the orifices.

For the evaluation of the orifice's pressure drop a generic diameter must be set, whereas the coefficient zeta was computed by the software from dp_nominal and m_flow_nominal; OpenModelica used the following equation for the estimation of the pressure drop in an orifice [10]:

$$\begin{aligned} dp &= 0.5 \cdot zeta \cdot \rho \cdot v \cdot |v| \\ &= 0.5 \cdot zeta \cdot \rho \cdot 1/(d \cdot A)^2 \cdot m\_flow \cdot |m\_flow| \\ &= 0.5 \cdot zeta/A^2 \cdot 1/\rho \cdot m\_flow \cdot |m\_flow| \\ &= k/\rho \cdot m\_flow \cdot |m\_flow| \end{aligned}$$

$$\begin{aligned} k &= 0.5 \cdot zeta/A^2 \\ &= 0.5 \cdot zeta/(pi \cdot (D/2)^2)^2 \\ &= 8 \cdot zeta/(pi \cdot D^2)^2 \end{aligned}$$

Equation 3.2 – Computation of the pressure drop in an orifice

where:

- Δp is the pressure drop: $\Delta p = port\_a.p - port\_b.p$
- D is the diameter of the orifice at the position where ζ is defined (either at port_a or port_b). If the orifice has not a circular cross section, $D = 4 \cdot A/P$, where A is the cross-section area and P is the wetted perimeter.

- ζ is the loss factor with respect to D that depends on the geometry of the orifice. In the turbulent flow regime, it is assumed that ζ is constant.
  For small mass flow rates, the flow is laminar and is approximated by a polynomial that has a finite derivative for m_flow=0.
- v is the mean velocity.
- ρ is the upstream density.

As for pipes, it was possible to verify if the flow crossed the orifice correctly and to evaluate the pressure drop in the orifice.

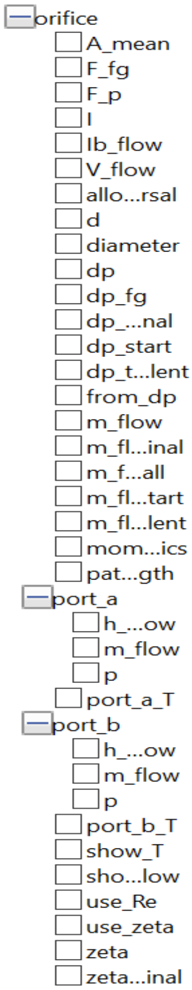


Figure 3.13 – Results for Orifices

Before starting the simulation, it must be checked if the number of variables was equal to the number of equations: this assessment was necessary in order to verify that each parameter was defined and that each component was properly collected.

3.4 Modelling of Branches

Before implementing the final model, each branch was designed separately, by using the pressure drop of the components as input data, and by checking among output data, in nominal conditions, that flows were distributed in a similar way (if not identical) to the desired ones.

- **Branch A**

For the modelling of Branch A, a Mass Flow Source was adopted, setting the flow equal to the value of the nominal one for the branch (2.376 kg/s). Branch A (as every other branch) ended with a Boundary, with ambient temperature and pressure. The same operations were repeated for Branch B and C, changing pipes' length, nominal flow of the branch and pressure drop linked with the orifice. The pipes circled in red represent the length of the branch, whereas the ones circled in yellow represent the length of the beam.

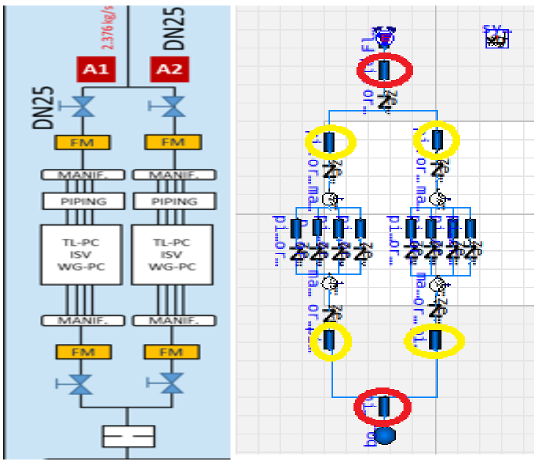


Figure 3.14 – Branch A

- **Branch B**

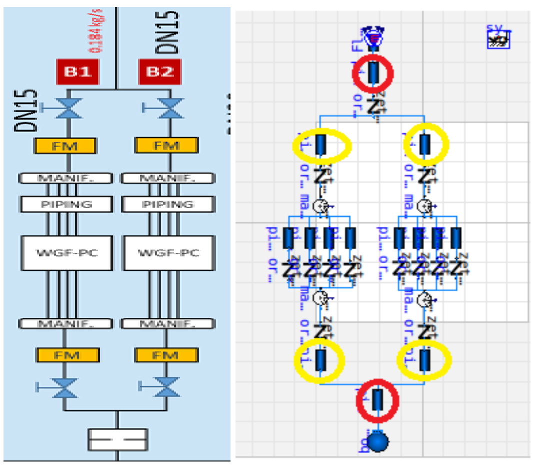


Figure 3.15 – Branch B

- **Branch C**

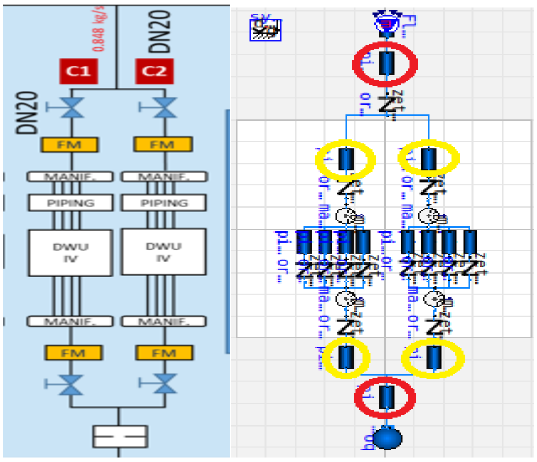


Figure 3.16 – Branch C

- **Branch D**

Branch D was considered like a black-box and was modelled with a single orifice, with a nominal pressure drop equal to the one of the TL-G component.

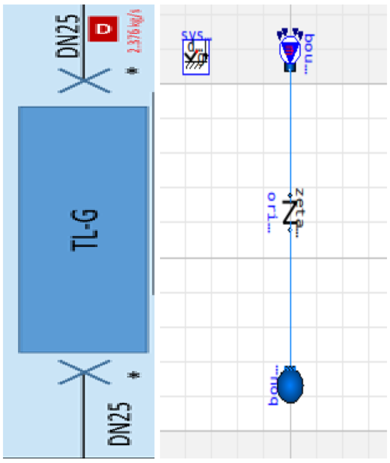


Figure 3.17 – Branch D

- **Branch E**

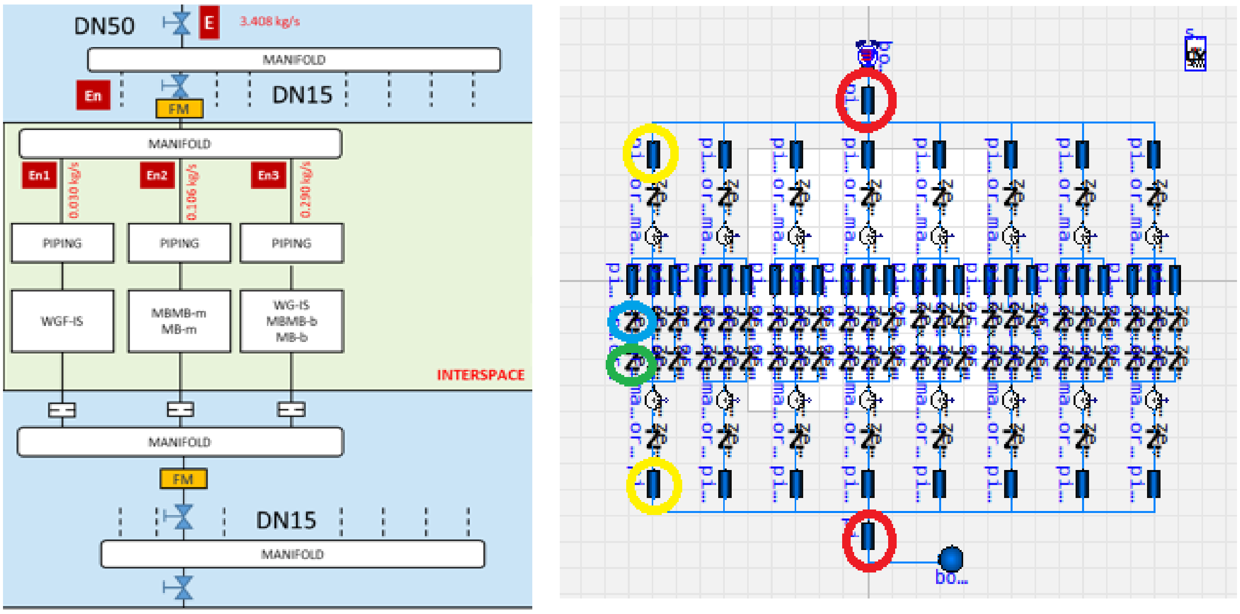


Figure 3.18 – Branch E

In the sub-branches E_n two orifices were added, one to model the component and one to model the orifice.

- **Branch F**

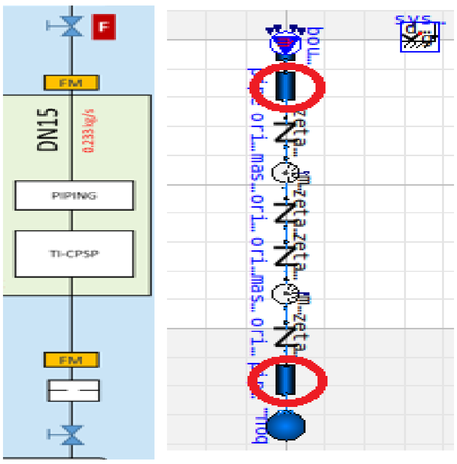


Figure 3.19 – Branch F

3.5 Implementation of the Model

Once all the data were added and after properly collecting all the components, it was possible to start the simulation. It was checked that, among output data, the pressure drops of the branches were equal to the value in Table 3.5, which represented the maximum pressure drop that the EVCS could have: these values represented the pressure drops each branch could have, considering that the different branches were in parallel.

LINE	ΔP [Pa]
Branch A	5,10E+05
Branch B	5,10E+05
Branch C	5,10E+05
Branch D	5,10E+05
Branch E	5,10E+05
Branch F	5,10E+05

Table 3.5 – Branch Pressure Drop

LINE	ΔP [Pa]
Branch A	5,1011406665968394E+05
Branch B	5,100022205811641E+05
Branch C	5,101266252591538E+05
Branch E	5,1011420132277475E+05
Branch F	5,1012510391823796E+05

Table 3.6 – Branch Pressure Drop after the simulation

Then the final model was built, creating a new one in which the models of each branch previously computed were copied.

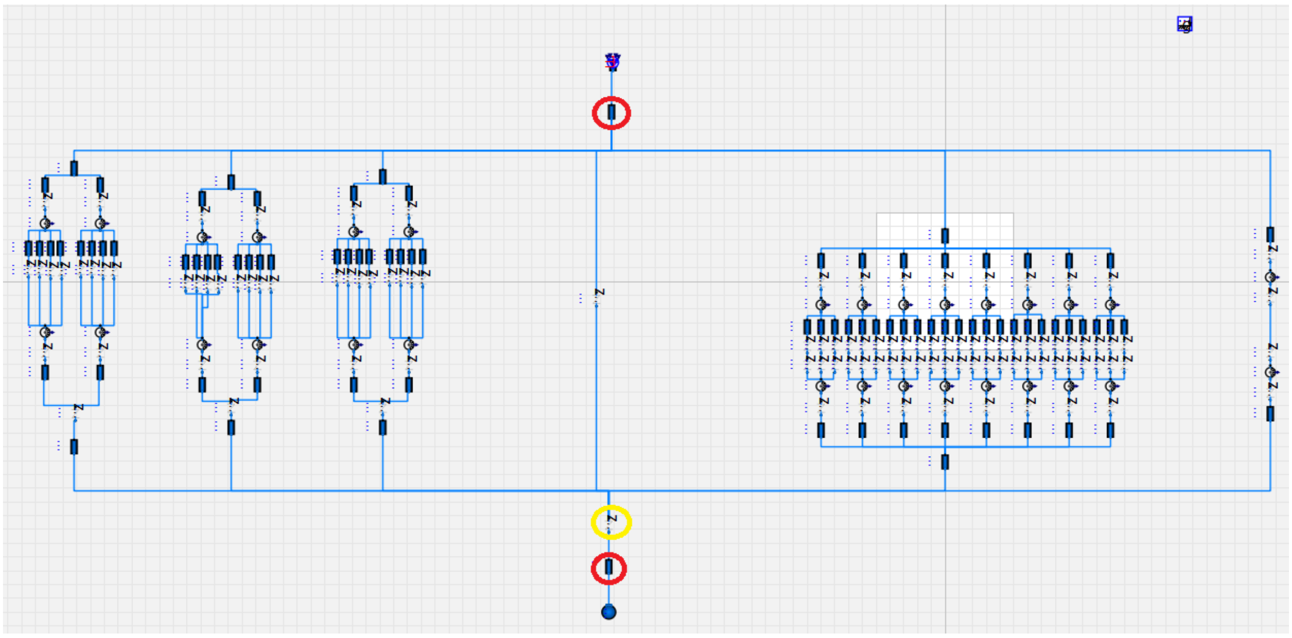


Figure 3.20 – Final Model

Inlet and outlet pipes were added in the final model: both with a length equal to the half of the value reported in Table 3.2. An orifice was also added, linked to the inlet-outlet line, with a pressure drop equal to the one in Table 3.4. Then it was evaluated that flows were correctly distributed among sub-branches, branches and beams, also monitoring that the pressure drops in them were comparable with the desired values represented in the following Table:

LINE	MFR [kg/s]	ΔP [Pa]
E_{n_1}	0,03	3,35E+05
E_{n_2}	0,106	3,35E+05
E_{n_3}	0,29	3,35E+05
Branch A_n losses	1,188	1,47E+05
Branch B_n losses	0,092	1,04E+05
Branch C_n losses	0,424	1,19E+05
N-th Beam A_n	0,297	1,44E+05
N-th Beam B_n	0,023	1,21E+05
N-th Beam C_n	0,106	2,91E+04

Table 3.7 – Mass Flow Rates and pressure drops

LINE	MFR [kg/s]	ΔP [Pa]
E_{n_1}	0,0299992819215291 8	3,353400358991654 E+05
E_{n_2}	0,1059961625000304	3,353400358991654 E+05
E_{n_3}	0,2899922339451395	3,353400358991654 E+05

Branch A_n losses	1,187964657359805	1,47088.66322448244 E+05
Branch B_n losses	0,09200747951639193	1,0432142446628353 E+05
Branch C_n losses	0,4239826544980565	1,1851540502448194 E+05
N-th Beam A_n	0,29699116433995125	1,4371174865476944E+05
N-th Beam B_n	0,0230018698790979825	1,2039538880781742 E+05
N-th Beam C_n	0,105995663624514125	2,910994252950151 E+04

Table 3.8 – Mass Flow Rates and pressure drops after the simulation

4 HYDRAULIC MODELLING OF EC UL EVCS WITH OBSTRUCTIONS

After the analysis of the system in nominal operating conditions, the study of the system in off-normal operating conditions was carried out, particularly in presence of obstructions. The aim was to check if the instrumentation system of the EC UL EVCS was able to detect, in case of an obstruction, if the mass flow rate in a certain component dropped below the minimum required value (which had to be higher than the uncertainty of the instrument). Each component has a minimum mass flow rate for safety purposes: this obviously resulted in a minimum mass flow rate for each branch.

4.1 Venturi Flowmeters

The flowmeters adopted in the EC UL EVCS design for detecting loss of cooling water were Venturi tubes. Venturi flowmeter belongs to the differential pressure devices family and "consists of a convergent inlet connected to a cylindrical throat which is in turn connected to a conical expanding section calling the divergent". Measuring the differential pressure Δp between the upstream section and the throat section, the volumetric flow rate q can be determined, given the value of the discharge coefficient C, depending on Venturi tube dimensions and manufacturing. The mass flow rate $\dot{m}$ calculation needs the conditions of the fluid at the inlet of the tube in terms of pressure p_1 and temperature T_1, in order to know the fluid density ρ_1.
The application requires Venturi tubes inserted in line having nominal size between DN15 and DN25. Such flow elements are provided with calibrated accuracy on the discharge coefficient between 0.25% and 0.5%. The accuracy from 0.5 to 0.63 was reached by considering that Venturi flowmeters measure volumetric flow rates which then need to be transformed in mass flow rates. At this point the inaccuracies due to pressure and temperature measurement must be considered. The accuracy of the device was set equal to 0.63%. Some devices present on the market are reported below with their technical characteristics:

BADGE METER – PRESO® - Venturi Flow Meter

Figure 4.1 – Badge Meter Preso® - Venturi Flow Meter

Applications:	Liquids, gases and steam
SSL – Classical (Herschel) Design / VISSL – Insert Version	
Pipe Sizes:	1/2…60 inches and larger (13…1524 mm)
Pressure & Temperature:	Varies, dependent upon materials of construction
Pressure Loss:	6% of DP maximum
Turndown Ratio:	10:1
Process Connections:	SSL; NPT, flanged, butt weld, socket weld, grooved VISSL; Insert fits between pair of flanges
Instrument Connections:	NPT, socket weld, flanged
Accuracy:	±1% of reading uncalibrated; ±0.5% of reading calibrated
Standard Beta Ratios:	0.35, 0.49, 0.63 and 0.75; Exact sizing available to provide custom beta ratios

Figure 4.2 – Badge Meter Preso® - Techincal Characteristics

ABB© – VTC - Venturi Tube

Figure 4.3 – ABB© - VTC – Venturi Tube

Accuracy

Calibrated within ±0.5% at design flowrate
Uncalibrated typically within ±1.5% at design flowrate

Pressure loss

5 to 12% of differential head, dependent on the beta ratio (throat/pipe diameter ratio)

Maximum working pressure

Dependent on the material selection and application

Maximum working temperature

Dependent on the material selection and application

Pipeline size range (standard)

25 to 1200mm (1 to 48 in.)
Fittings for larger pipelines are available to special order

Figure 4.4 – ABB© - VTC – Technical Characteristics

The accuracy of the instruments is ± 0.5% in both cases, with an accuracy of the Venturi adopted in the system of 0.63%, comparable with the values obtained in the model, as indicated in Table 4.13.

4.2 Obstructions Modelling

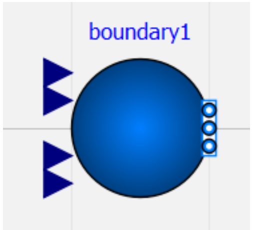


Figure 4.5 – Boundary with prescribed pressure

Mass flow sources and boundaries used in the previous simulation were replaced with two boundaries with prescribed pressure: one was placed at the input of the system, with a pressure of 9.5 bar and one was placed at the output of the system, with a pressure of 4 bar. In this way the model could be implemented working with a prescribed pressure drop for the system (equal to 5.5 bar, as shown in Figure 3.2), with mass flow rates redistributing through the various sections of the system (depending on where the obstruction was located).

An orifice was placed in each branch to model the obstruction within the system (as shown in the following Figures) with a pressure drop so that the minimum cooling mass flow rate was provided in the perturbed branch.

LINE	MFR_{MIN}
E_{n_1}	0,02
E_{n_2}	0,087
E_{n_3}	0,27
N-th Beam A	0,27
N-th Beam B	0,02
N-th Beam C	0,087
Branch F	0,2

Table 4.1 – Minimum Mass Flow Rate

Each branch was extended time by time to simplify the system, after checking the proper value of the pressure drop and of the mass flow rates of the total model. The other branches were modelled with an orifice, to which it was assigned a pressure drop equal to the one indicated in Table 3.5: this caused a small variation to the nominal mass flow rates of the system.

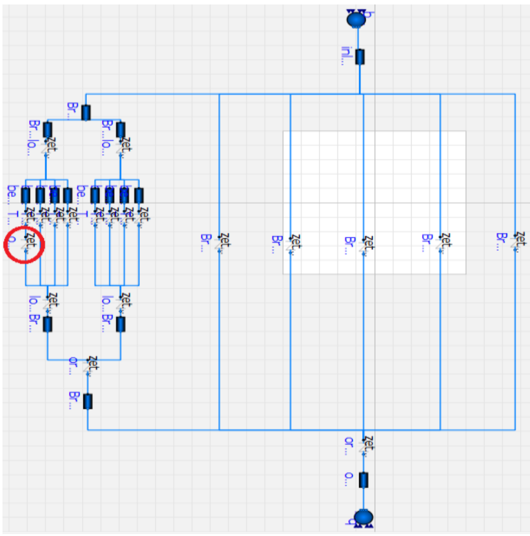


Figure 4.6 – Obstruction Branch A

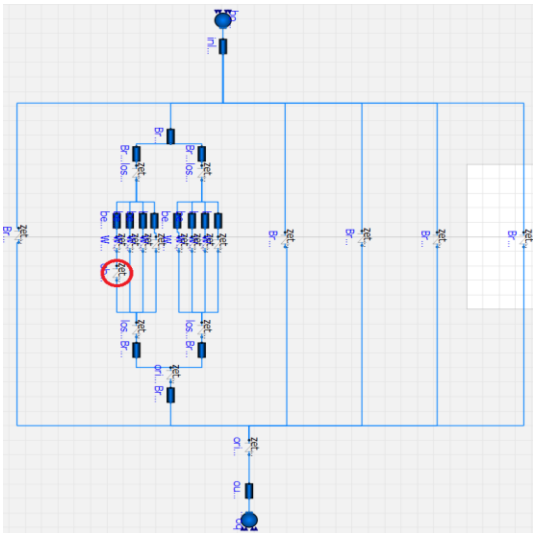


Figure 4.7 – Obstruction Branch B

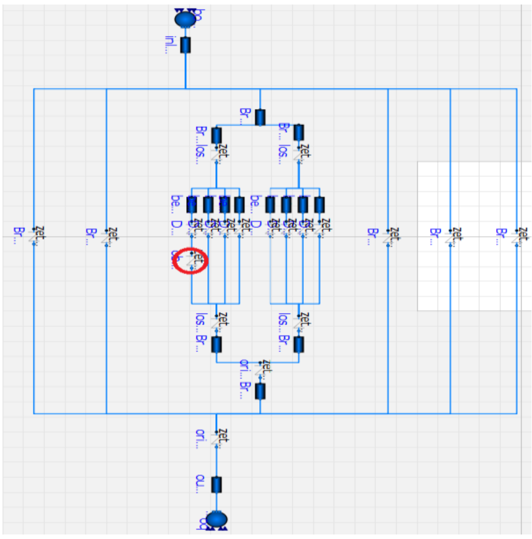


Figure 4.8 – Obstruction Branch C

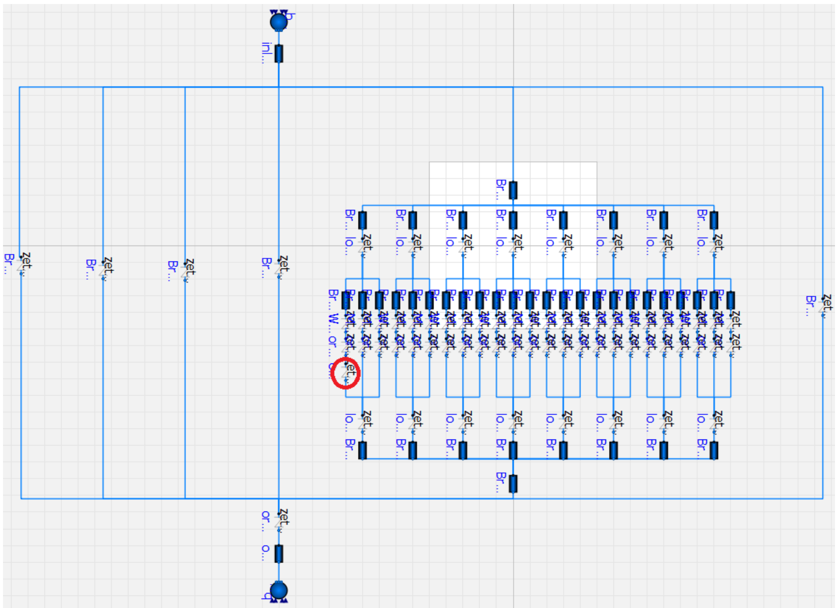


Figure 4.9 – Obstruction Branch E_1

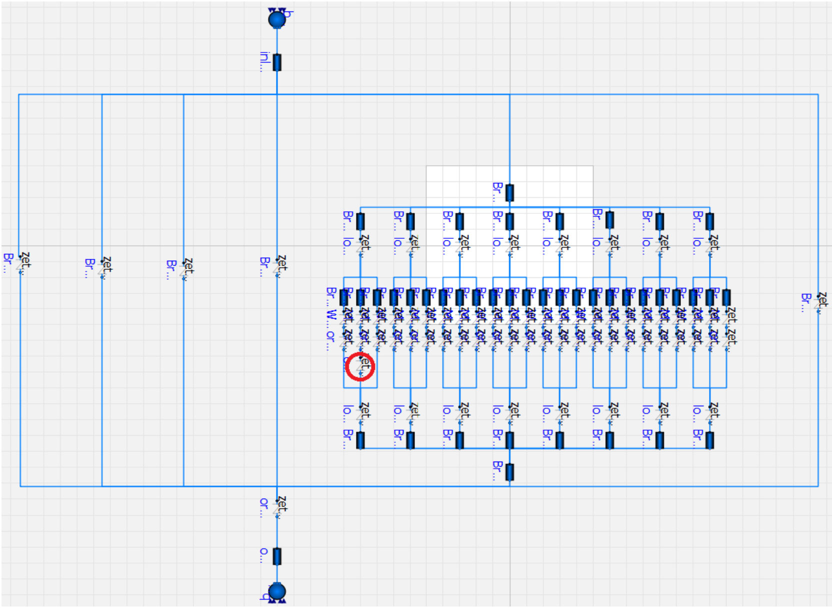


Figure 4.10 – Obstruction Branch E_2

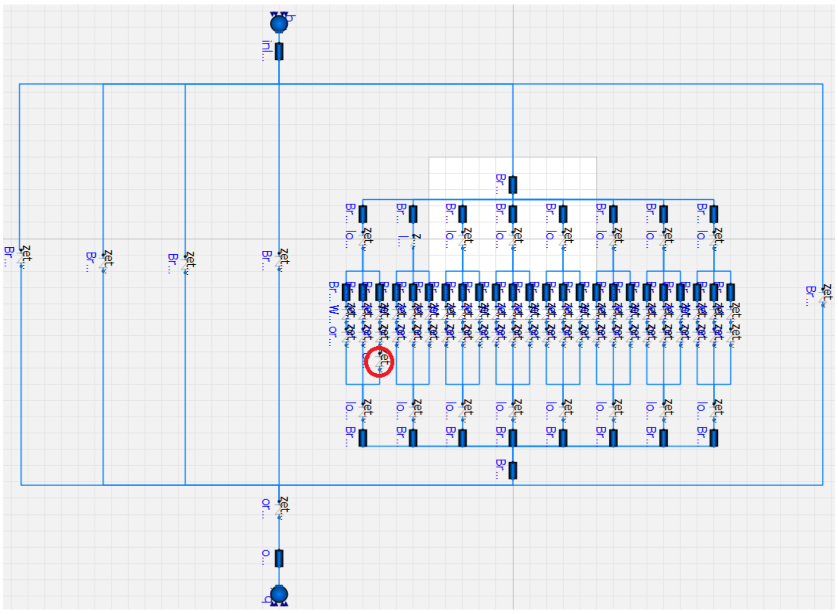


Figure 4.11 – Obstruction Branch E_3

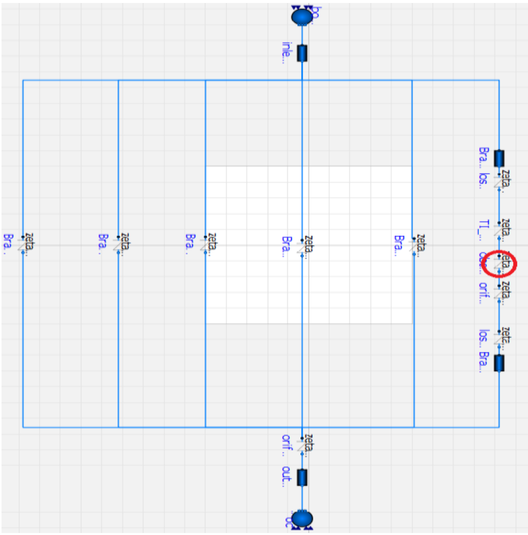


Figure 4.12 – Obstruction Branch F

The first point that needed to be checked was that in the perturbed beam the minimum mass flow rate was provided (as represented in Table 4.1), getting the following values:

LINE	MFR_{MIN}[kg/s]
E_{n_1}	0.020823
E_{n_2}	0.087460
E_{n_3}	0.271525
N-th Beam A	0.270476
N-th Beam B	0.020505
N-th Beam C	0.087047
Branch F	0,200343

Table 4.2 – Minimum Mass Flow Rate in the model

This assessment has been carried out through OMPython, creating a script in which the value of the pressure drop of the obstruction was iteratively increased until the minimum mass flow rate in the component was reached.

A Python class (Figure 4.13) was developed and it allowed to load and simulate the model, to change the value of the pressure drop to assign to the orifice (which represented the obstruction in the model), and to get the results.

```
# Definition of the class
class OpenModelicaSession:
```

```
    def __init__(self, omc):  # Initialize the class
        self.omc = omc
        self.currentModel = None

    def loadModel(self, modelPath, modelName):
        # Loading the model requires modelPath and modelName
        answ = self.omc.sendExpression(‘loadFile(“’+modelPath+’”)’)
        # loadfile requires a string “”
        self.currentModel = modelName

        return answ

    def setParam(self, component, value):
        # setting a parameters (watch the script on Jupyter)
        cmd = (‘setComponentModifierValue(‘ +
               self.currentModel+’,’ +
               component+’,’ +
               ‘$Code(=’+str(value)+’))’)
        answ = self.omc.sendExpression(cmd)

        return answ

    def simulateModel(self, modelName):
        # simulate the model requires modelName
        answ = self.omc.sendExpression(‘simulate(‘+modelName+’)’)
        # simulate doesn’t require strings so I use only ‘’

        return answ

    def getResults(self, parameter):
        # getting the results, indicating the parameter I’m interested in
        answ = self.omc.sendExpression(‘val(‘+parameter+’)’)
        # val doesn’t require strings so I use only ‘’

        return answ


omc = OMCSessionZMQ()  # creating a OMCSessionZMQ
```

Figure 4.13 – Class

The following script relates to the modelling of an obstruction in Branch A: the same script was used for other branches, changing model name and model path, the names of the components, m_flow_min's value (depending on the branch in which the obstruction was modelled) and the parameter in which the minimum mass flow rate had be reached.

```
# script

# Path of the model to simulate
modelPath = r'C:\Users\loren\Documents\OpenModelica\ModelAPert.mo'
# Model name of the model to simulate
modelName = 'ModelAPert'
# I want to change the value of this component
component = 'obstruction.dp_nominal'
# I want to check the value of this parameter
parameter = 'TL_PC_ISV_WG_PC_beam1_BranchA1.m_flow'

# Mass flow inlet system
mass_flow_system_inlet = 'inlet_system.port_a.m_flow'
# Mass flow outlet system
mass_flow_system_outlet = 'outlet_system.port_a.m_flow'
# Mass flow inlet Branch A
mass_flow_BranchA_inlet = 'BranchA_inlet.port_a.m_flow'
# Mass flow outlet Branch A
mass_flow_BranchA_outlet = 'BranchA_outlet.port_a.m_flow'
# Mass flow Branch B
mass_flow_BranchB = 'BranchB.m_flow'
# Mass flow Branch C
mass_flow_BranchC = 'BranchC.m_flow'
# Mass flow Branch D
mass_flow_BranchD = 'BranchD.m_flow'
# Mass flow Branch E
mass_flow_BranchE = 'BranchE.m_flow'
# Mass flow Branch F
mass_flow_BranchF = 'BranchF.m_flow'
# Mass flow rate meter inlet Branch A1
mass_flow_reader_inlet_A1 = 'loss_massFlowRate_inlet_BranchA1.m_flow'
# Mass flow rate meter outlet Branch A1
mass_flow_reader_outlet_A1 = 'loss_massFlowRate_outlet_BranchA1.m_flow'
# Mass flow rate meter outlet Branch A2
```

```
mass_flow_reader_inlet_A2 = 'loss_massFlowRate_inlet_BranchA2.m_flow'
# Mass flow rate meter outlet Branch A2
mass_flow_reader_outlet_A2 = 'loss_massFlowRate_outlet_BranchA2.m_flow'
# Mass flow Branch A1 beam 2
mass_flow_beam2_BranchA1 = 'beam2_BranchA1.port_a.m_flow'
# Mass flow Branch A2 beam 1
mass_flow_beam_A2 = 'beam1_BranchA2.port_a.m_flow'
# inlet pressure branch
inletPressureA1 = 'BranchA1_inlet.port_a.p'
# outlet pressure branch
outletPressureA1 = 'BranchA1_outlet.port_b.p'
# inlet pressure beam
inletPressureBeamA1 = 'beam1_BranchA1.port_a.p'
# outlet pressure beam
outletPressureBeamA1 = 'obstruction.port_b.p'
# inlet pressure loss
inletPressureLossA1 = 'BranchA1_inlet.port_a.p'
# outlet pressure loss
outletPressureLossA1 = 'loss_massFlowRate_inlet_BranchA1.port_b.p'
# nominal mass flow of the orifice modelling the obstruction
nominal_mass_flow_obstruction = 'obstruction.m_flow_nominal'


alpha = 0.1 # set as the initial k_increment
epsilon = 0.005 # definition of our tolerance
m_flow_min = 0.27
# this is the minimum mass flow rate for the component in the branch

new_dp = 0.1e5  # initial value for dp
perc_error = 100  # initial value for perc_error
old_error = 100  # initial value for old_error

# First run
session = OpenModelicaSession(omc)
session.loadModel(modelPath, modelName)
session.setParam(component, new_dp)
session.simulateModel(modelName)
# mass flow in the component
m_flow_beam = session.getResults(parameter)
perc_error = (m_flow_beam - m_flow_min)/m_flow_min
#  calculation of the first perc_error
```

```
i = 0
results = [] # list in which it is appended the result dictionary
while perc_error > epsilon:
    i = i+1
    print('iteration :'+ str(i)) # to see in which iteration it is

    # decrement K*
    K_old = 2*new_dp/(session.getResults(nominal_mass_flow_obstruction))**2
    new_K = (1+alpha)*K_old
    # adjournment of the obstruction's pressure drop
    new_dp = new_K*(session.getResults(nominal_mass_flow_obstruction))**2/2

# I adjourn everytime the value of new_dp, of m_flow_beam, of old_error and of perc_error

    # adjourned run
    session.setParam(component, new_dp)
    session.simulateModel(modelName)
    m_flow_beam = session.getResults(parameter)
    old_error = perc_error
    perc_error = (m_flow_beam - m_flow_min)/m_flow_min

# creation of a dictionary with the results and from which I can make a plot
    result = {'New Dp': new_dp, 'Mass Flow Rate component': m_flow_beam,
                    'Mass Flow Rate Inlet system': session.getResults(mass_flow_system_inlet),
                    'Mass Flow Rate Outlet system': session.getResults(mass_flow_system_outlet),
                    'Branch A Inlet': session.getResults(mass_flow_BranchA_inlet),
                    'Branch A Outlet': session.getResults(mass_flow_BranchA_outlet),
                    'Branch B': session.getResults(mass_flow_BranchB),
                    'Branch C': session.getResults(mass_flow_BranchC),
                    'Branch D': session.getResults(mass_flow_BranchD),
                    'Branch E': session.getResults(mass_flow_BranchE),
                    'Branch F': session.getResults(mass_flow_BranchF),
                    'Mass Flow Rate FlowMeter inlet BranchA1': session.getResults(mass_flow_reader_inlet_A1),
```

```
                    'Mass Flow Rate FlowMeter outlet BranchA1': session.getResults(mass_flow_reader_outlet_A1),
                     'Mass Flow Rate FlowMeter inlet BranchA2': session.getResults(mass_flow_reader_inlet_A2),
                     'Mass Flow Rate FlowMeter outlet BranchA2': session.getResults(mass_flow_reader_outlet_A2),
                     'Mass Flow Rate beam2 BranchA1': session.getResults(mass_flow_beam2_BranchA1),
                     'Mass Flow Rate beam1 BranchA2': session.getResults(mass_flow_beam_A2),
                     'Total Branch A1 pressure drop': session.getResults(inletPressureA1)-session.getResults(outletPressureA1),
                    'Pressure drop beam Branch A1': session.getResults(inletPressureBeamA1)-session.getResults(outletPressureBeamA1),
                    'Branch A1 pressure losses': (session.getResults(inletPressureLossA1)-session.getResults(outletPressureLossA1))*2}
        results.append(result) # append the result dictionary to the results list

        if perc_error*old_error < 0:
            'Difference has changed sign'
            break


    print("\n")
    print("obstruction dp:", new_dp)
    print("\n")
    print("Mass Flow Rate component:", m_flow_beam)
    print("\n")
    print("Inlet system:", session.getResults(mass_flow_system_inlet))
    print("\n")
    print("Outlet system:", session.getResults(mass_flow_system_outlet))
    print("\n")
    print("Branch A inlet:", session.getResults(mass_flow_BranchA_inlet))
    print("\n")
    print("Branch A outlet:", session.getResults(mass_flow_BranchA_outlet))
    print("\n")
    print("Branch B:", session.getResults(mass_flow_BranchB))
    print("\n")
    print("Branch C:", session.getResults(mass_flow_BranchC))
    print("\n")
```

```
    print("Branch D:", session.getResults(mass_flow_BranchD))
    print("\n")
    print("Branch E:", session.getResults(mass_flow_BranchE))
    print("\n")
    print("Branch F:", session.getResults(mass_flow_BranchF))
    print("\n")
    print("Mass Flow Rate Meter Branch A1 inlet:", session.getResults(mass_flow_reader_inlet_A1))
    print("\n")
    print("Mass Flow Rate Meter Branch A1 outlet:", session.getResults(mass_flow_reader_outlet_A1))
    print("\n")
    print("Mass Flow Rate Meter Branch A2 inlet:", session.getResults(mass_flow_reader_inlet_A2))
    print("\n")
    print("Mass Flow Rate Meter Branch A2 outlet:", session.getResults(mass_flow_reader_outlet_A2))
    print("\n")
    print("Mass Flow Rate beam2 BranchA1:", session.getResults(mass_flow_beam2_BranchA1))
    print("\n")
    print("Branch A2 beam1:", session.getResults(mass_flow_beam_A2))
    print("\n")
    print("Total Branch A1 pressure drop:", session.getResults(inletPressureA1)-session.getResults(outletPressureA1))
    print("\n")
    print("Pressure drop beam Branch A1:", session.getResults(inletPressureBeamA1)-session.getResults(outletPressureBeamA1))
    print("\n")
    print("Branch A1 pressure losses:", (session.getResults(inletPressureLossA1)-session.getResults(outletPressureLossA1))*2)
    print("\n")
```

Script 4.1 – Obstruction Branch A

4.3 Outcomes

- Branch A

  - dp providing the minimum mass flow rate in the component = 34522.712144 [Pa]

	Obstruction BranchA			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch A1	1,175898	-0,012102	1,019%	✓
FlowMeter outlet Branch A1	1,175898	-0,012102	1,019%	✓
FlowMeter inlet Branch A2	1,191466	0,003466	0,292%	×
FlowMeter outlet Branch A2	1,191466	0,003466	0,292%	×
Mass Flow Rate FlowMeter inlet nominal = 1.188 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 1.188 [kg/s]				

Figure 4.14 – Detection Branch A perturbed

- Branch B

  - dp providing the minimum mass flow rate in the component = 37129.30 [Pa]

	Obstruction Branch B			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch B1	0,090862	-0,001138	1,237%	✓
FlowMeter outlet Branch B1	0,090862	-0,001138	1,237%	✓
FlowMeter inlet Branch B2	0,092457	0,000457	0,497%	×
FlowMeter outlet Branch B2	0,092457	0,000457	0,497%	×
Mass Flow Rate FlowMeter inlet nominal = 0,092 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,092 [kg/s]				

Figure 4.15 – Detection Branch B perturbed

- Branch C

  - dp providing the minimum mass flow rate in the component = 18061.112347 [Pa]

	Obstruction Branch C			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch C1	0,420891	-0,003109	0,733%	✓
FlowMeter outlet Branch C1	0,420891	-0,003109	0,733%	✓
FlowMeter inlet Branch C2	0,425727	0,001727	0,407%	×
FlowMeter outlet Branch C2	0,425727	0,001727	0,407%	×
Mass Flow Rate FlowMeter inlet nominal = 0,424 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,424 [kg/s]				

Figure 4.16 – Detection Branch C perturbed

- Branch E1

  - dp providing the minimum mass flow rate in the component = 371293.0 [Pa]

	Obstruction Branch E1			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,419772	-0,006228	1,462%	✓
FlowMeter outlet Branch E0 beam 1	0,419772	-0,006228	1,462%	✓
FlowMeter inlet Branch E0 beam 2	0,426026	0,000026	0,006%	×
FlowMeter outlet Branch E0 beam 2	0,426026	0,000026	0,006%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				

Figure 4.17 – Detection Branch E1 perturbed

- Branch E2

  - dp providing the minimum mass flow rate in the component = 172613.560720 [Pa]

	Obstruction Branch E2			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,412545	-0,013455	3,158%	✓
FlowMeter outlet Branch E0 beam 1	0,412545	-0,013455	3,158%	✓
FlowMeter inlet Branch E0 beam 2	0,426051	0,000051	0,0120%	×
FlowMeter outlet Branch E0 beam 2	0,426051	0,000051	0,0120%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				

Figure 4.18 – Detection Branch E2 perturbed

- Branch E3

  - dp providing the minimum mass flow rate in the component = 61159.090448 [Pa]

	Obstruction Branch E3			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,410057	-0,015943	3,742%	✓
FlowMeter outlet Branch E0 beam 1	0,410057	-0,015943	3,742%	✓
FlowMeter inlet Branch E0 beam 2	0,426060	0,00006	0,0140%	×
FlowMeter outlet Branch E0 beam 2	0,426060	0,00006	0,0140%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				

Figure 4.19 – Detection Branch E3 perturbed

- Branch F

  - dp providing the minimum mass flow rate in the component = 179000 [Pa]

	Obstruction Branch F			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch F	0,200343	-0,032657	14,016%	✓
FlowMeter outlet Branch F	0,200343	-0,032657	14,016%	✓
Mass Flow Rate FlowMeter inlet nominal = 0,233 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,233 [kg/s]				

Figure 4.20 – Detection Branch F perturbed

4.4 Comparison Excel/OpenModelica

In the Excel file implemented by NIER, to define the obstruction (so the pressure drop) **a)** a K_{eq} in nominal conditions is computed (Equation 4.4.1) and **b)** a K^* normalised is computed for each branch (Equation 4.4.2), as shown in Table 4.3.

$$K_{eq} = \frac{2 * \rho * A_{ref} * \Delta p}{\dot{m}^2}$$

Equation 4.1 – Computation of K_{eq}

$$K_{eq} = \frac{K}{\rho * A^2}$$

Equation 4.2 – Computation of K^*

A Multiplier is then searched, which is the value that if it is multiplied for Nominal K^* gives a perturbed value of K^* (Pert. K^*), providing a mass flow rate at least equal to the minimum one in the perturbed beam. These Multipliers are reported in the column MF of the following Table: in the Excel file an iterative process is carried out to define them.

Input sensitivity					
Sub Branch	**Nominal K***	**Multiplier**	**Pert. K***	**MF**	**min MFR**
En_1	7,45E+08	1	7,45E+08	2,28	0,02
En_2	5,97E+07	1	5,97E+07	1,533	0,087
En_3	7,98E+06	1	7,98E+06	1,2	0,27
N-th Beam A	3,26E+06	1	3,26E+06	1,25	0,27
N-th Beam B	4,56E+08	1	4,56E+08	1,385	0,02
N-th Beam C	5,18E+06	1	5,18E+06	1,635	0,087
Branch F	1,88E+07	1	1,88E+07	1,35	0,2

Table 4.3 – Input Sensitivity

On the other hand, an orifice was put to model the obstruction in OpenModelica: given **a)** the nominal mass flow rate that crosses the beam and **b)** the K^* to apply (Pert K^* - Nominal K^*): the pressure drop to assign to the orifice that provides the minimum mass flow rate could be evaluated by using the following Equation:

$$\Delta p = \frac{1}{2} K^* * m^2$$

Equation 4.3 – Computation of the pressure drop

4.5 Final Checks

Once assessed that the minimum mass flow rate was provided with the introduction of the obstruction, it was checked that the pressure drops and the mass flow rates of the branches and of the perturbed beams were equal to the values indicated in the Tables below:

LINE	$MFR_{nominal}$ [kg/s]	ΔP [Pa]
Total A_n perturbed	1,175628012	2,93E+05
Total B_n perturbed	0,090621315	2,27E+05
Total C_n perturbed	0,420849648	1,49E+05
Perturbed A_n losses	1,175628012	1,44E+05
Perturbed B_n losses	0,090621315	1,01E+05
Perturbed C_n losses	0,420849648	1,17E+05
N-th Beam A	0,301874436	1,48E+05
N-th Beam B	0,023	1,21E+05
N-th Beam C	0,106	0,291E+05

Table 4.4 – Perturbed Pressure Drop and Perturbed Mass Flow Rates

LINE	$MFR_{nominal}$ [kg/s]	ΔP [Pa]
Total A_n perturbed	1,175753137201689	2,925027245872653 E+05
Total B_n perturbed	0,09078344113719934	2,270342921751415E+05
Total C_n perturbed	0,4209096736933117	1,488295366321616 E+05
Perturbed A_n losses	1,175753137201689	1,4413696727953712E+05
Perturbed B_n losses	0,09078344113719934	1,0157671925206482 E+05
Perturbed C_n losses	0,4209096736933117	1,1682468343232688E+05
N-th Beam A	0,3018645297964206	1,4836575730772805 E+05
N-th Beam B	0,02312031749888197	1,2545757292307657 E+05
N-th Beam C	0,1064335409296618	0,3200485319983482 E+05

Table 4.5 – Perturbed Pressure Drop and Perturbed Mass Flow Rates of the model

The same controls were carried out for branch E, perturbing a sub-branch at a time:

LINE	$MFR_{nominal}$ [kg/s]	ΔP [Pa]
E_{n_1}	0,03	3,35E+05
E_{n_2}	0,106	3,35E+05
E_{n_3}	0,29	3,35E+05
Perturbed E_{n_1}	0,020030532	3,41E+05
Perturbed E_{n_2}	0,106867222	3,41E+05
Perturbed E_{n_3}	0,29237259	3,41E+05

Table 4.6 – Perturbed Pressure Drop and Perturbed Mass Flow Rates, Branch E_{n_1}

LINE	$MFR_{nominal}$ [kg/s]	ΔP [Pa]
E_{n_1}	0,02999928192152918	3,353400358991654 E+05
E_{n_2}	0,1059961625000304	3,353400358991654 E+05
E_{n_3}	0,2899922339451395	3,353400358991654 E+05
Perturbed E_{n_1}	0,02002601373341007	3,4117603678212326E+05
Perturbed E_{n_2}	0,1069164706402815	3,4117603678212326E+05
Perturbed E_{n_3}	0,2925269008071824	3,4117603678212326E+05

Table 4.7 – Perturbed Pressure Drop and Perturbed Mass Flow Rates of the model, Branch E_{n_1}

LINE	$MFR_{nominal}$ [kg/s]	ΔP [Pa]
E_{n_1}	0,03	3,35E+05
E_{n_2}	0,106	3,35E+05

E_{n_3}	0,29	3,35E+05
Perturbed E_{n_1}	0,030493904	3,46E+05
Perturbed E_{n_2}	0,0870215	3,46E+05
Perturbed E_{n_3}	0,294774407	3,46E+05

Table 4.8 – Perturbed Pressure Drop and Perturbed Mass Flow Rates, Branch E_{n_2}

LINE	**$MFR_{nominal}$ [kg/s]**	**ΔP [Pa]**
E_{n_1}	0,02999928192152918	3,353400358991654E+05
E_{n_2}	0,1059961625000304	3,353400358991654E+05
E_{n_3}	0,2899922339451395	3,353400358991654E+05
Perturbed E_{n_1}	0,03052503099772613	3,4719707005943626E+05
Perturbed E_{n_2}	0,08706315735643298	3,4719707005943626E+05
Perturbed E_{n_3}	0,295119381354908	3,4719707005943626E+05

Table 4.9 – Perturbed Pressure Drop and Perturbed Mass Flow Rates of the model, Branch E_{n_2}

LINE	**$MFR_{nominal}$ [kg/s]**	**ΔP [Pa]**
E_{n_1}	0,03	3,35E+05
E_{n_2}	0,106	3,35E+05
E_{n_3}	0,29	3,35E+05
Perturbed E_{n_1}	0,030612064	3,49E+05
Perturbed E_{n_2}	0,108162627	3,49E+05
Perturbed E_{n_3}	0,270133681	3,49E+05

Table 4.10 – Perturbed Pressure Drop and Perturbed Mass Flow Rates, Branch E_{n_3}

LINE	**$MFR_{nominal}$ [kg/s]**	**ΔP [Pa]**
E_{n_1}	0,02999928192152918	3,353400358991654 E+05
E_{n_2}	0,1059961625000304	3,353400358991654 E+05
E_{n_3}	0,2899922339451395	3,353400358991654 E+05
Perturbed E_{n_1}	0,03063722904790152	3,497539505559582E+05
Perturbed E_{n_2}	0,10825500784211	3,497539505559582E+05
Perturbed E_{n_3}	0,2709157874304511	3,497539505559582E+05

Table 4.11 – Perturbed Pressure Drop and Perturbed Mass Flow Rates of the model, Branch E_{n_3}

The following figures illustrate the development of mass flow rates in different branches' components, compared to the pressure drops of the orifices which represent the obstruction.

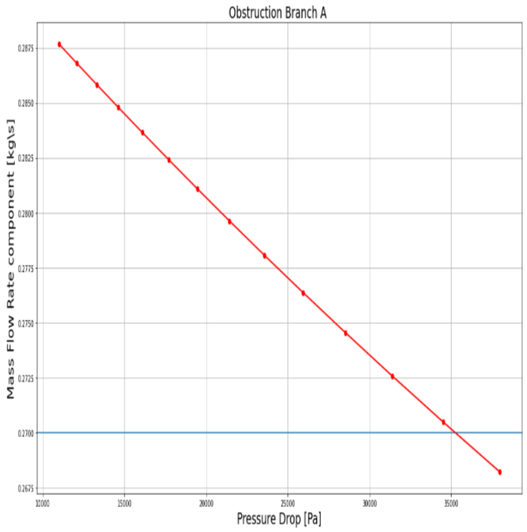


Figure 4.22 – Obstruction Branch A, plot

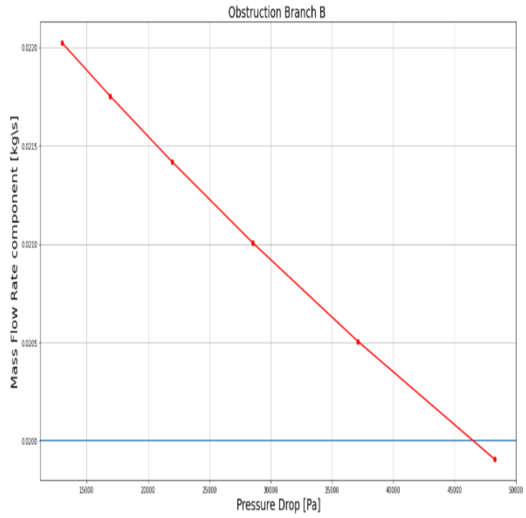


Figure 4.21 – Obstruction Branch B, plot

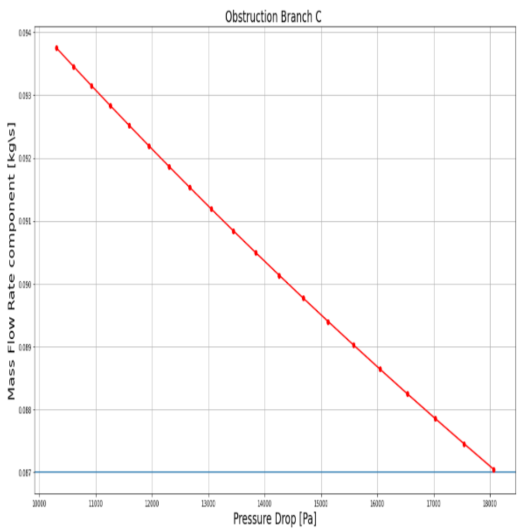


Figure 4.24 – Obstruction Branch C, plot

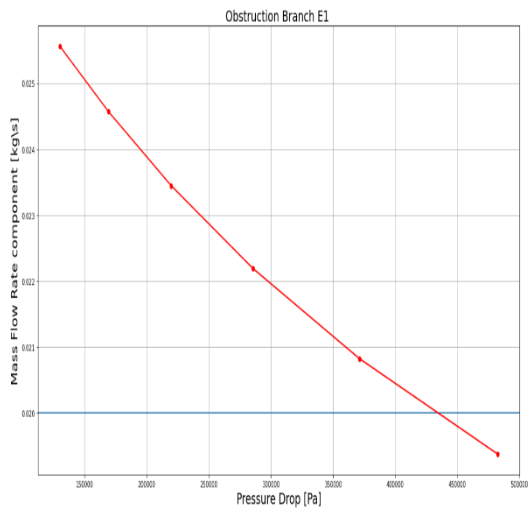


Figure 4.23 – Obstruction Branch E1, plot

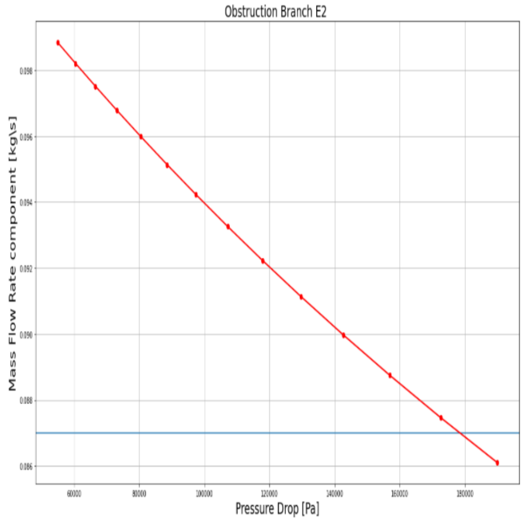


Figure 4.26 – Obstruction Branch E2, plot

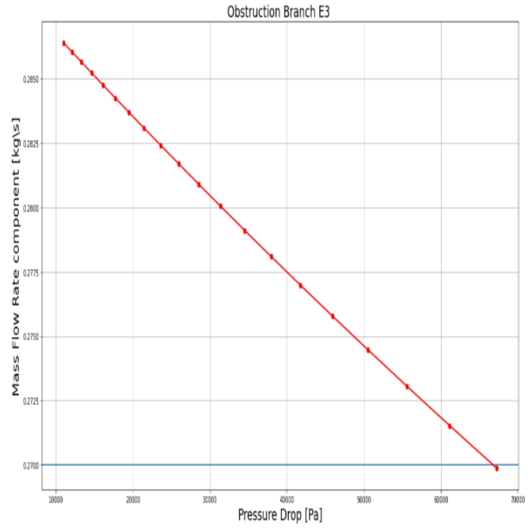


Figure 4.25 – Obstruction Branch E3, plot

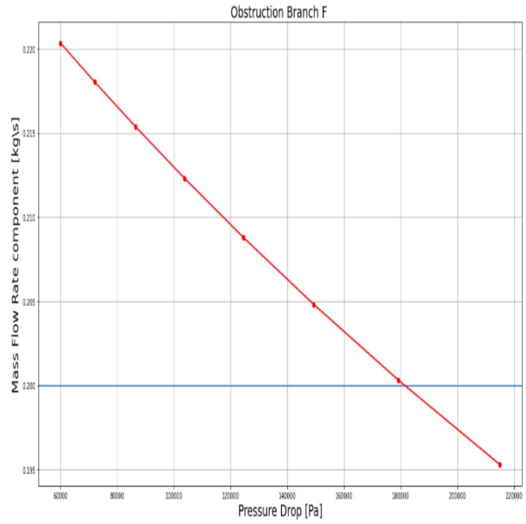


Figure 4.27 – Obstruction Branch F, plot

As shown in the plots, by increasing the pressure drop assigned to the orifice, the mass flow rate in the component decreases until it drops below the minimum one (blue line).
Finally, it was proved that the percentages differences between the nominal mass flow rates in the branches and the mass flow rates in the perturbed ones were comparable with the percentages differences evaluated in the Excel file implemented by NIER [3]:

Flowmeter (FM) Location	Obstruction Location	Components	FM nominal MFR [kg/s]	FM perturbed MFR [kg/s]	FM ΔMFR [kg/s]	FM ΔMFR [%]
Sub branches A_1-A_2	**$A_{n\text{-}y}$ (n=1,2) (y=1,…, 4)**	TL-PC, ISV, WG-PC	1,188	1,175628012	1,237E-02	**1.04%**
Sub branches B_1-B_2	**$B_{n\text{-}y}$ (n=1,2) (y=1,…, 4)**	WGF-PC	0,092	0,090621315	1,3786E-03	**1.49%**
Sub branches C_1-C_2	**$C_{n\text{-}y}$ (n=1,2) (y=1,…, 4)**	DWU, IV	0,424	0,420849648	3,15E-03	**0.743%**
Beam E_n (n=1,…,8)	**E_{n_1}**	WGF-IS	0,426	0,419270344	6,729E-03	**1.579%**
Beam E_n (n=1,…,8)	**E_{n_2}**	MBMB-m, MB-m	0,426	0,412289811	1,37E-02	**3.218%**
Beam E_n (n=1,…,8)	**E_{n_3}**	WG-IS, MBMB-b, MB-b	0,426	0,408908372	1,709E-02	**4.01%**
Branch F	**Branch F**	TI-CPSP	0,233	0,200584478	3,24E-02	**13.91%**

Table 4.12 – FM ΔMFR [%]

Flowmeter (FM) Location	Obstruction Location	Components	FM nominal MFR [kg/s]	FM perturbed MFR [kg/s]	FM ΔMFR [kg/s]	FM ΔMFR [%]
Sub branches A_1-A_2	**$A_{n\text{-}y}$ (n=1,2) (y=1,…, 4)**	TL-PC, ISV, WG-PC	1, 1879646	1,175898	0,010157	**1.015%**
Sub branches B_1-B_2	**$B_{n\text{-}y}$ (n=1,2) (y=1,…, 4)**	WGF-PC	0, 0920074	0,090862	0,0011454	**1.245%**
Sub branches C_1-C_2	**$C_{n\text{-}y}$ (n=1,2) (y=1,…, 4)**	DWU, IV	0, 4239826	0,420891	3,0916E-03	**0.729%**
Beam E_n (n=1,…,8)	**E_{n_1}**	WGF-IS	0, 4259876	0,419772	6,2156E-03	**1.459%**

Beam E_n (n=1,…,8)	**E_{n_2}**	MBMB-m, MB-m	0, 4259876	0,412545	1,344E-02	**3.155%**
Beam E_n (n=1,…,8)	**E_{n_3}**	WG-IS, MBMB-b, MB-b	0, 4259876	0,410057	1,593E-02	**3.739%**
Branch F	**Branch F**	TI-CPSP	0, 2329907	0,200343	3,264E-02	**14,01%**

Table 4.13 – FM ΔMFR [%] model

The loss of mass flow rate in the flowmeters (difference between **FM nominal MFR** and **FM perturbed MFR**) is always higher than the acceptable variation, detectable by the Venturi (equal to 0.63%) as shown in Table 4.13.

5 HYDRAULIC MODELLING OF EC UL EVCS WITH LEAKAGES

The leakages would cause a redistribution of flow rates through the various sections of the circuit. Therefore, one or more cooled components could be affected by a loss of cooling, for instance the minimum mass flow rate could not be reached.

The model on OpenModelica has been refined: compared to the one for the obstructions, components were added separately, each one with its own pressure drop. Moreover, in beams affected by a leak, several pipes were added to split the components. The mass flow sources in the model have been replaced with boundaries with prescribed pressure (as for the obstruction modelling). Two different scenarios were considered: small breaks and double ended guillotine. This analysis was carried out in a single beam for each branch. For each scenario, three different locations for the leaks were considered in a beam: start, middle and end.

The objectives of this analysis were to:

- assess that the minimum mass flow rates were provided in the components;
- assess that the instruments of the system could detect the loss of coolant;
- validate the data shown in the EVCS hydraulic model report [1];

5.1 Small Breaks

For modelling small breaks, the beam affected by loss of coolant was collected to an orifice, connected in turn to ambient: a model for each location of the leak was created. For the leakage at the end of the beam, regardless of the pressure drop assigned to the orifice, the minimum mass flow rate in components parallel to the affected beam was provided.

The following figures show the models implemented with OpenModelica:

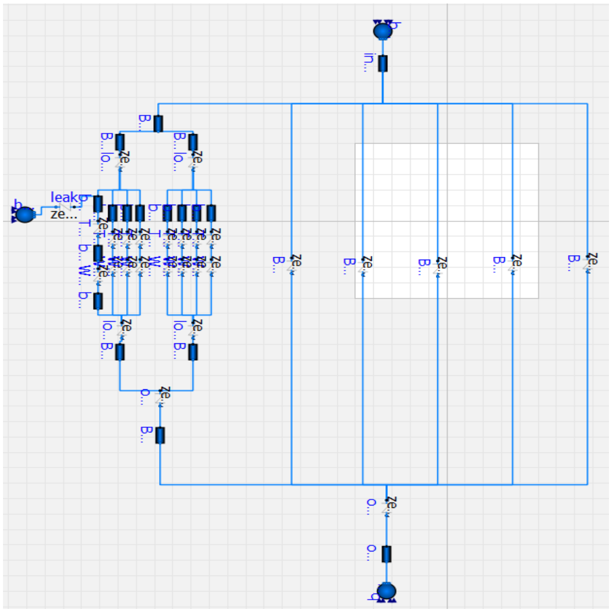


Figure 5.1 – Branch A Leak start

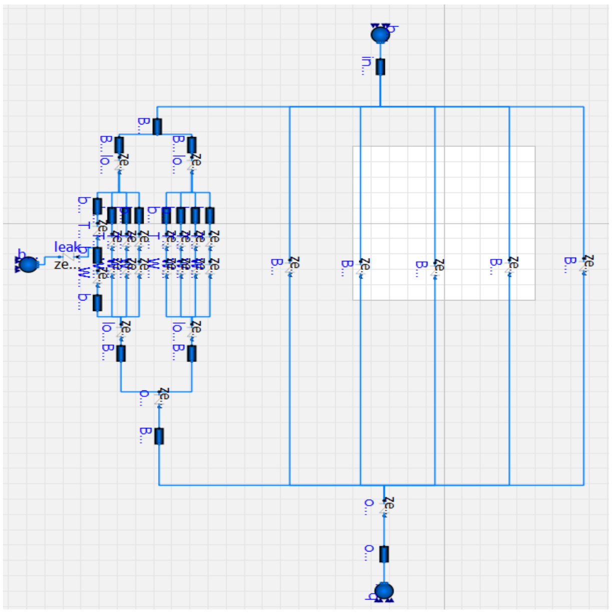


Figure 5.2 – Branch A Leak middle

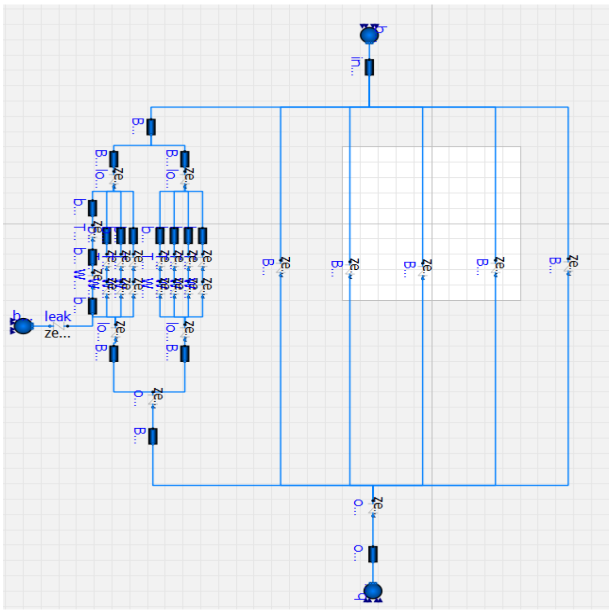


Figure 5.3 – Branch A Leak end

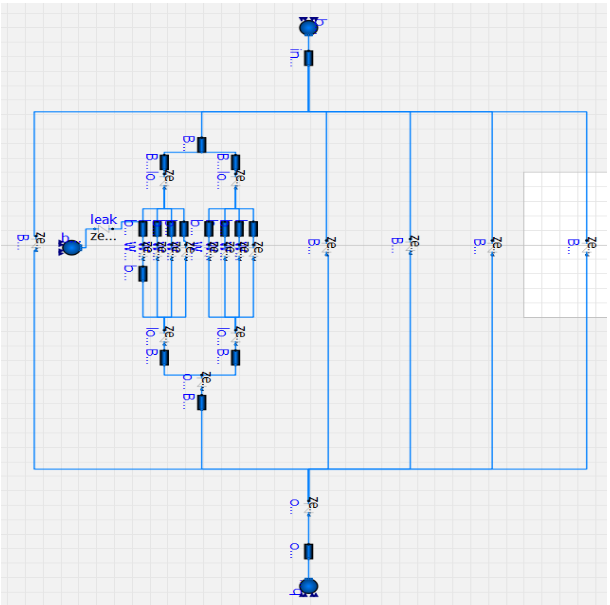


Figure 5.4 – Branch B Leak start

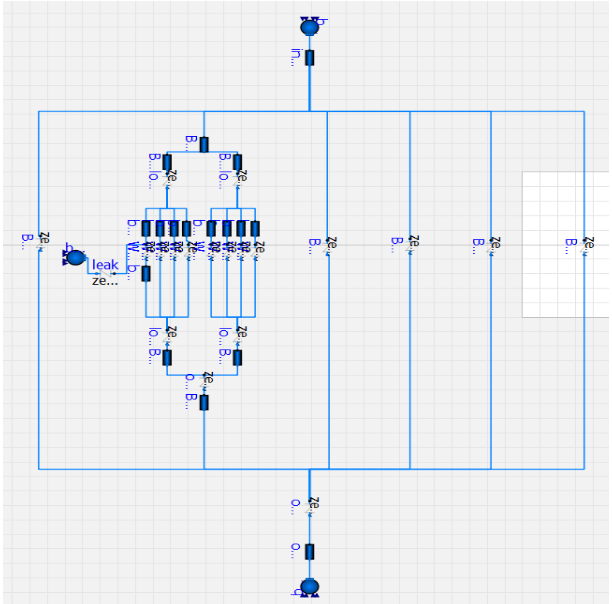


Figure 5.5 – Branch B Leak middle

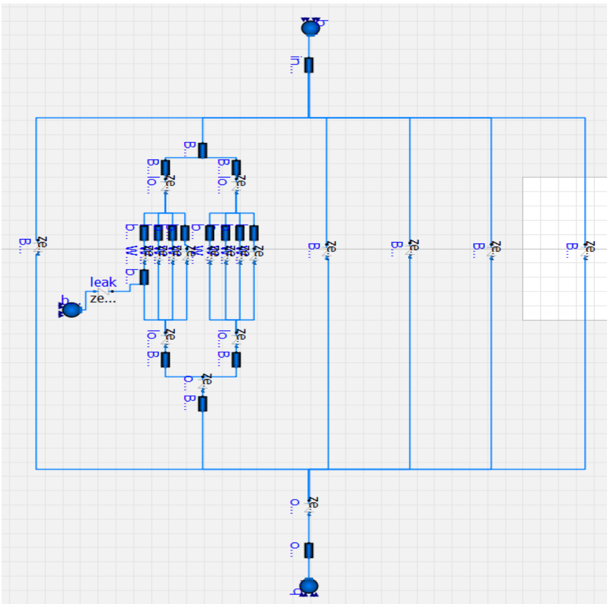


Figure 5.6 – Branch B Leak end

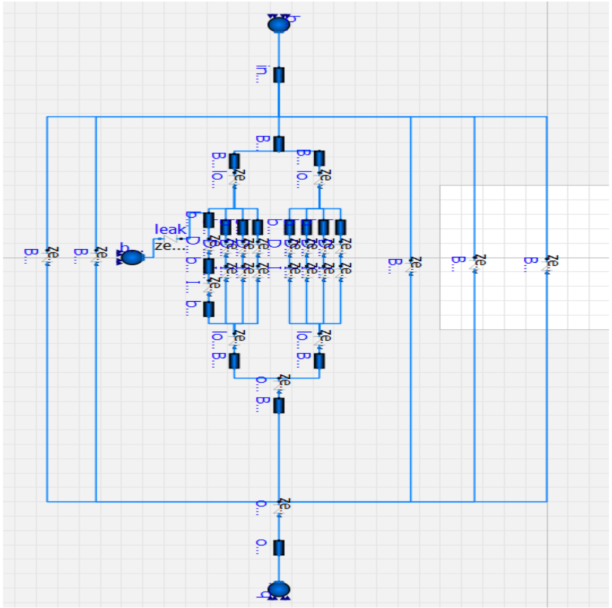


Figure 5.7 – Branch C Leak start

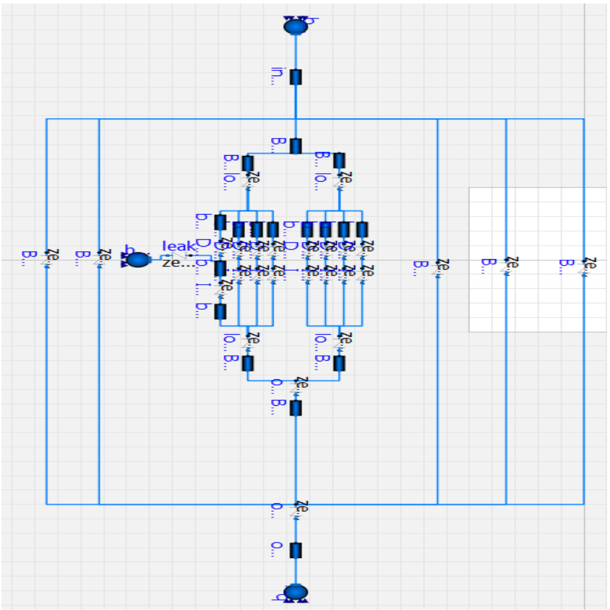


Figure 5.8 – Branch C Leak middle

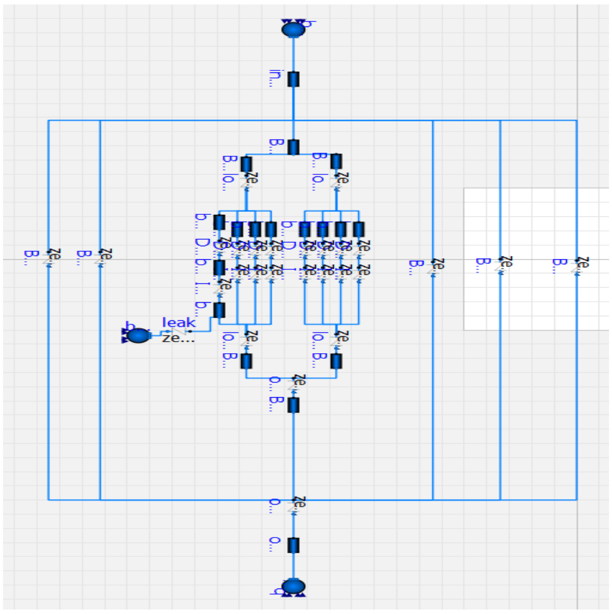


Figure 5.9 – Branch C Leak end

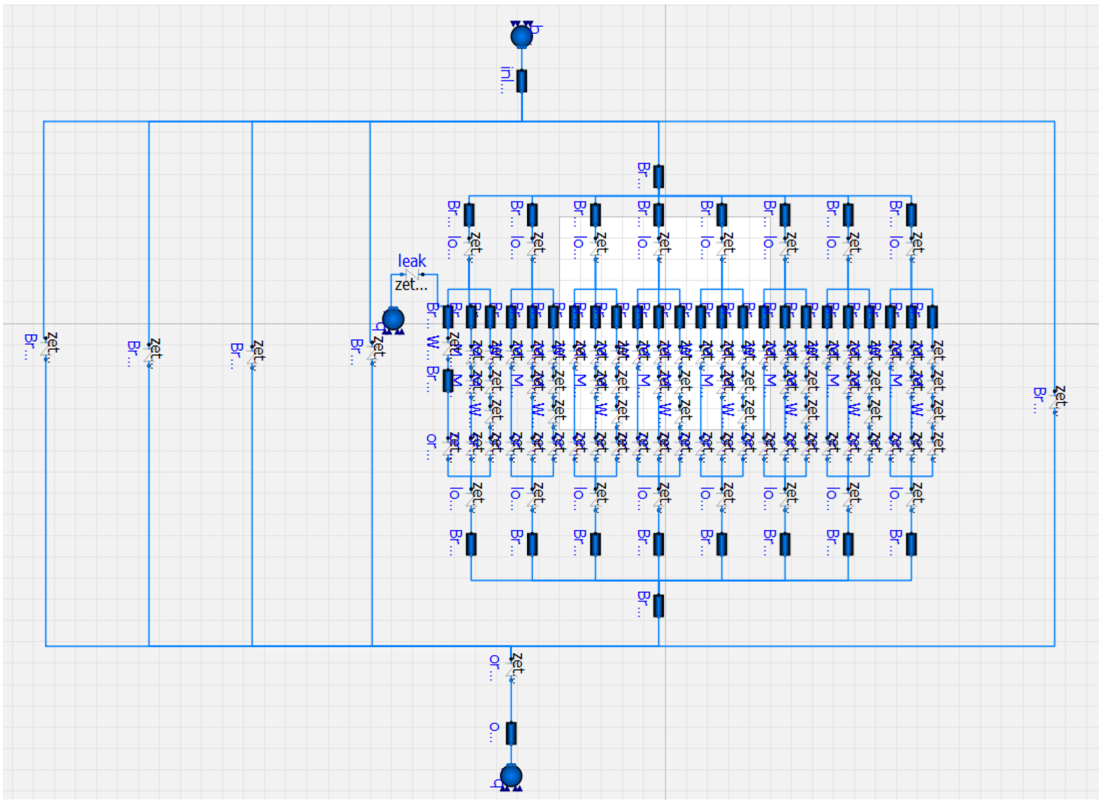


Figure 5.10 – Branch E1 Leak start

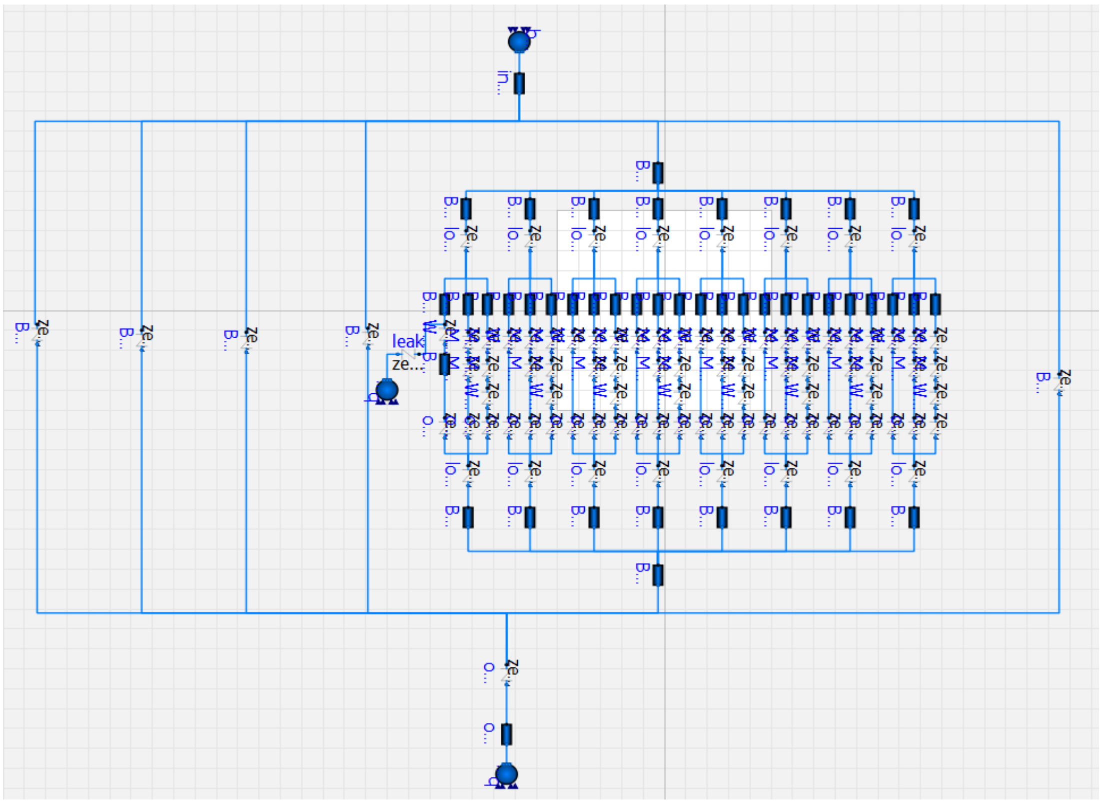


Figure 5.11 – Branch E1 Leak middle

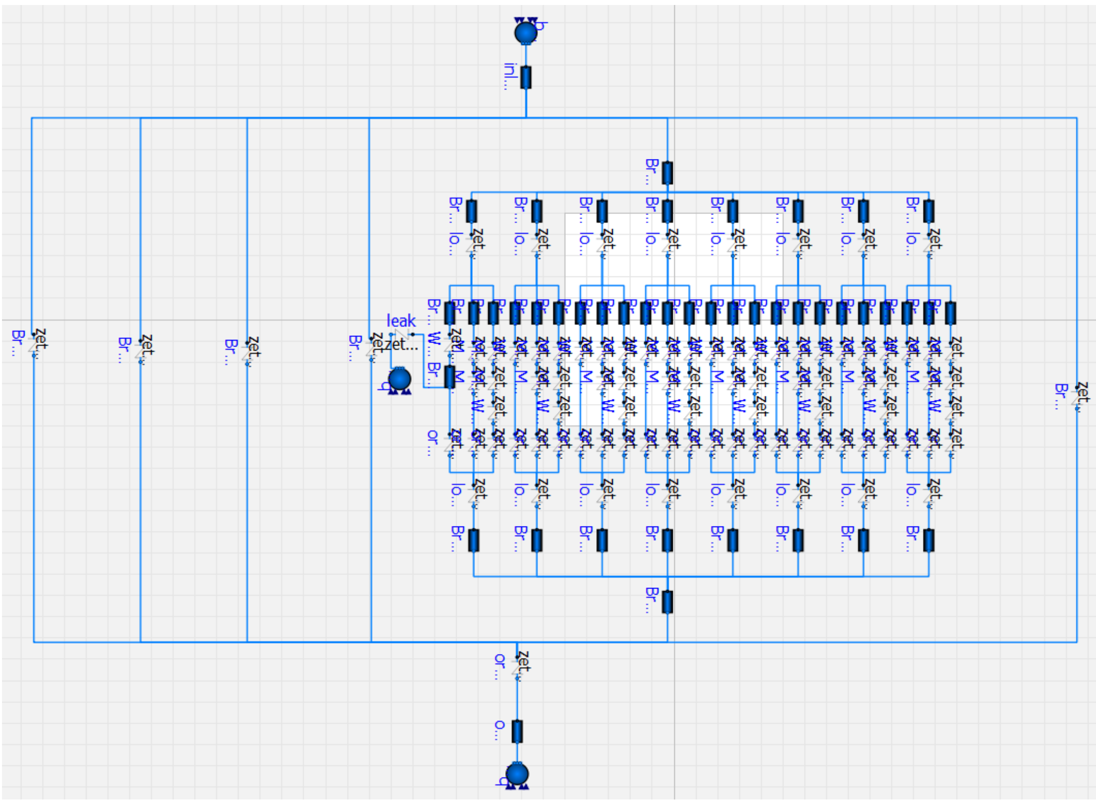


Figure 5.12 – Branch E1 Leak end

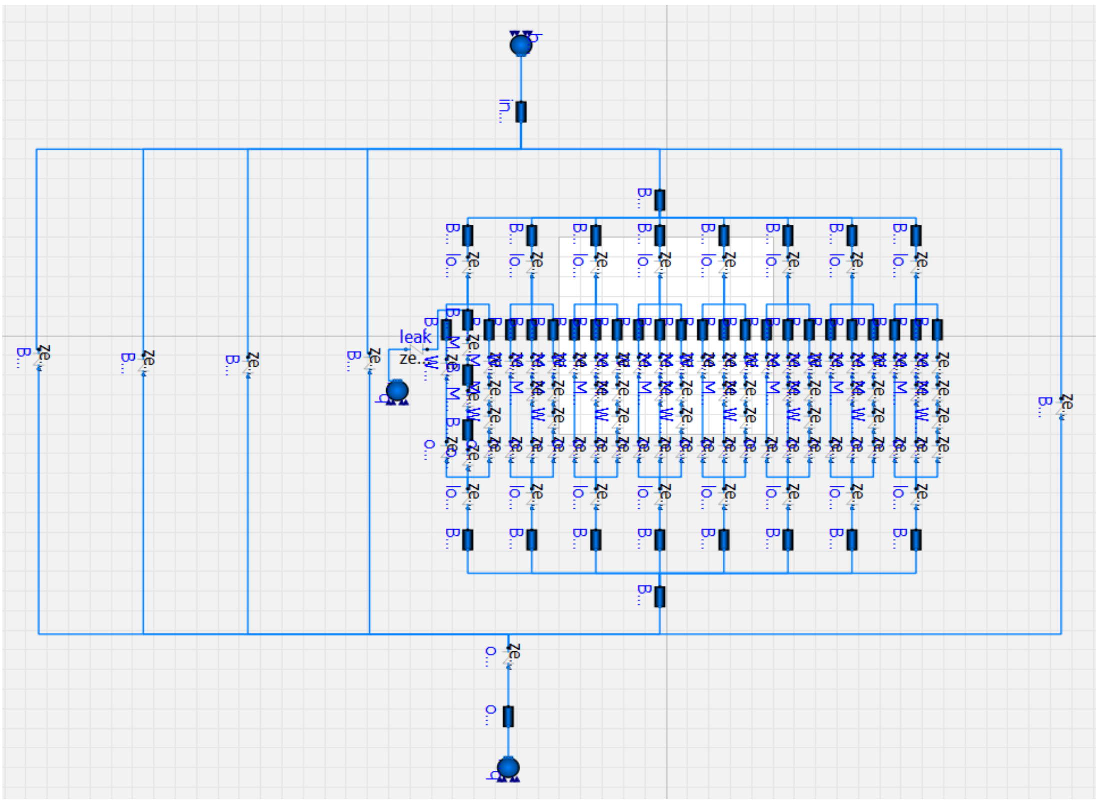


Figure 5.13 – Branch E2 Leak start

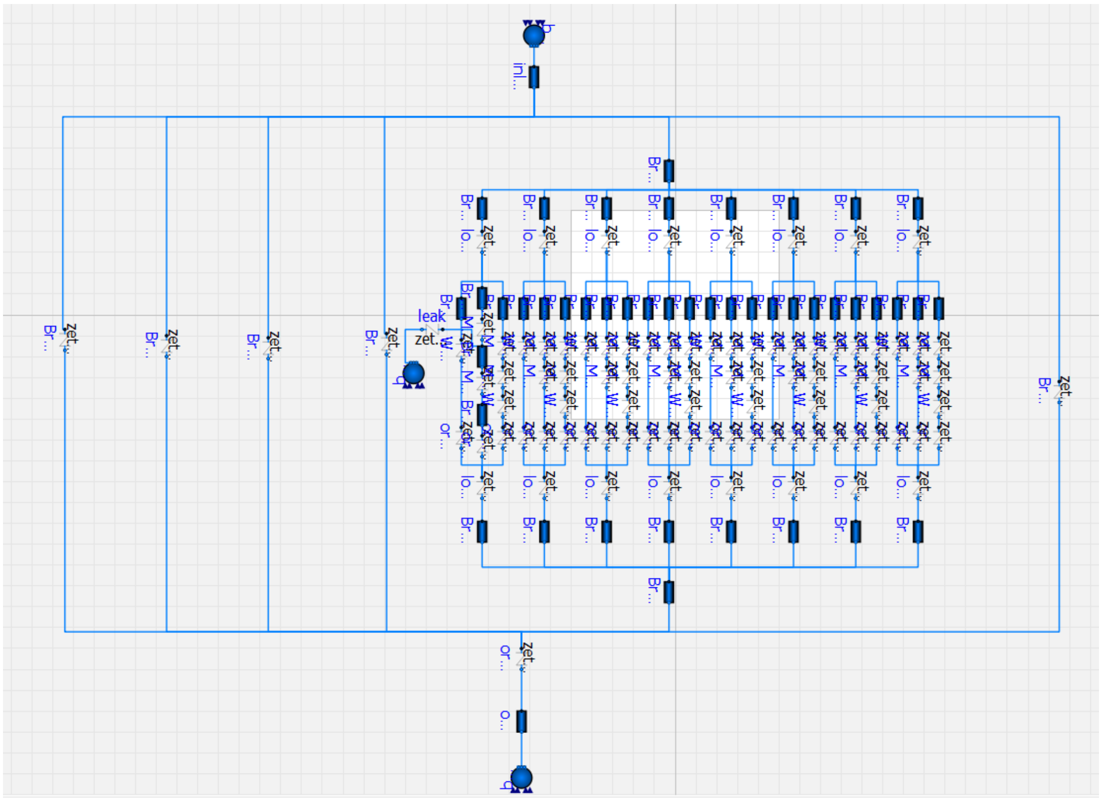


Figure 5.14 – Branch E2 Leak middle

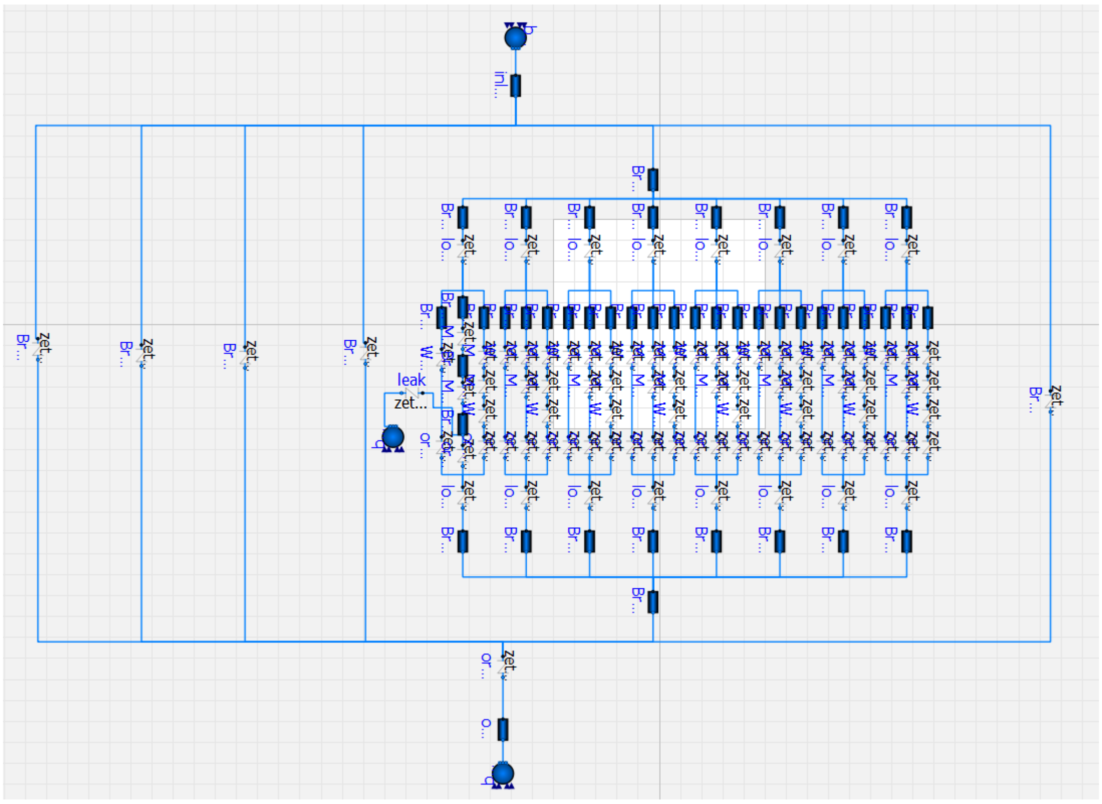


Figure 5.15 – Branch E2 Leak end

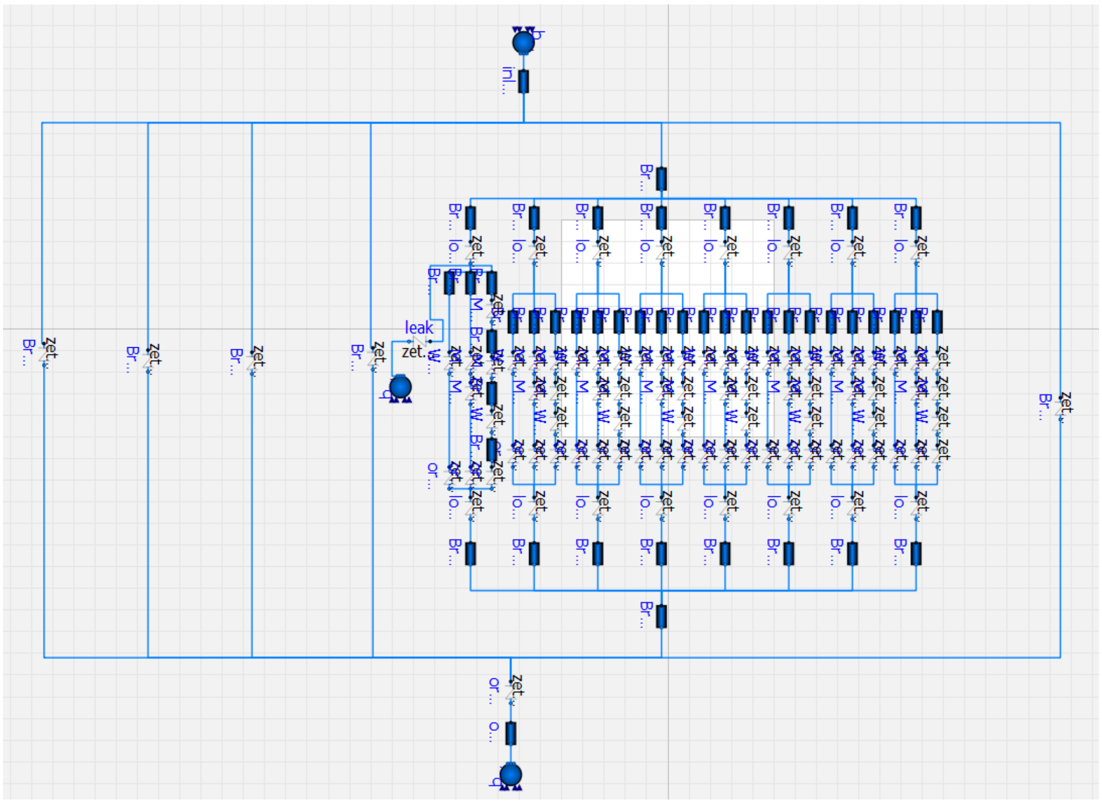


Figure 5.16 – Branch E3 Leak start

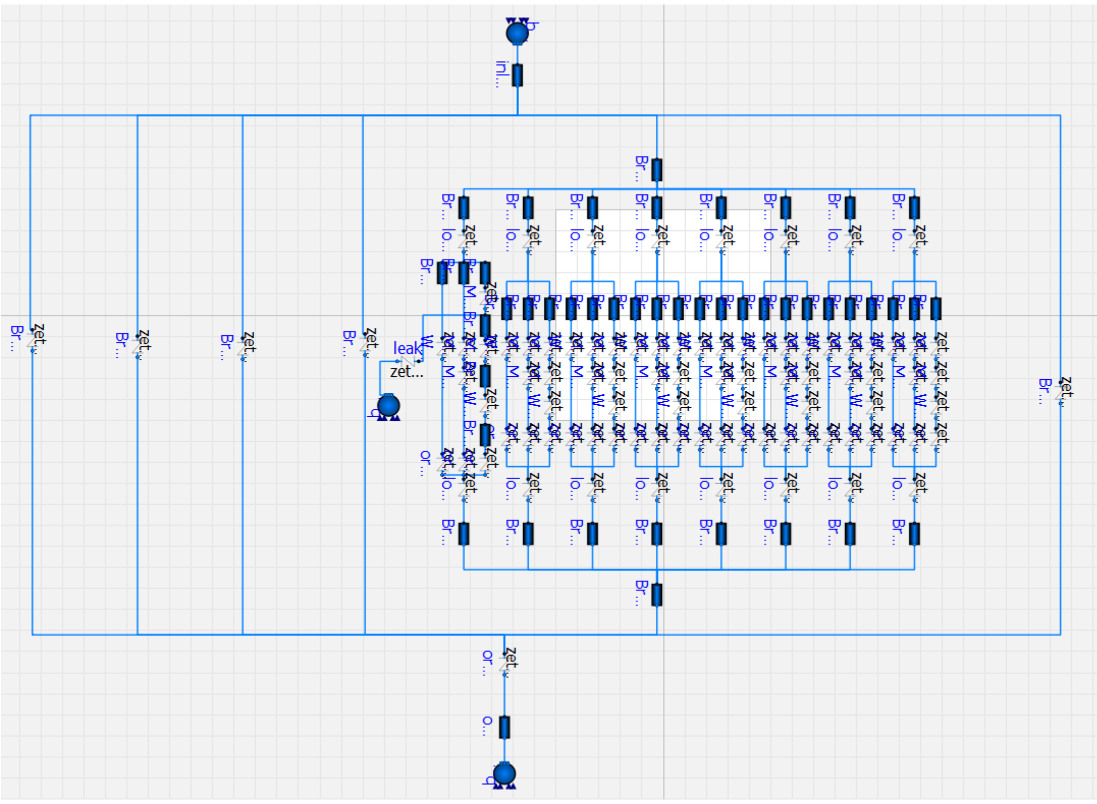


Figure 5.17 – Branch E3 Leak middle_1

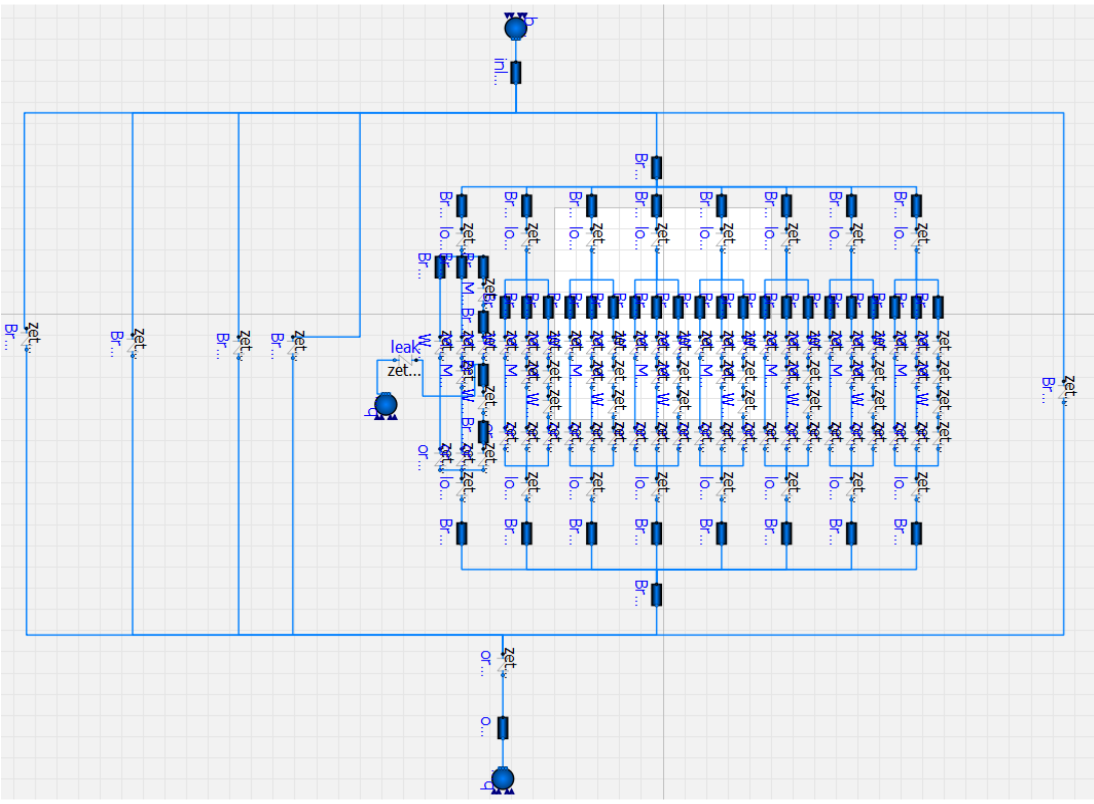


Figure 5.18 – Branch E3 Leak middle_2

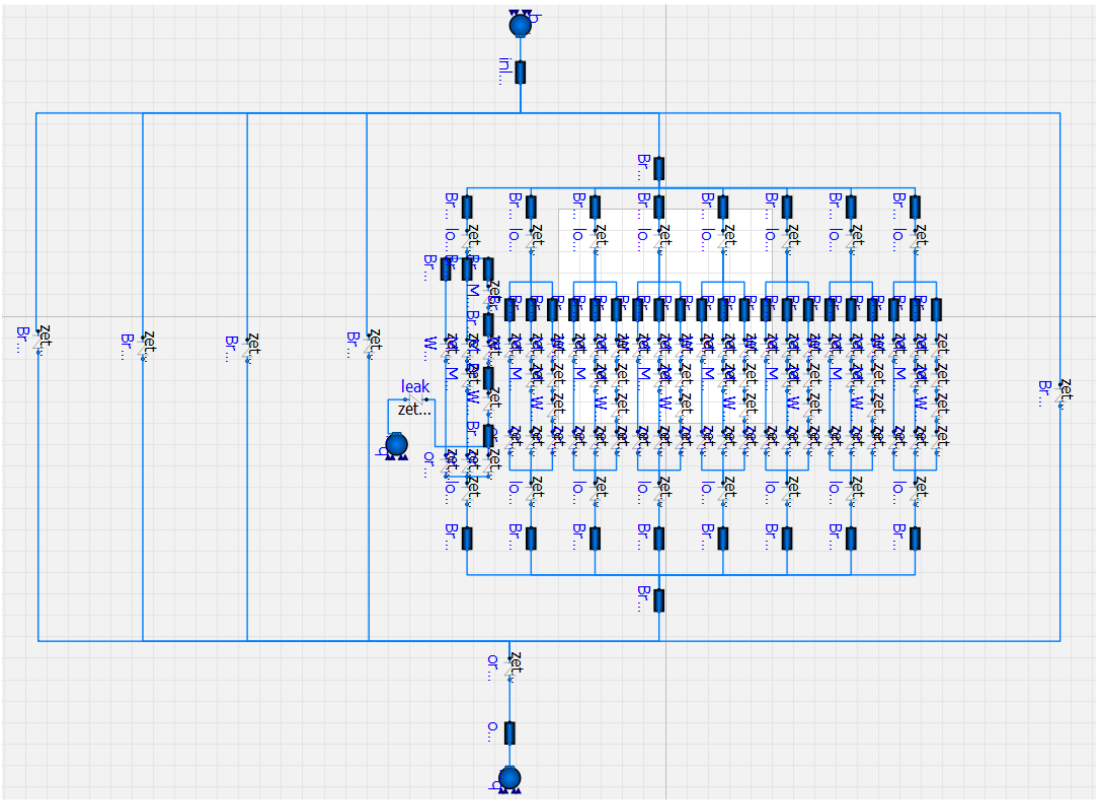


Figure 5.19 – Branch E3 Leak end

OMPython was adopted for the simulation using the class previously introduced (Figure 4.13), creating a script with an iterative cycle which allowed to change the pressure drop of the orifice connected to ambient and to determine the value which provided the minimum mass flow rate in the component following the leak.

The following script relates to a leakage at the beginning of the beam in Branch A: the same script was used for other branches, changing model name and model path, the names of the components, m_flow_min's value (depending on the branch in which the leak was modelled) and the parameter in which the minimum mass flow rate had to be reached.

```
# script

# Path of the model to simulate
modelPath = r'C:\Users\loren\Documents\OpenModelica\LeakageBranchA_start.mo'
# Model name of the model to simulate
modelName = 'LeakageBranchA_start'
# I want to change the value of this component
component = 'leak.dp_nominal'
# I want to check the value of this parameter
parameter = 'TL_PC_ISV_BranchA1_beam1.m_flow'

```

```
# Mass flow inlet system
mass_flow_system_inlet = 'inlet_system.port_a.m_flow'
# Mass flow outlet system
mass_flow_system_outlet = 'outlet_system.port_a.m_flow'
# Mass flow Branch B
mass_flow_BranchB = 'BranchB.m_flow'
# Mass flow Branch C
mass_flow_BranchC = 'BranchC.m_flow'
# Mass flow Branch D
mass_flow_BranchD = 'BranchD.m_flow'
# Mass flow Branch E
mass_flow_BranchE = 'BranchE.m_flow'
# Mass flow Branch F
mass_flow_BranchF = 'BranchF.m_flow'
# Mass flow inlet Branch A
mass_flow_BranchA_inlet = 'BranchA_inlet.port_a.m_flow'
# Mass flow outlet Branch A
mass_flow_BranchA_outlet = 'BranchA_outlet.port_a.m_flow'
# Mass flow rate meter inlet Branch A1
mass_flow_reader_inlet_A1 = 'loss_massFlowRate_branchA1_inlet.m_flow'
# Mass flow rate meter outlet Branch A1
mass_flow_reader_outlet_A1 = 'loss_massFlowRate_branchA1_outlet.m_flow'
# mass flow of the component following the leak
mass_flow_WG_PC_A1 = 'WG_PC_BranchA1_beam1.m_flow'
# Mass flow rate meter outlet Branch A2
mass_flow_reader_inlet_A2 = 'loss_massFlowRate_branchA2_inlet.m_flow'
# Mass flow rate meter outlet Branch A2
mass_flow_reader_outlet_A2 = 'loss_massFlowRate_branchA2_outlet.m_flow'
# Mass flow Branch A1 beam 2 (unaffected beam)
mass_flow_unaffected_beam = 'beam2_BranchA1.port_a.m_flow'
# Mass flow Branch A2 beam 1
mass_flow_beam_A2 = 'beam1_BranchA2.port_a.m_flow'
# Mass flow of the leak
mass_flow_leak = 'leak.m_flow'
# nominal mass flow of the leak
nominal_mass_flow_leak = 'leak.m_flow_nominal'


alpha = 0.3 # set as the initial k_decrement
epsilon = 0.005 # definition of our tolerance
m_flow_min = 0.27
```

```
# this is the minimum mass flow rate for the component in the branch

new_dp = 20e5  # initial value for dp
perc_error = 100  # initial value for perc_error
old_error = 100  # initial value for old_error

# First run
session = OpenModelicaSession(omc)
session.loadModel(modelPath, modelName)
session.setParam(component, new_dp)
session.simulateModel(modelName)
# mass flow of the component following the leak
m_flow_beam = session.getResults(parameter)
perc_error = (m_flow_beam - m_flow_min)/m_flow_min
#  calculation of the first perc_error

i = 0
results = [] # list in which it is appended the result dictionary
while perc_error > epsilon:
    i = i+1
    print('iteration :'+ str(i)) # to see in which iteration it is

    # decrement K*
    K_old = 2*new_dp/(session.getResults(nominal_mass_flow_leak))**2
    new_K = (1-alpha)*K_old
    # adjournment of the leak's pressure drop
    new_dp = new_K*(session.getResults(nominal_mass_flow_leak))**2/2

# I adjourn everytime the value of new_dp, of m_flow_beam, of old_error and of perc_error

    # adjourned run
    session.setParam(component, new_dp)
    session.simulateModel(modelName)
    m_flow_beam = session.getResults(parameter)
    old_error = perc_error
    perc_error = (m_flow_beam - m_flow_min)/m_flow_min

# creation of a dictionary with the results and from which I can make a plot
    result = {'New Dp': new_dp, 'Mass Flow Rate TL_PC_ISV BranchA1 beam1': m_flow_beam,
```

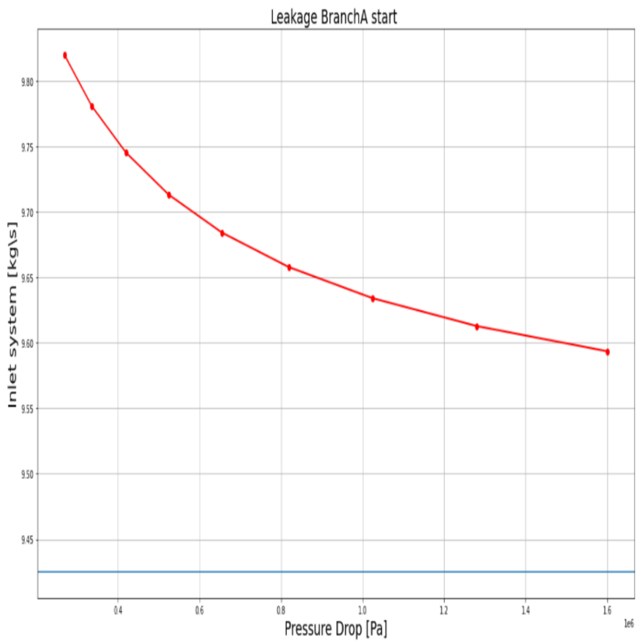
```
            'Mass Flow Rate Inlet system': session.getResults(mass_flow_system_inlet),
            'Mass Flow Rate Outlet system': session.getResults(mass_flow_system_outlet),
            'Branch A Inlet': session.getResults(mass_flow_BranchA_inlet),
            'Branch A Outlet': session.getResults(mass_flow_BranchA_outlet),
            'Branch B': session.getResults(mass_flow_BranchB),
            'Branch C': session.getResults(mass_flow_BranchC),
            'Branch D': session.getResults(mass_flow_BranchD),
            'Branch E': session.getResults(mass_flow_BranchE),
                  'Branch F': session.getResults(mass_flow_BranchF),
                  'Mass Flow Rate FlowMeter inlet BranchA1': session.getResults(mass_flow_reader_inlet_A1),
                 'Mass Flow Rate FlowMeter outlet BranchA1': session.getResults(mass_flow_reader_outlet_A1),
                  'Mass Flow Rate WG_PC BranchA1 beam1': session.getResults(mass_flow_WG_PC_A1),
                  'Mass Flow Rate FlowMeter inlet BranchA2': session.getResults(mass_flow_reader_inlet_A2),
                  'Mass Flow Rate FlowMeter outlet BranchA2': session.getResults(mass_flow_reader_outlet_A2),
                  'Mass Flow Rate unaffected beam BranchA1': session.getResults(mass_flow_unaffected_beam),
                  'Mass Flow Rate beam1 BranchA2': session.getResults(mass_flow_beam_A2),
                 'Mass Flow Leak': session.getResults(mass_flow_leak)}
        results.append(result) # append the result dictionary to the results list

        if perc_error*old_error < 0:
            'Difference has changed sign'
            break


    print("\n")
    print("leak dp:", new_dp)
    print("\n")
    print("Mass Flow Rate TL_PC_ISV BranchA1 beam1:", m_flow_beam)
    print("\n")
    print("Inlet system:", session.getResults(mass_flow_system_inlet))
    print("\n")
```

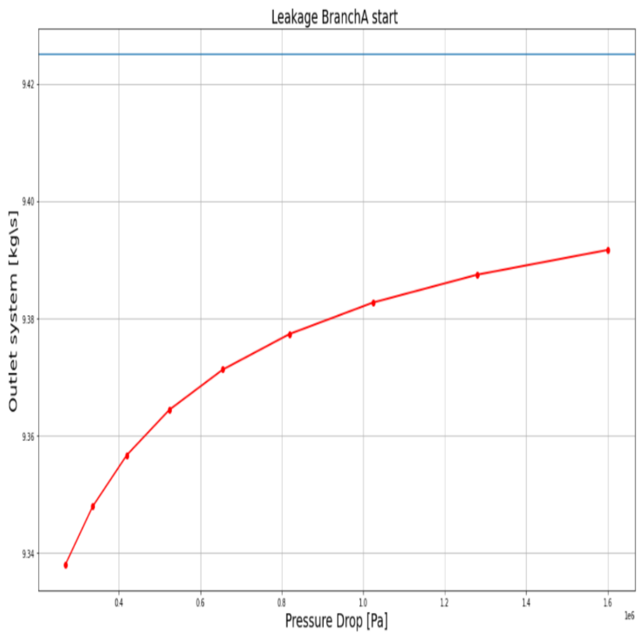
```
    print("Outlet system:", session.getResults(mass_flow_system_outlet))
    print("\n")
    print("Branch A inlet:", session.getResults(mass_flow_BranchA_inlet))
    print("\n")
    print("Branch A outlet:", session.getResults(mass_flow_BranchA_outlet))
    print("\n")
    print("Branch B:", session.getResults(mass_flow_BranchB))
    print("\n")
    print("Branch C:", session.getResults(mass_flow_BranchC))
    print("\n")
    print("Branch D:", session.getResults(mass_flow_BranchD))
    print("\n")
    print("Branch E:", session.getResults(mass_flow_BranchE))
    print("\n")
    print("Branch F:", session.getResults(mass_flow_BranchF))
    print("\n")
    print("Mass Flow Rate Meter Branch A1 inlet:", session.getResults(mass_flow_reader_inlet_A1))
    print("\n")
    print("Mass Flow Rate Meter Branch A1 outlet:", session.getResults(mass_flow_reader_outlet_A1))
    print("\n")
    print("Mass Flow Rate WG_PC BranchA1 beam1:", session.getResults(mass_flow_WG_PC_A1))
    print("\n")
    print("Mass Flow Rate Meter Branch A2 inlet:", session.getResults(mass_flow_reader_inlet_A2))
    print("\n")
    print("Mass Flow Rate Meter Branch A2 outlet:", session.getResults(mass_flow_reader_outlet_A2))
    print("\n")
    print("Mass Flow Rate unaffected beam BranchA1:", session.getResults(mass_flow_unaffected_beam))
    print("\n")
    print("Branch A2 beam1:", session.getResults(mass_flow_beam_A2))
    print("\n")
    print("Mass Flow leak:", session.getResults(mass_flow_leak))
```

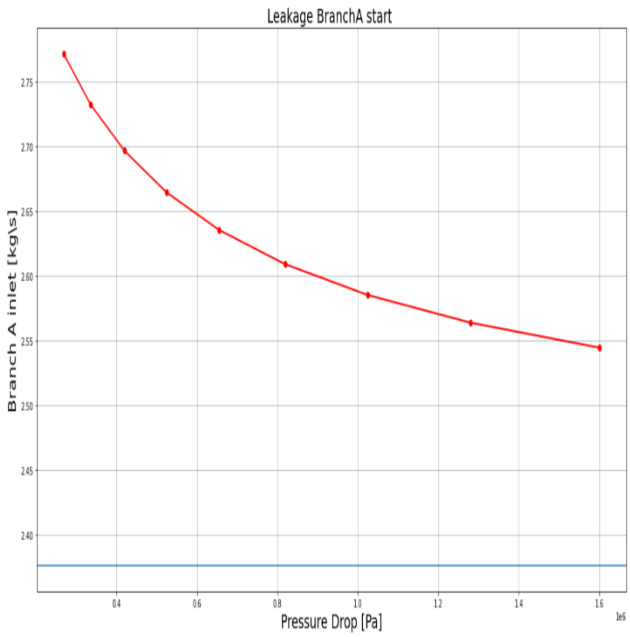
Script 5.1 – Leakage Branch A start

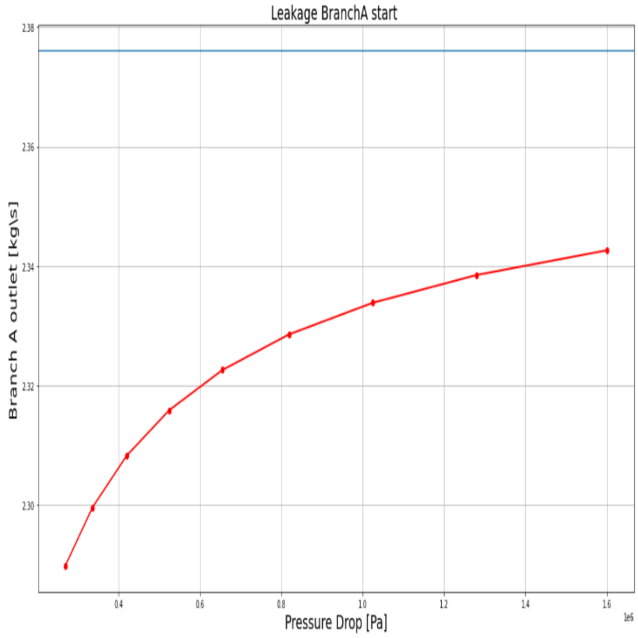
5.2 Development of mass flow rates for small break

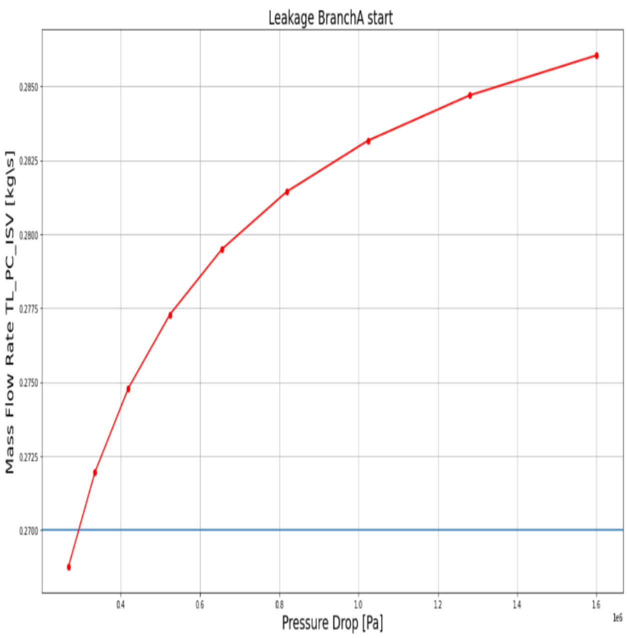
The following figures illustrate the development of mass flow rates at the inlet and outlet of the system, the inlet and outlet of branches and in different components affected by the leak, compared to the pressure drops of the orifices which represent the leakage. The blue line represents the nominal mass flow rate for the inlet and outlet of the system and of the branches, whereas it represents the minimum mass flow rate for components affected by the leak. Regarding the mass flow rate in the component following the leak, it can be seen how, with the decrease of pressure, the mass flow rate in the component decreases in turn until reaching the minimum value. On the other hand, the mass flow rate in the component preceding the leak increases with the decrease of pressure. For the mass flow rate at the inlet of the system and of the branch, with the decrease of pressure the mass flow rate increases, keeping always above the nominal value. As regards the mass flow rate at the outlet of the system and of the branch, it has an opposite trend, decreasing with the decrease of pressure, keeping always below the nominal value.

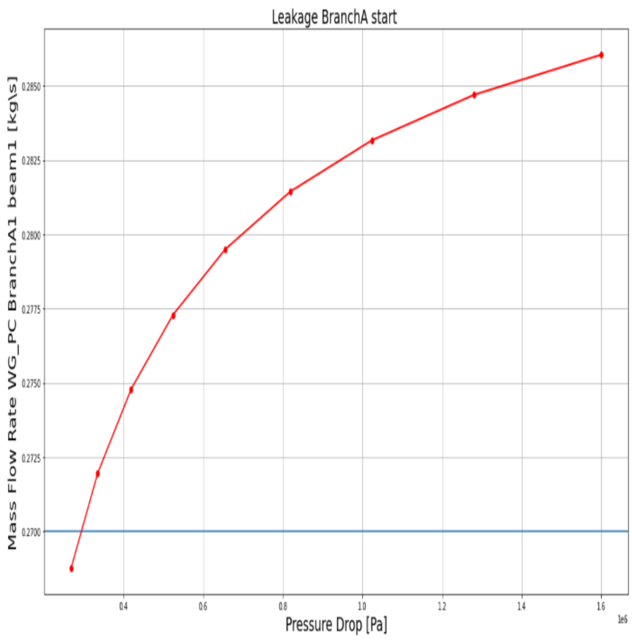





Leakage BranchA start
Branch A inlet [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchA start
Branch A outlet [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchA start
Mass Flow Rate TL_PC_ISV [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchA start
Mass Flow Rate WG_PC BranchA1 beam1 [kg\s]
Pressure Drop [Pa]
1e6

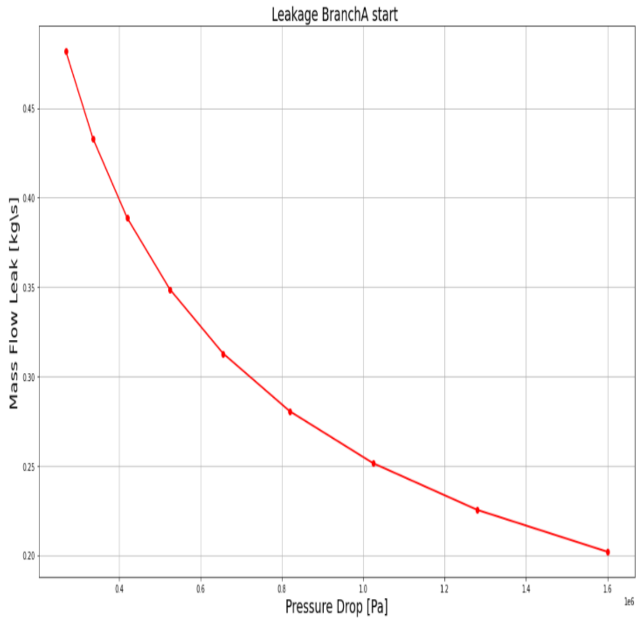
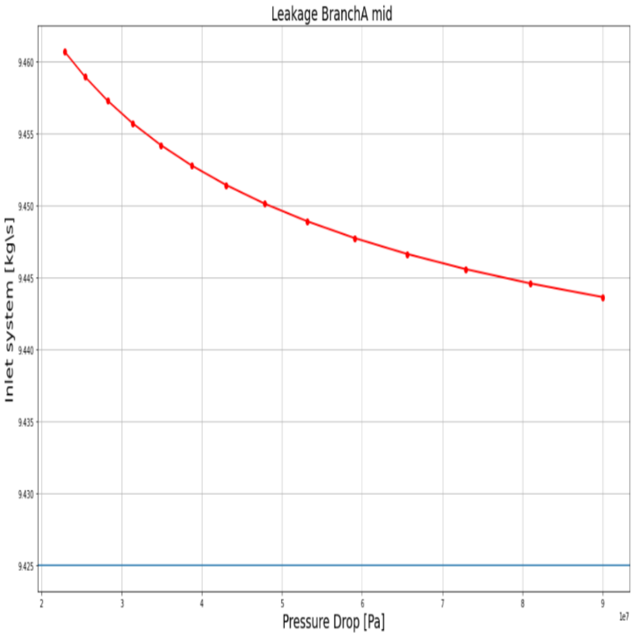
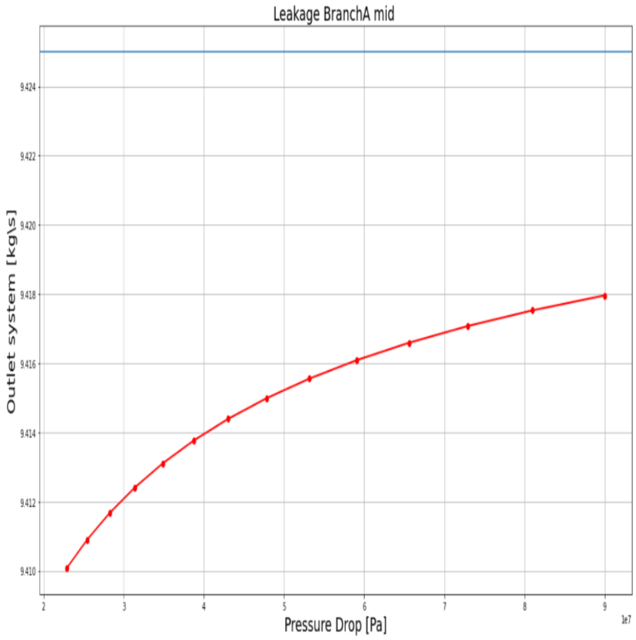
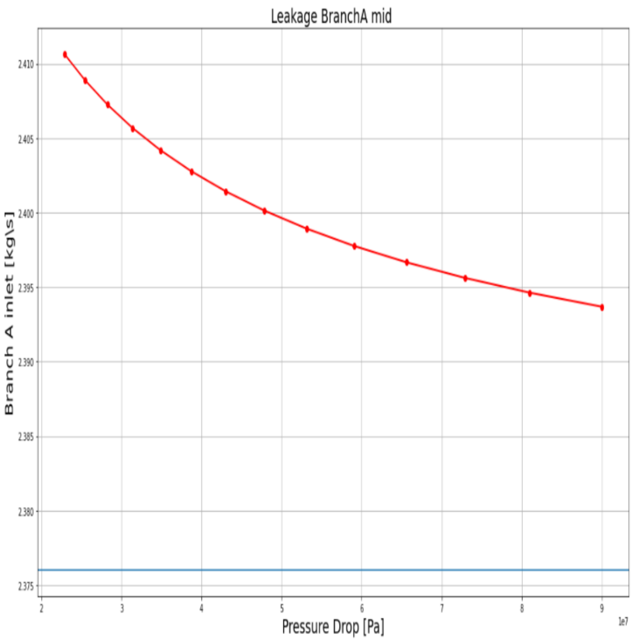
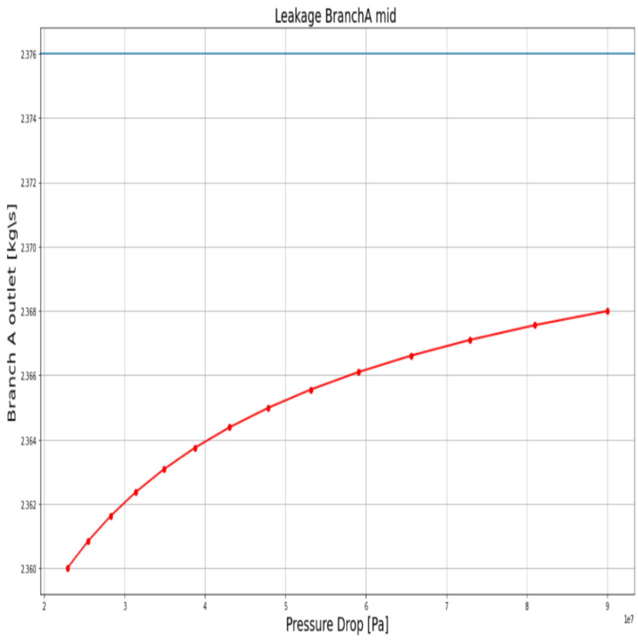


Figure 5.20 – Leakage Branch A start


Leakage BranchA mid
Inlet system [kg\s]
Pressure Drop [Pa]
1e7

Leakage BranchA mid
Outlet system [kg\s]
Pressure Drop [Pa]
1e7

Leakage BranchA mid
Branch A inlet [kg\s]
Pressure Drop [Pa]
1e7

Leakage BranchA mid
Branch A outlet [kg\s]
Pressure Drop [Pa]
1e7

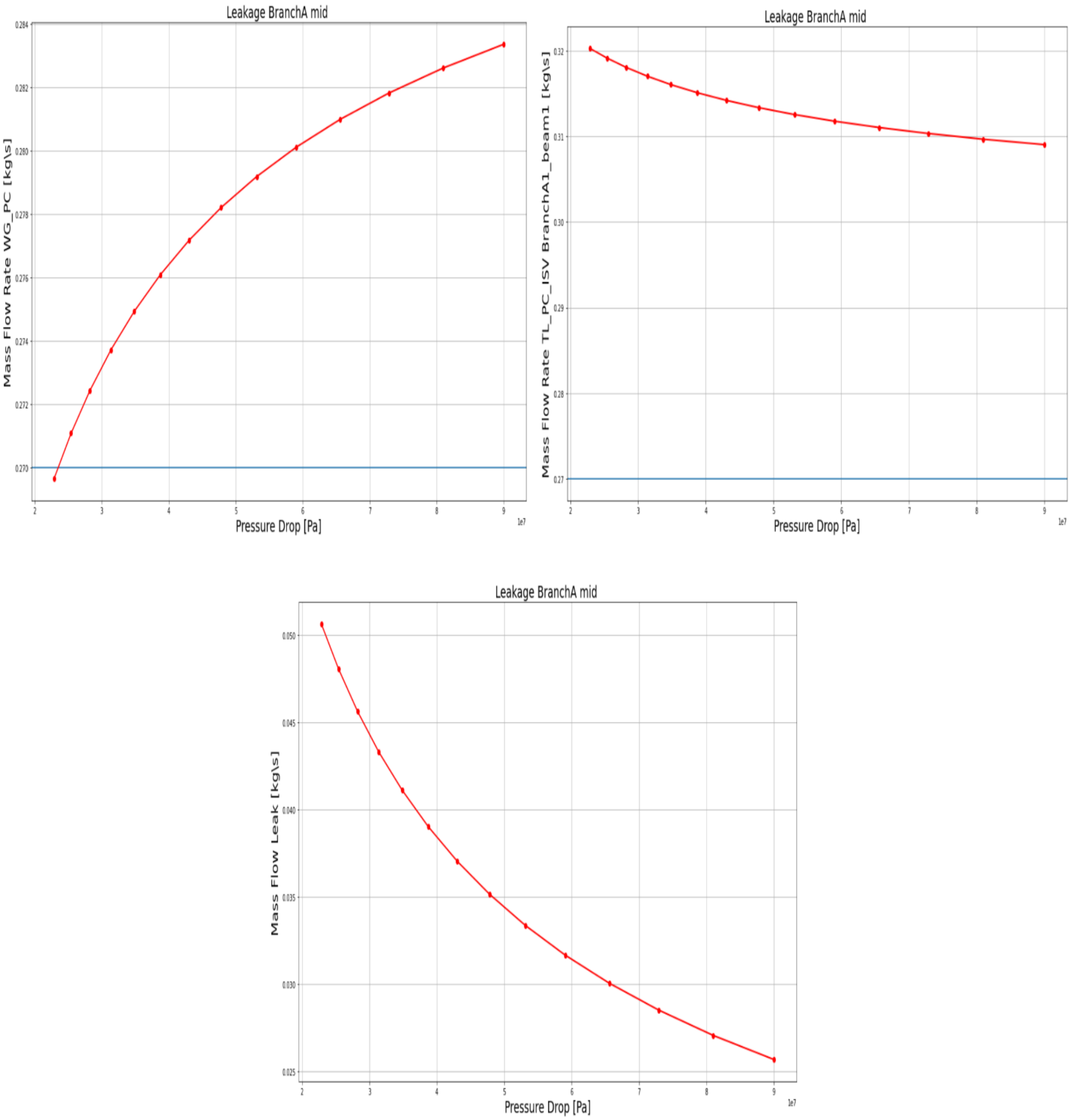
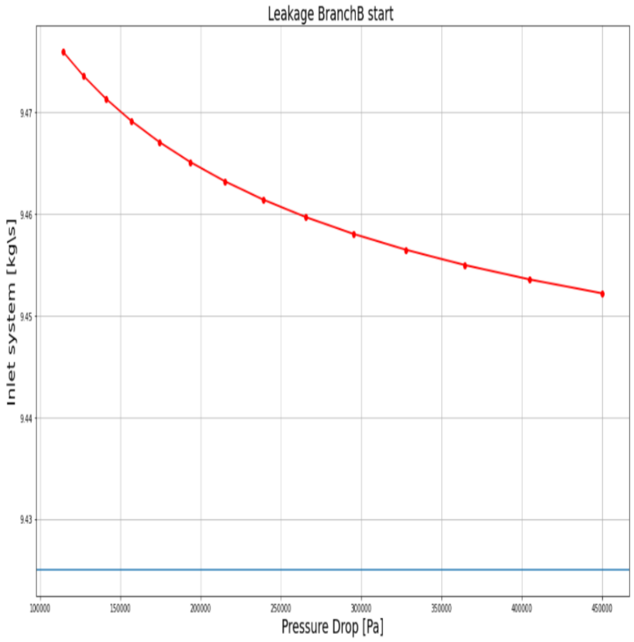
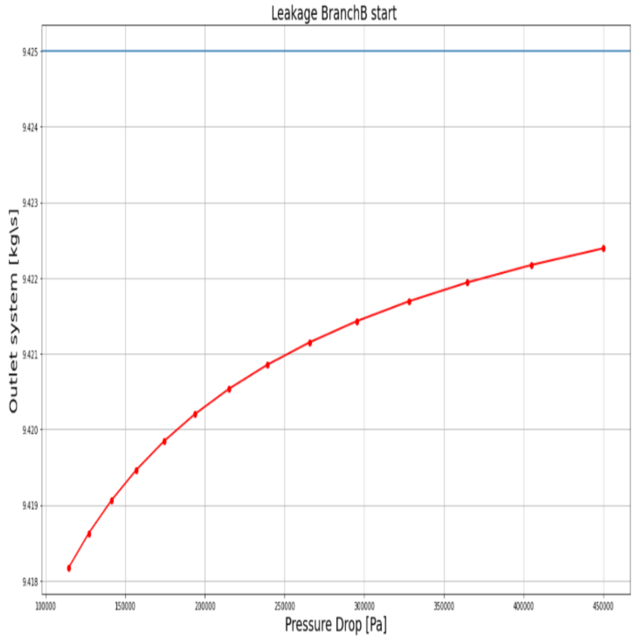
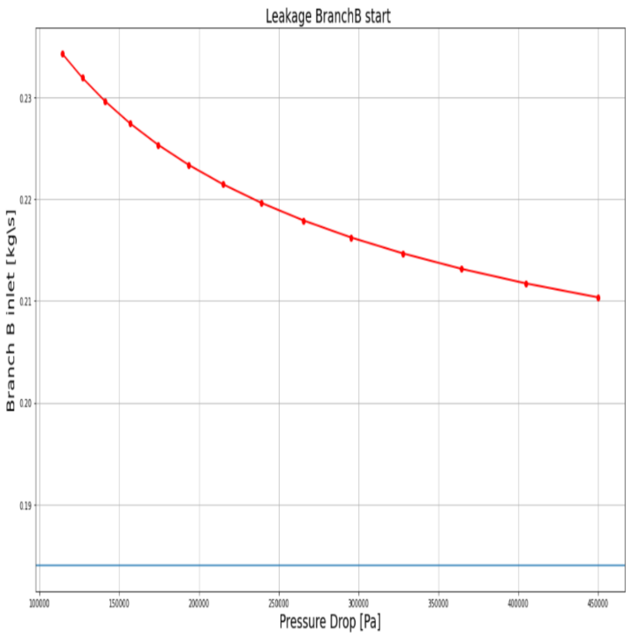
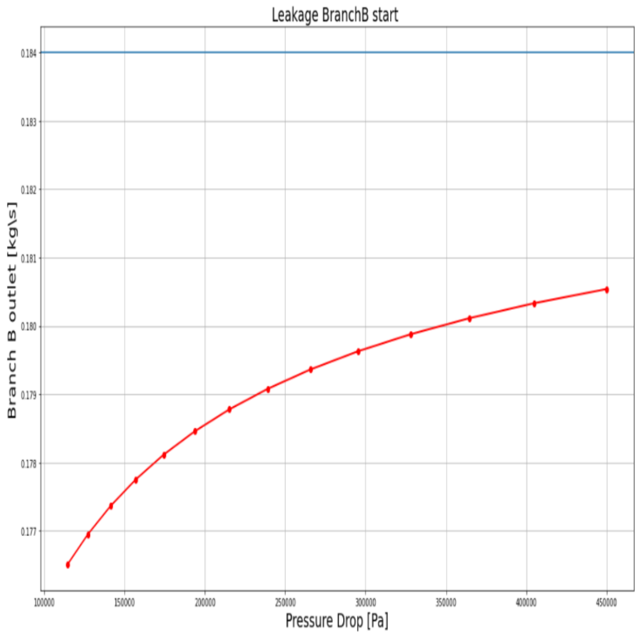


Figure 5.21 – Leakage Branch A middle


Leakage BranchB start
Inlet system [kg\s]
Pressure Drop [Pa]


Leakage BranchB start
Outlet system [kg\s]
Pressure Drop [Pa]


Leakage BranchB start
Branch B inlet [kg\s]
Pressure Drop [Pa]


Leakage BranchB start
Branch B outlet [kg\s]
Pressure Drop [Pa]

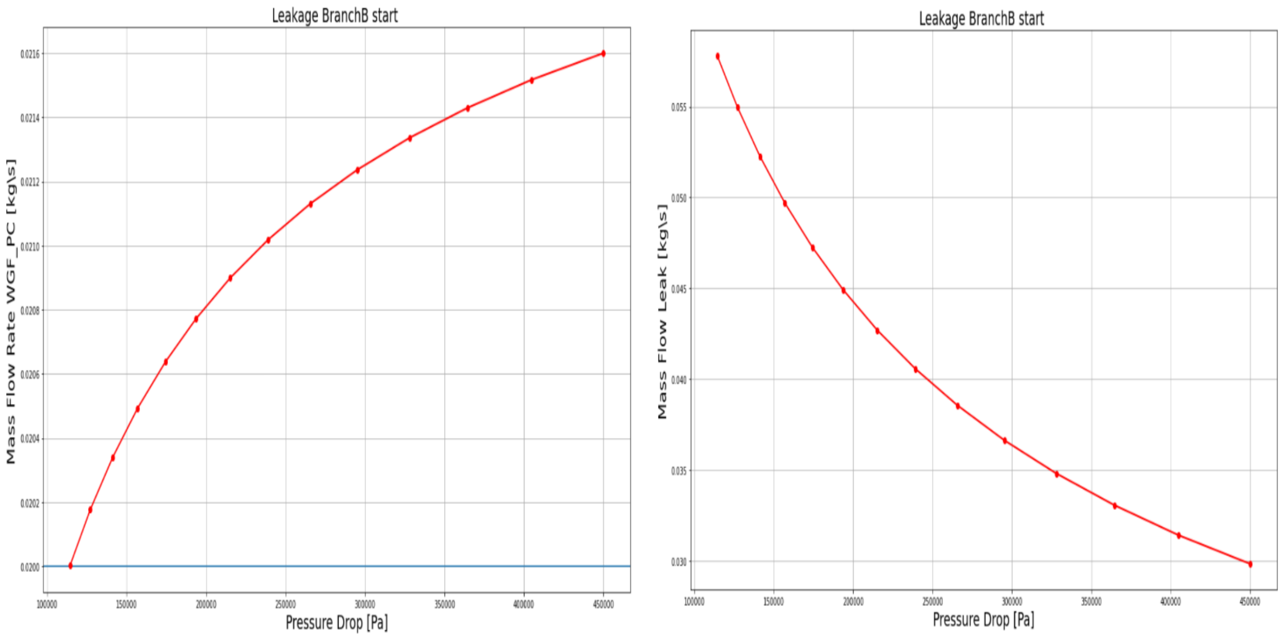
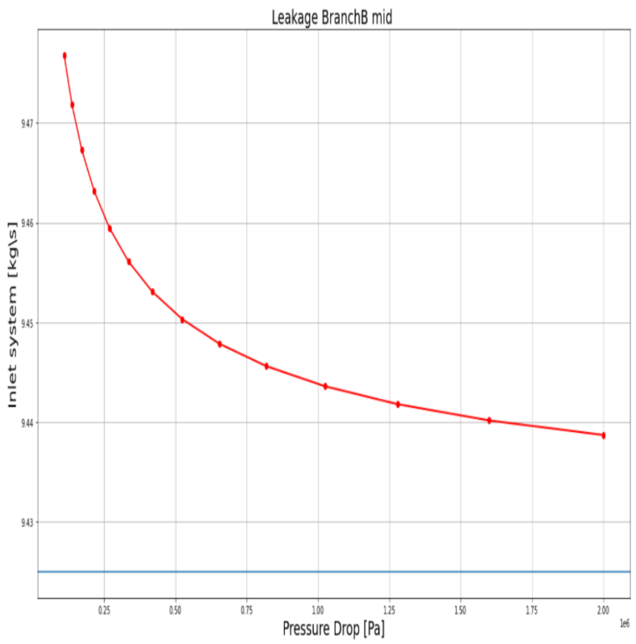
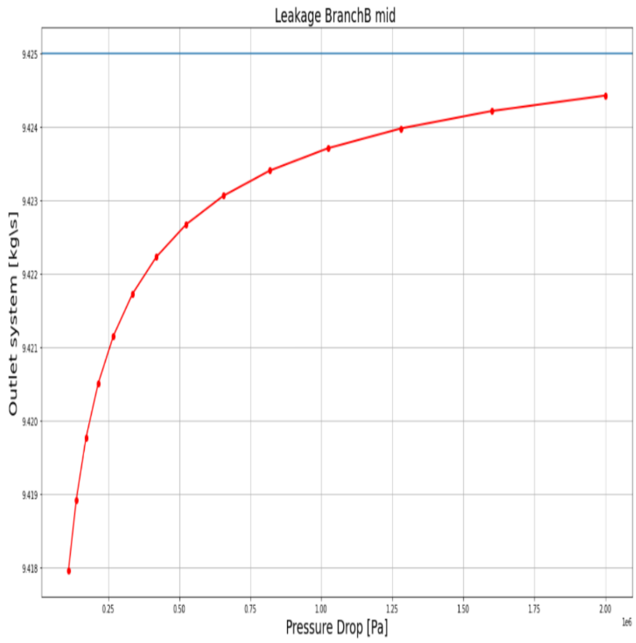
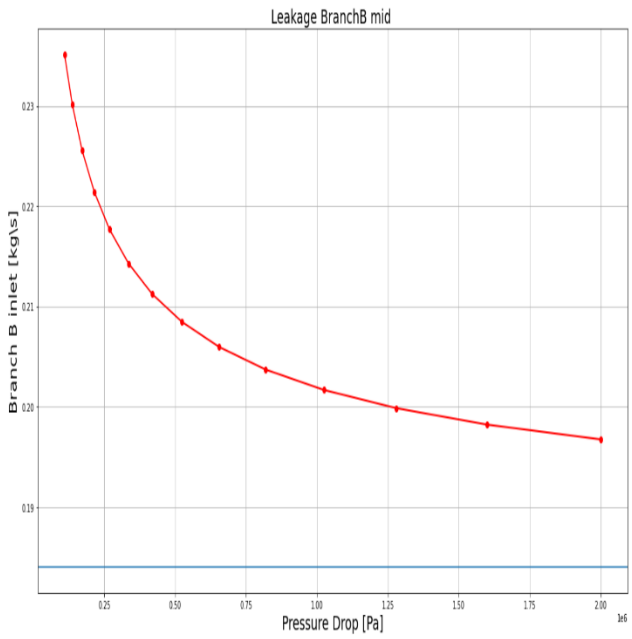
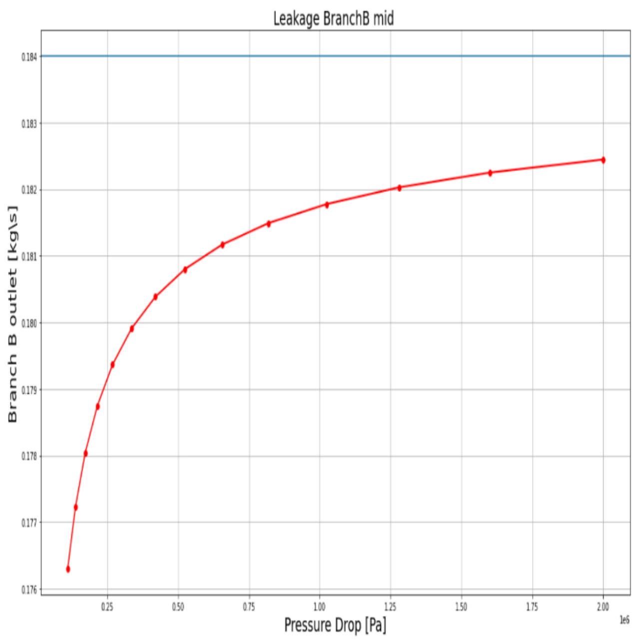


Figure 5.22 – Leakage Branch B start


Leakage BranchB mid
Inlet system [kg\s]
9.47
9.46
9.45
9.44
9.43
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e6
Pressure Drop [Pa]


Leakage BranchB mid
Outlet system [kg\s]
9.425
9.424
9.423
9.422
9.421
9.420
9.419
9.418
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e6
Pressure Drop [Pa]


Leakage BranchB mid
Branch B inlet [kg\s]
0.23
0.22
0.21
0.20
0.19
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e6
Pressure Drop [Pa]


Leakage BranchB mid
Branch B outlet [kg\s]
0.184
0.183
0.182
0.181
0.180
0.179
0.178
0.177
0.176
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e6
Pressure Drop [Pa]

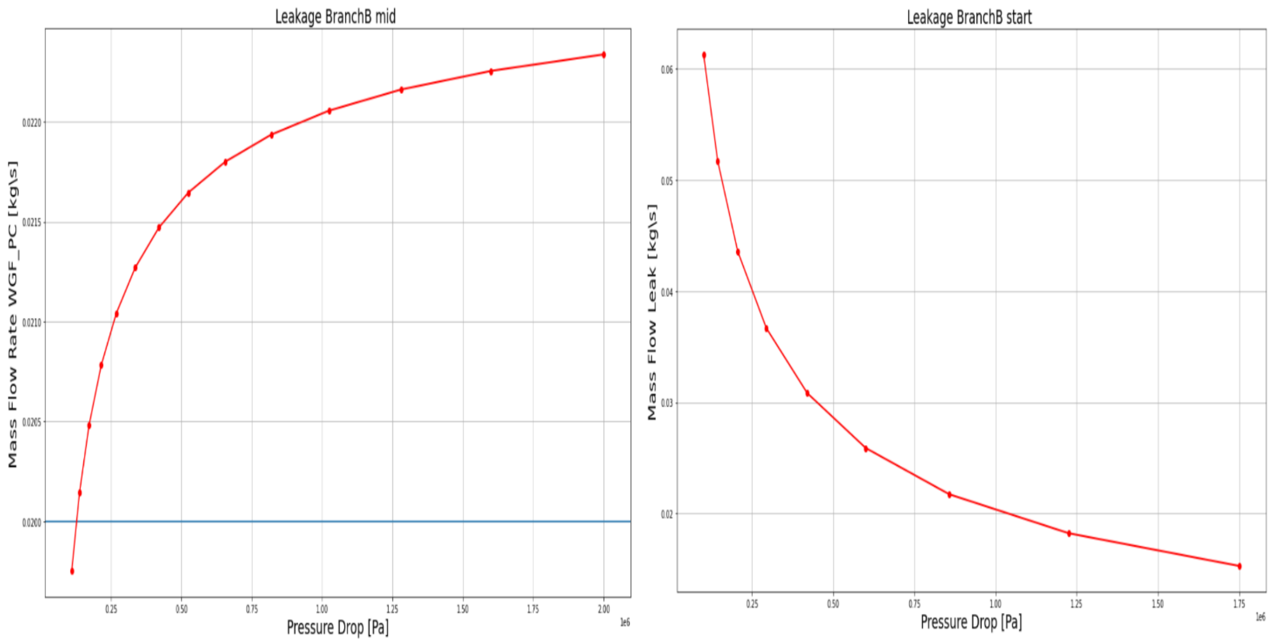
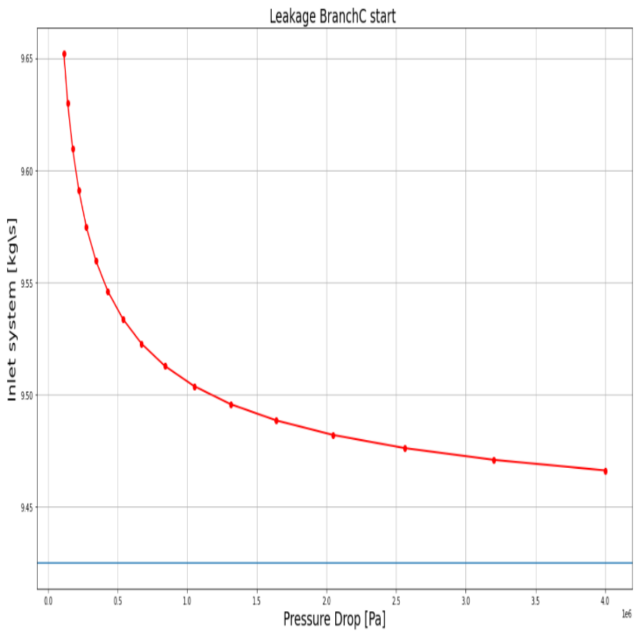
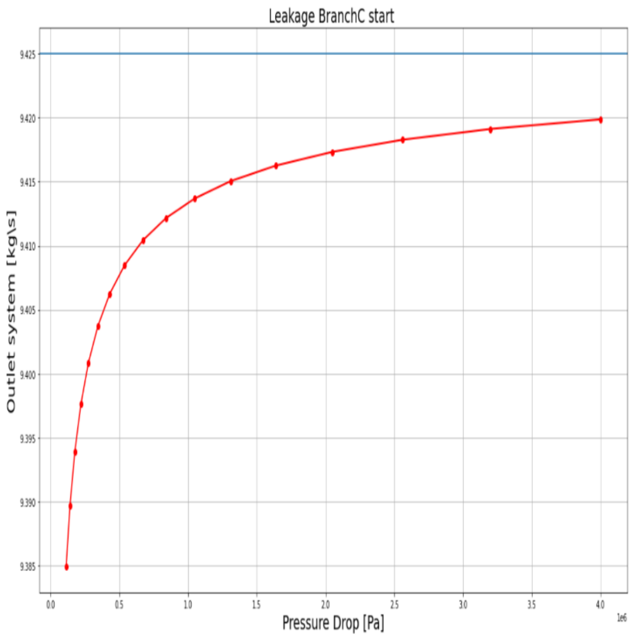
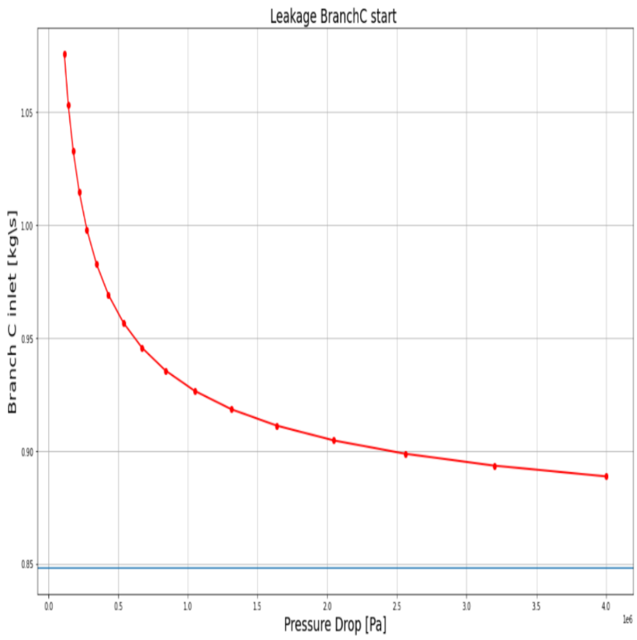
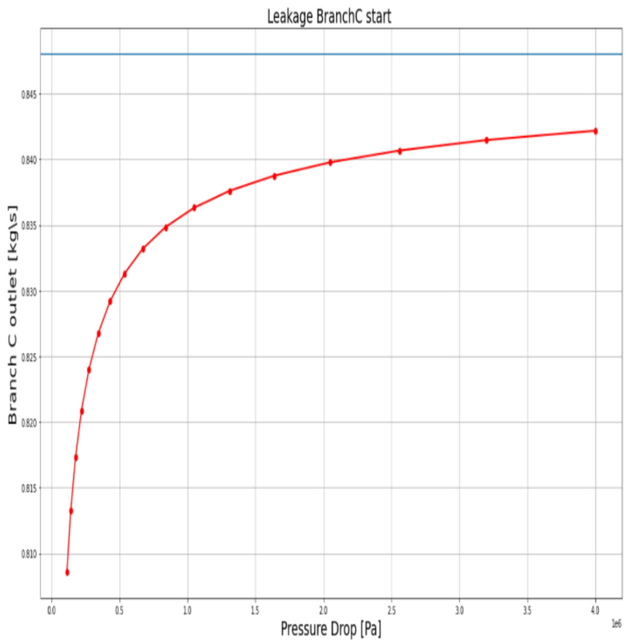


Figure 5.23 – Leakage Branch B middle


Leakage BranchC start
Inlet system [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchC start
Outlet system [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchC start
Branch C inlet [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchC start
Branch C outlet [kg\s]
Pressure Drop [Pa]
1e6

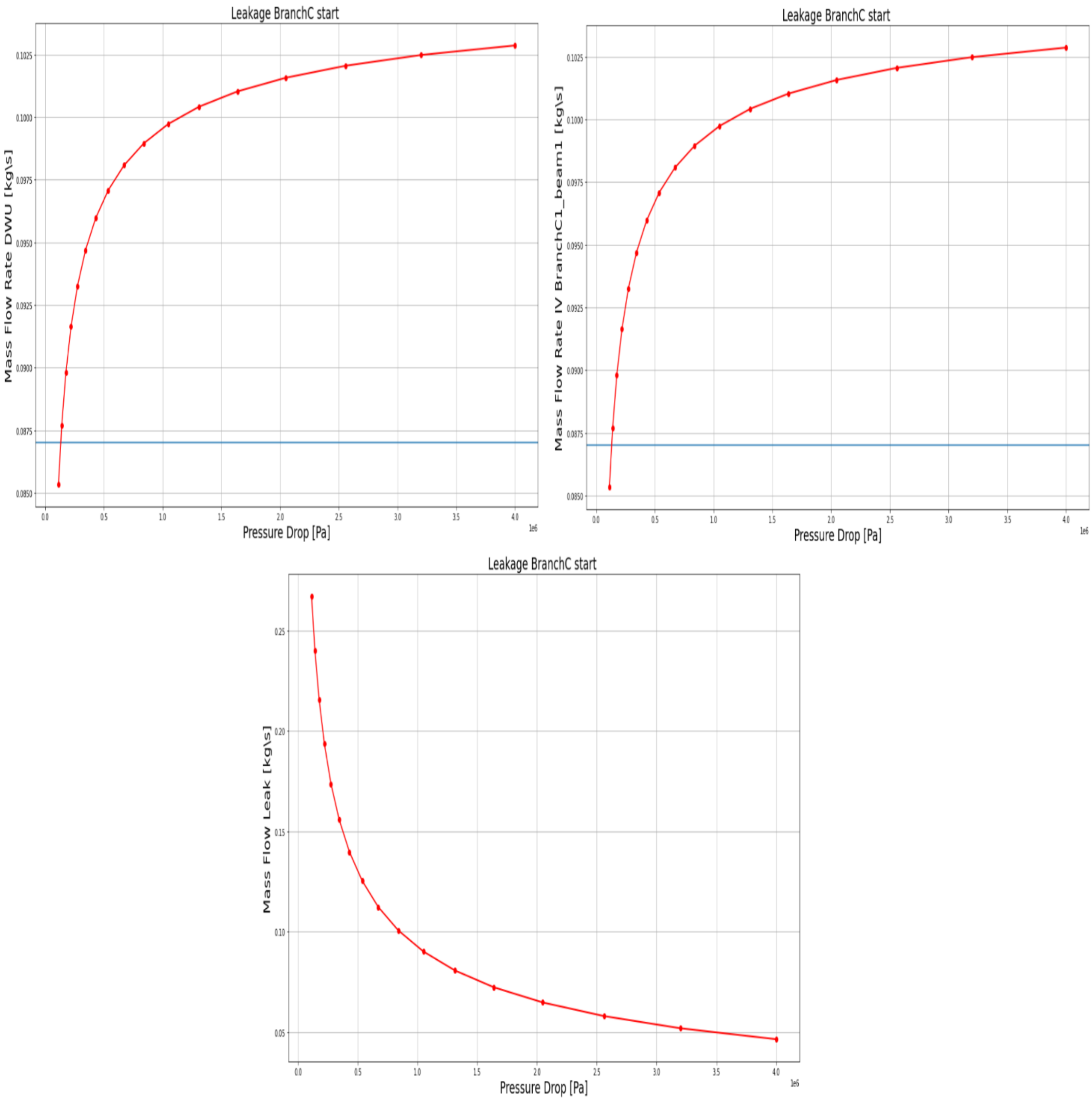
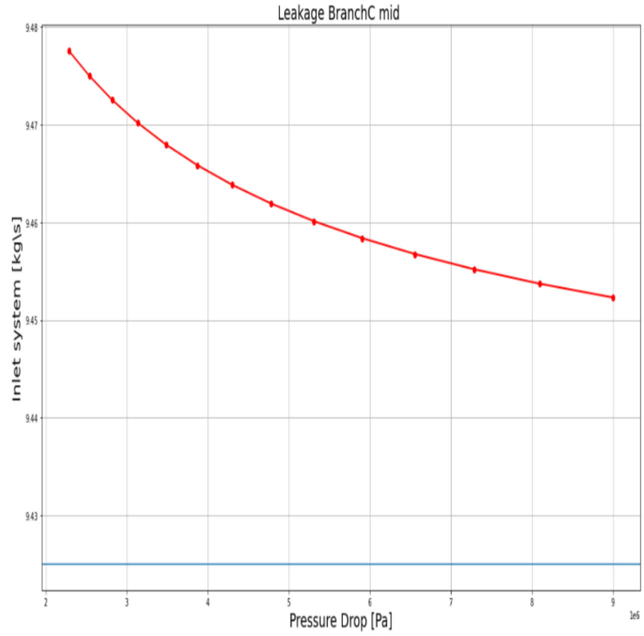
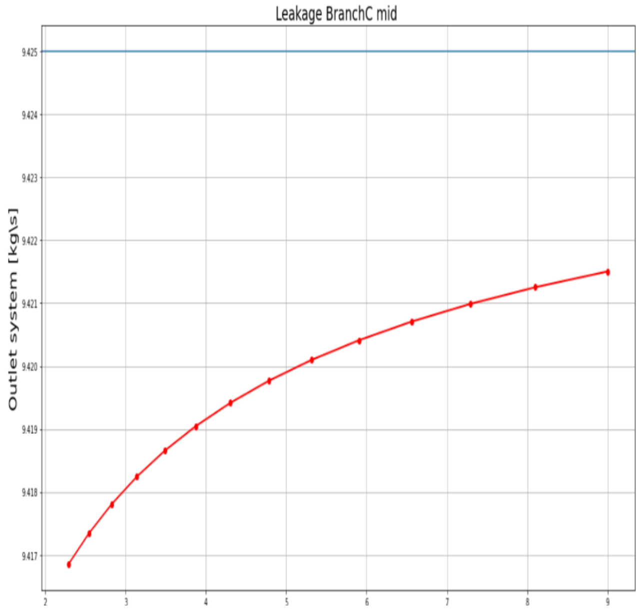
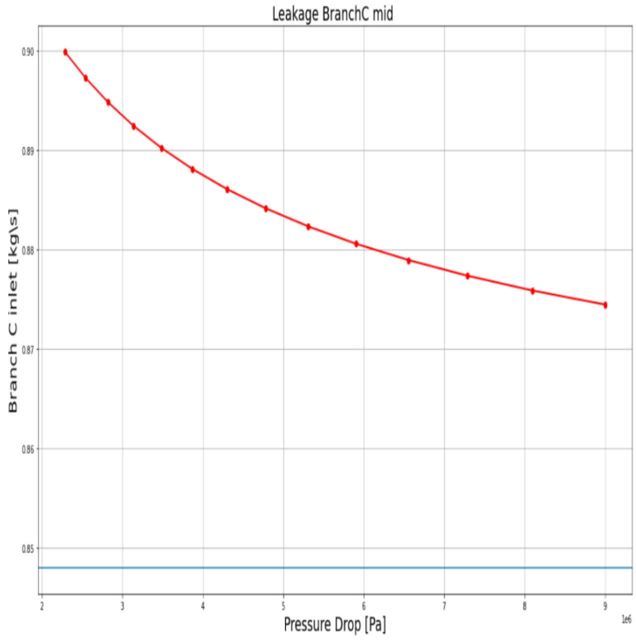
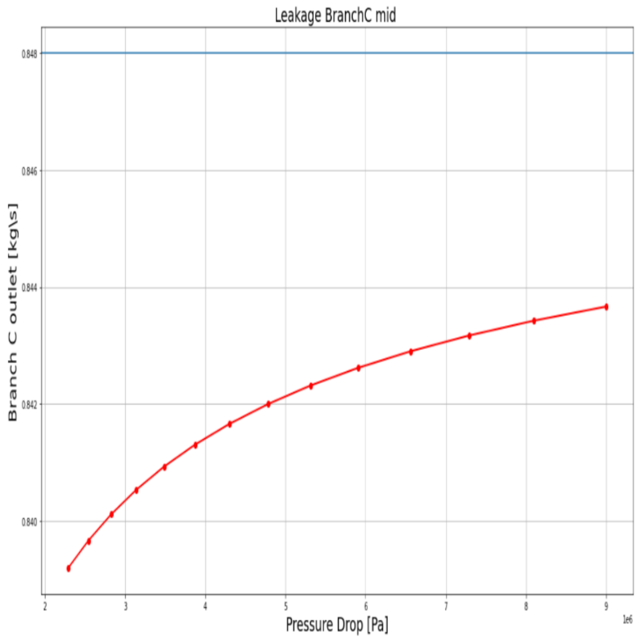


Figure 5.24 – Leakage Branch C start


Leakage BranchC mid
Inlet system [kg\s]
9.48
9.47
9.46
9.45
9.44
9.43
2
3
4
5
6
7
8
9
1e6
Pressure Drop [Pa]


Leakage BranchC mid
Outlet system [kg\s]
9.425
9.424
9.423
9.422
9.421
9.420
9.419
9.418
9.417
2
3
4
5
6
7
8
9


Leakage BranchC mid
Branch C inlet [kg\s]
0.90
0.89
0.88
0.87
0.86
0.85
2
3
4
5
6
7
8
9
1e6
Pressure Drop [Pa]


Leakage BranchC mid
Branch C outlet [kg\s]
0.848
0.846
0.844
0.842
0.840
2
3
4
5
6
7
8
9
1e6
Pressure Drop [Pa]

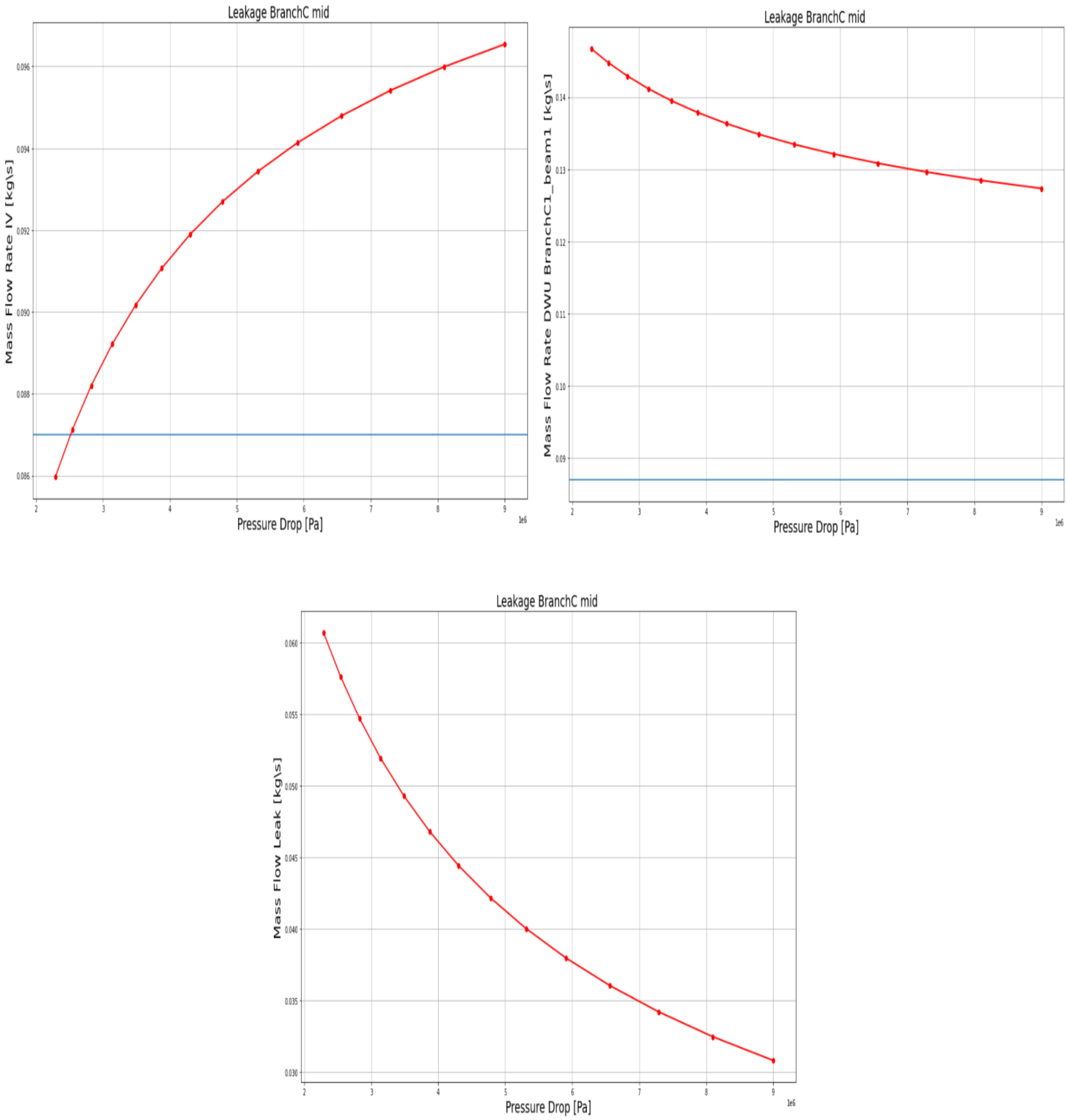
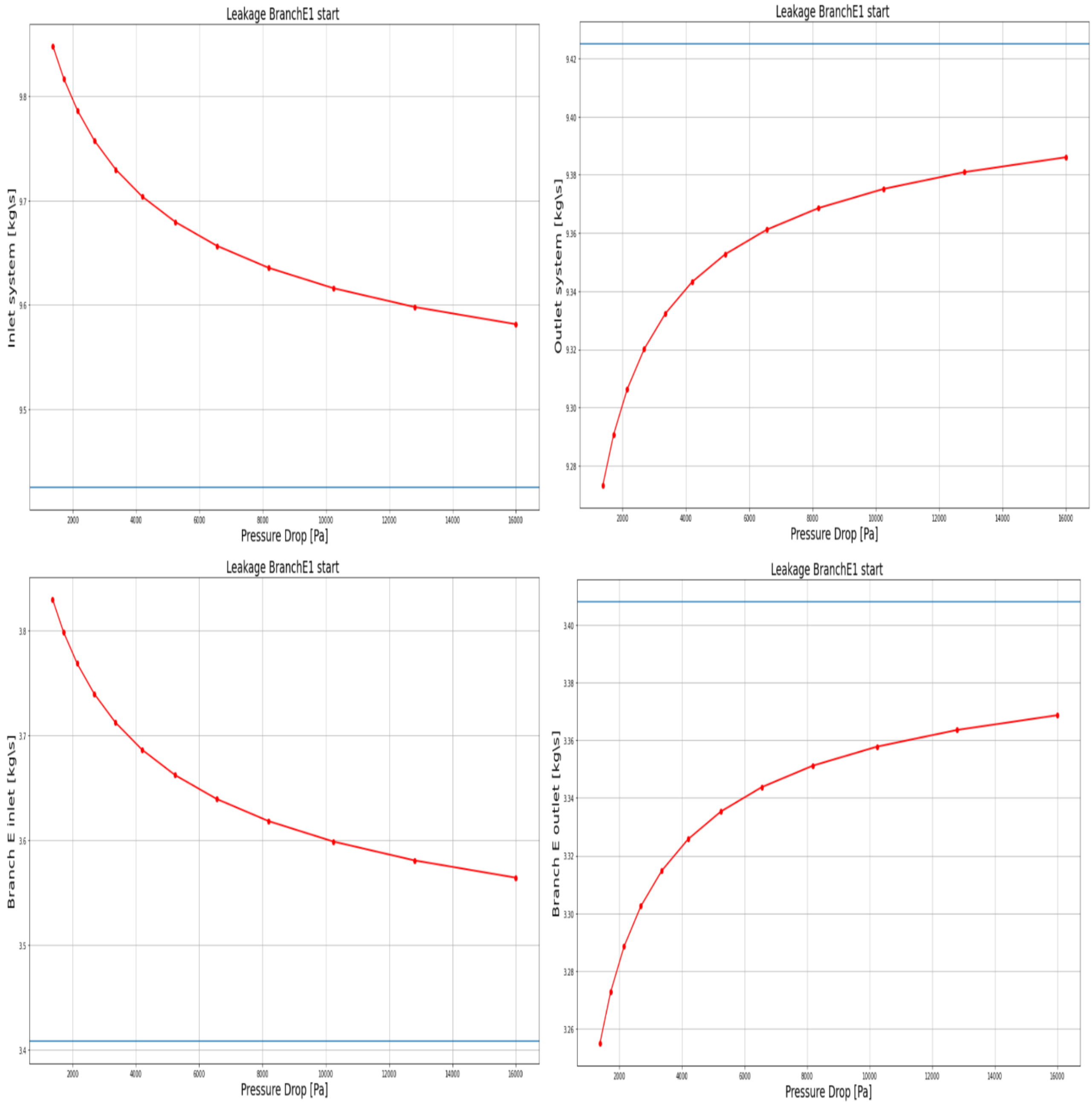


Figure 5.25 – Leakage Branch C middle


Leakage BranchE1 start
Inlet system [kg\s]
Pressure Drop [Pa]
Leakage BranchE1 start
Outlet system [kg\s]
Pressure Drop [Pa]
Leakage BranchE1 start
Branch E inlet [kg\s]
Pressure Drop [Pa]
Leakage BranchE1 start
Branch E outlet [kg\s]
Pressure Drop [Pa]

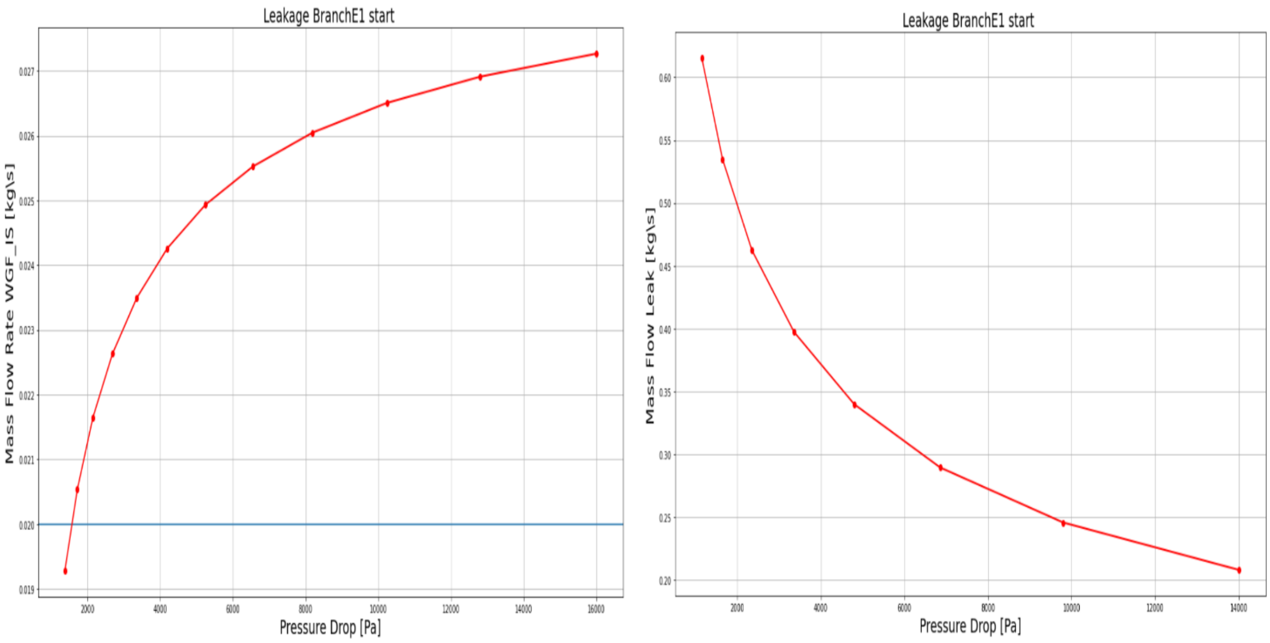
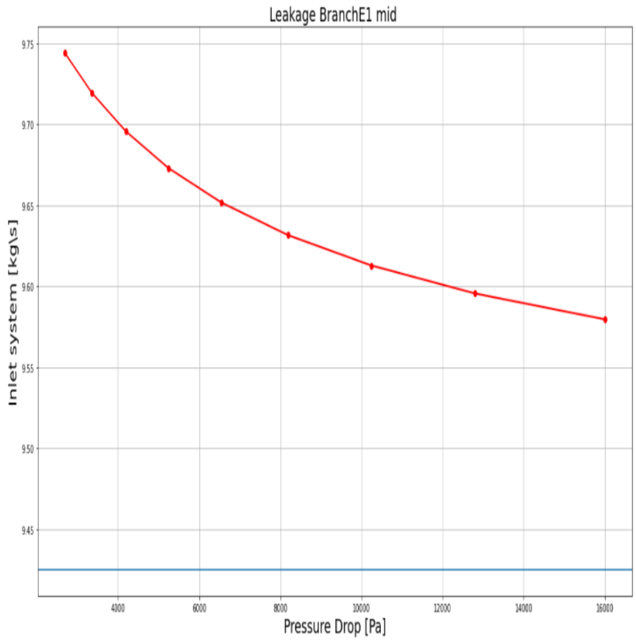
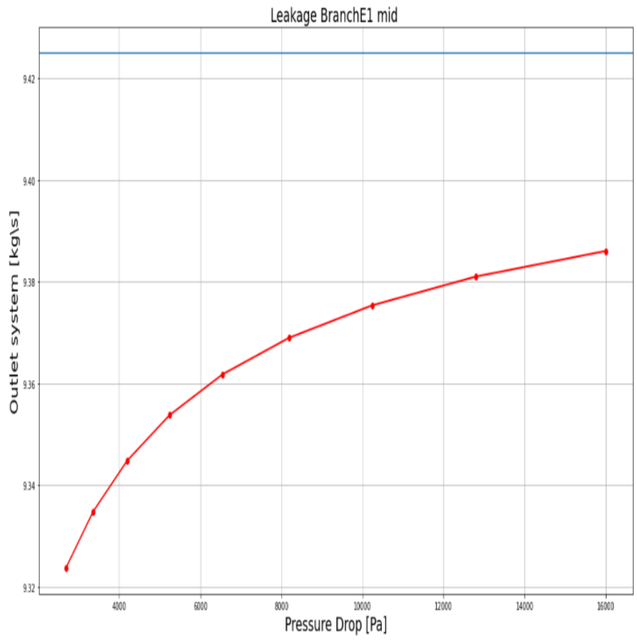
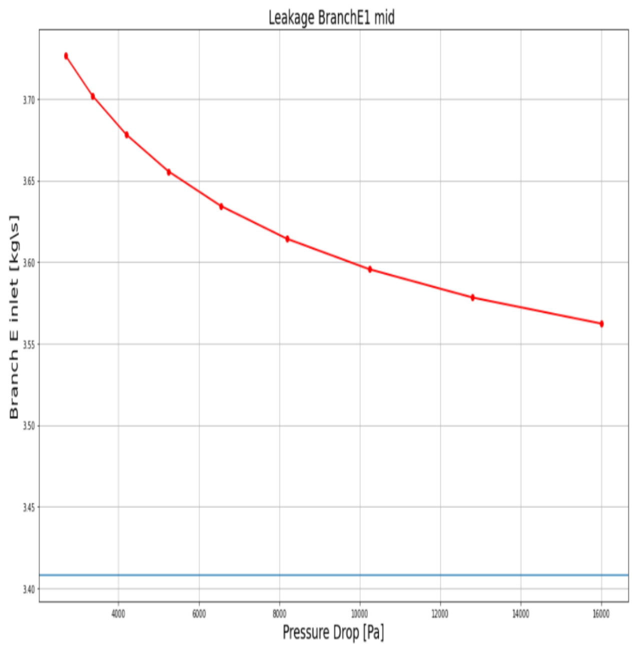
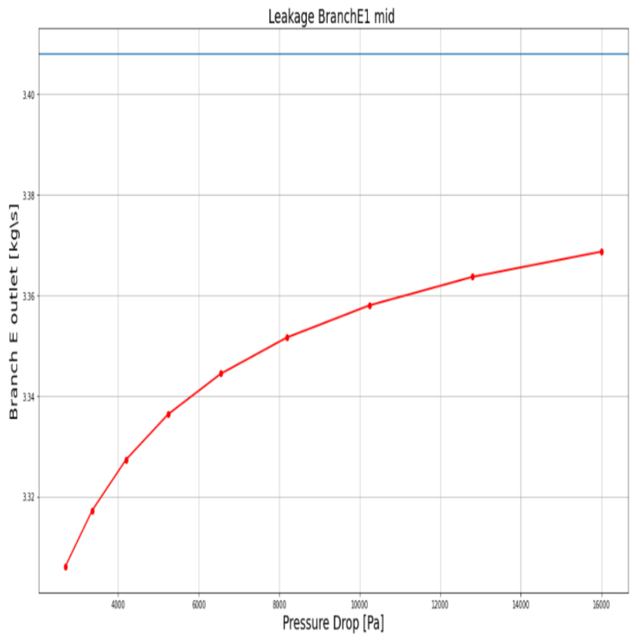


Figure 5.26 – Leakage Branch E1 start


Leakage BranchE1 mid
Inlet system [kg\s]
Pressure Drop [Pa]


Leakage BranchE1 mid
Outlet system [kg\s]
Pressure Drop [Pa]


Leakage BranchE1 mid
Branch E inlet [kg\s]
Pressure Drop [Pa]


Leakage BranchE1 mid
Branch E outlet [kg\s]
Pressure Drop [Pa]

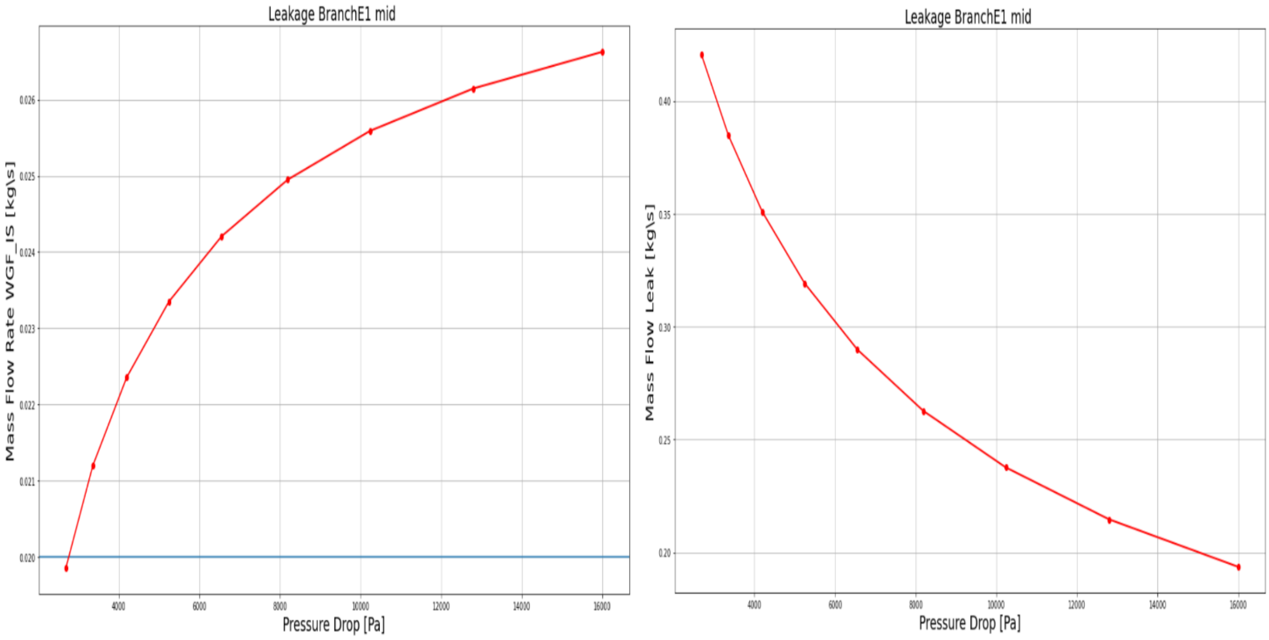
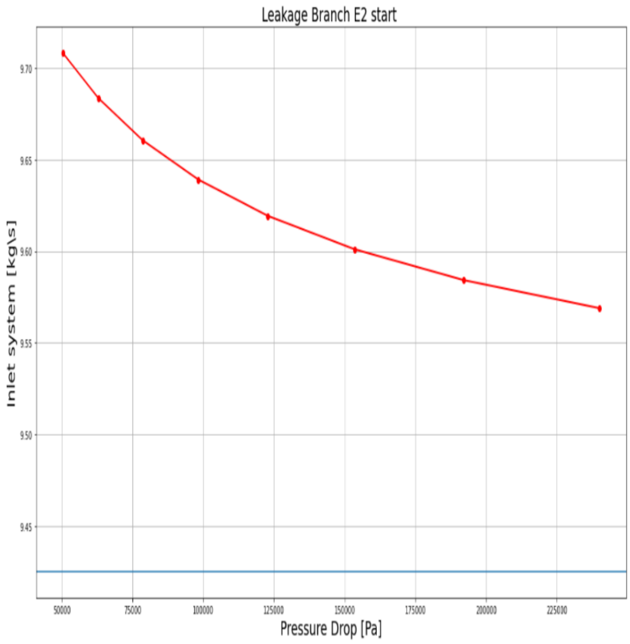
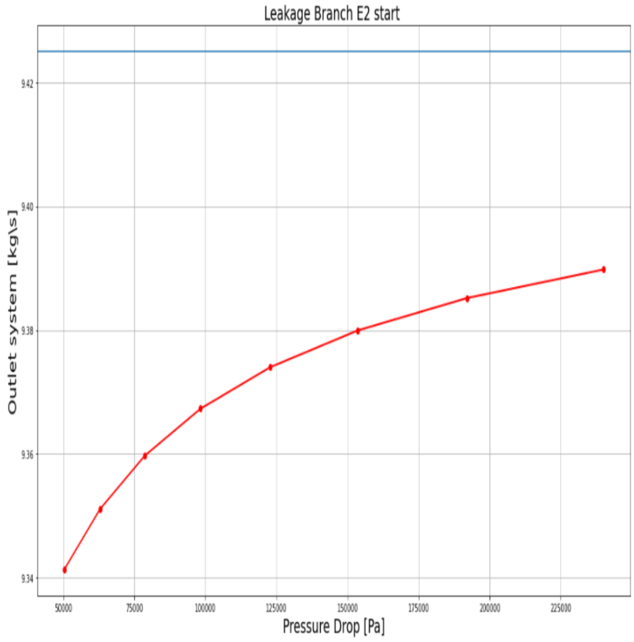
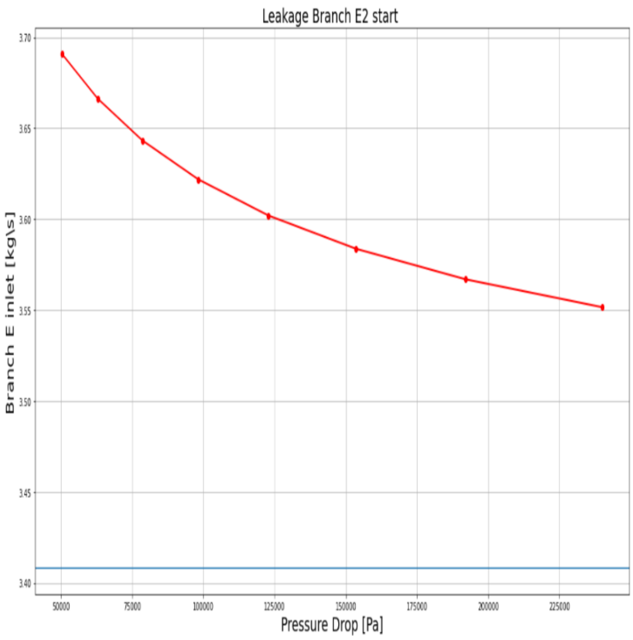
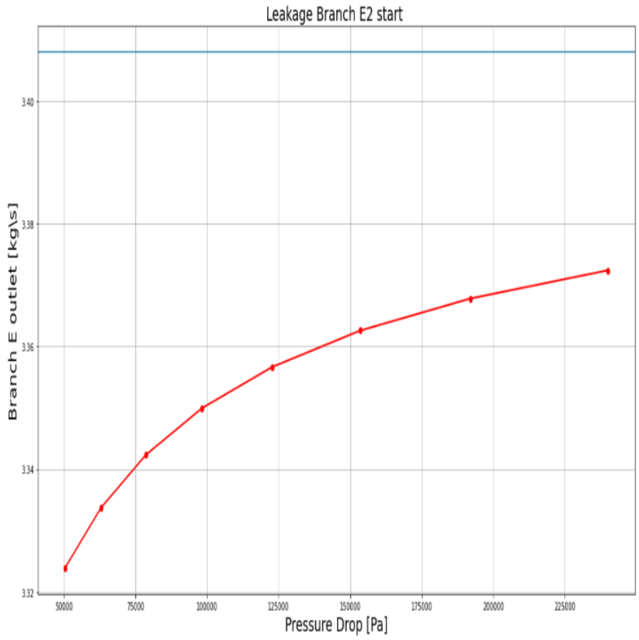


Figure 5.27 – Leakage Branch E1 middle


Leakage Branch E2 start
Inlet system [kg\s]
Pressure Drop [Pa]


Leakage Branch E2 start
Outlet system [kg\s]
Pressure Drop [Pa]


Leakage Branch E2 start
Branch E inlet [kg\s]
Pressure Drop [Pa]


Leakage Branch E2 start
Branch E outlet [kg\s]
Pressure Drop [Pa]

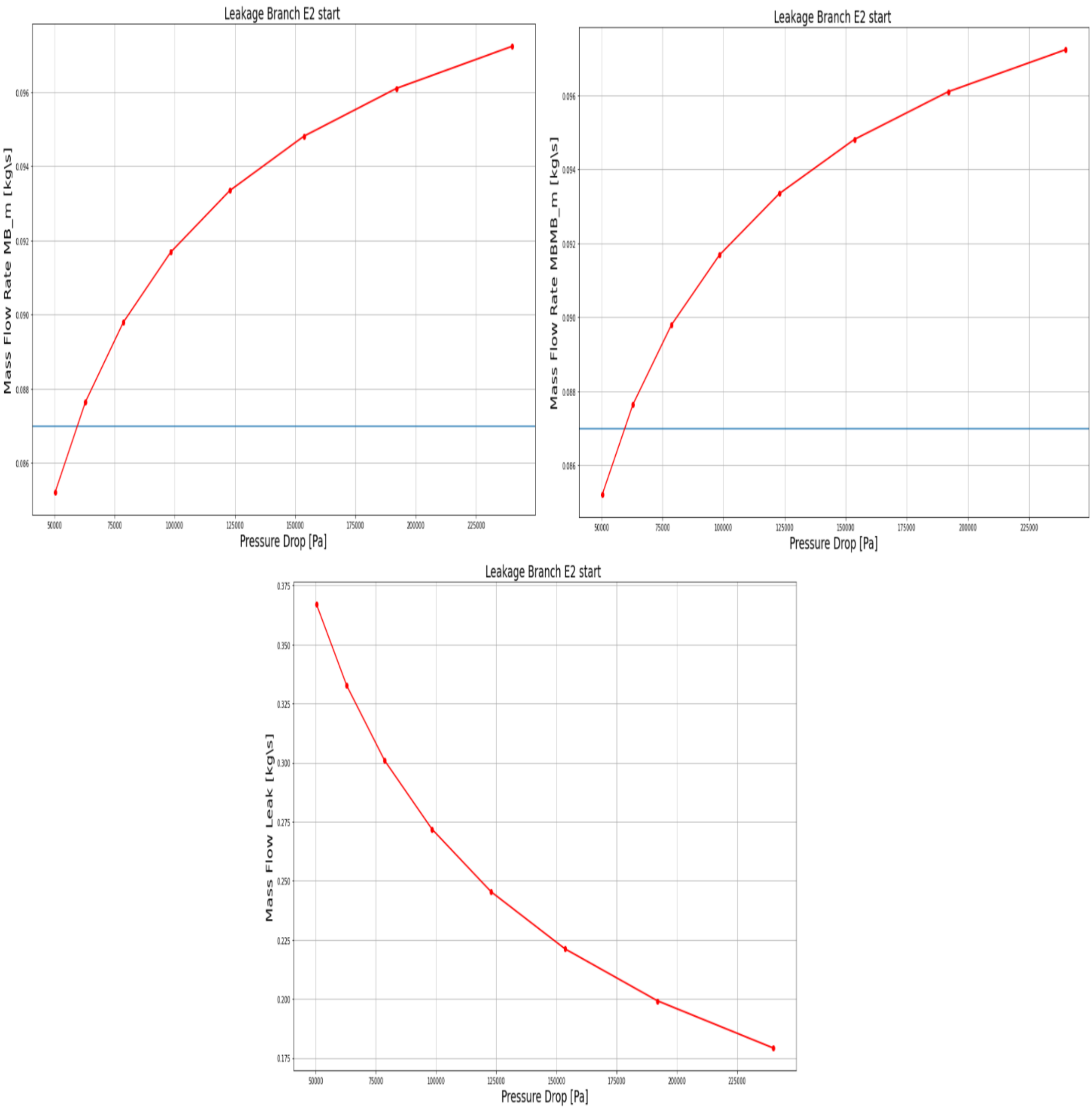
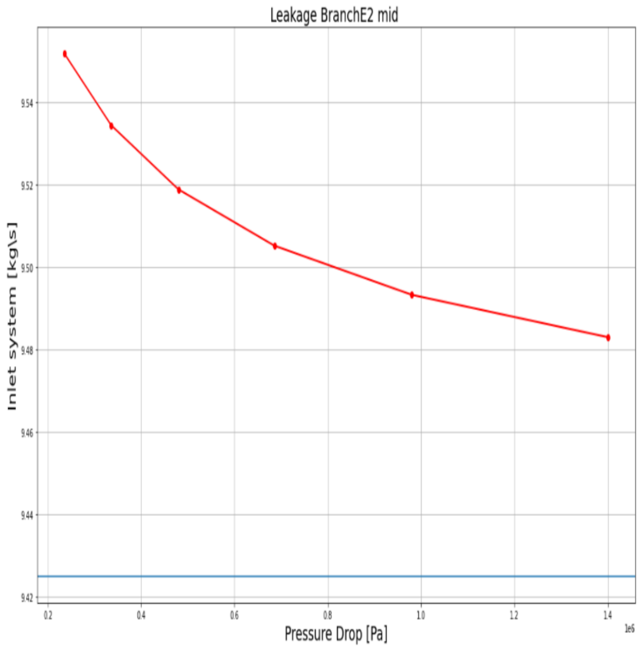
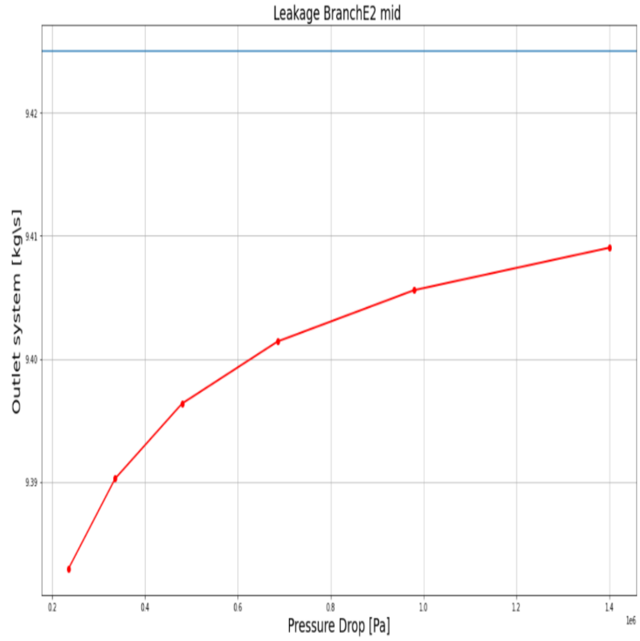
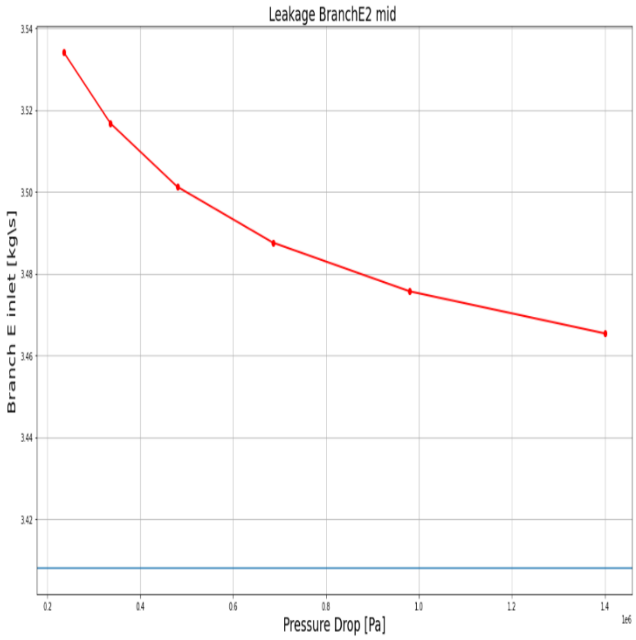
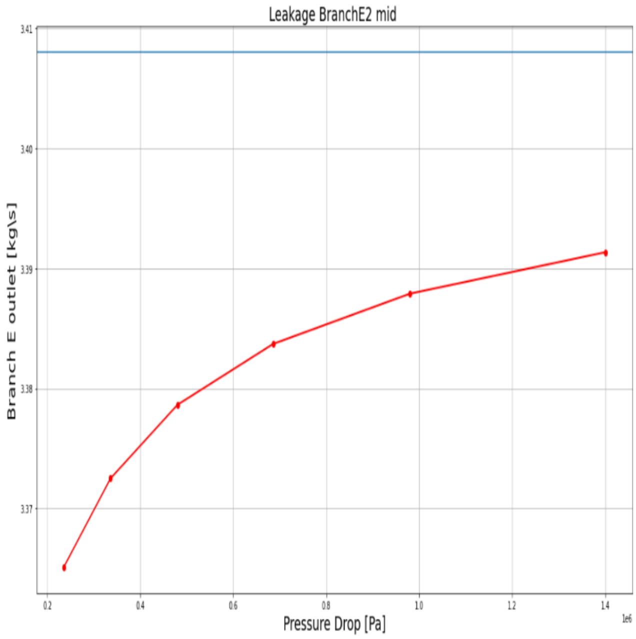


Figure 5.28 – Leakage Branch E2 start


Leakage BranchE2 mid
Inlet system [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchE2 mid
Outlet system [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchE2 mid
Branch E inlet [kg\s]
Pressure Drop [Pa]
1e6


Leakage BranchE2 mid
Branch E outlet [kg\s]
Pressure Drop [Pa]
1e6

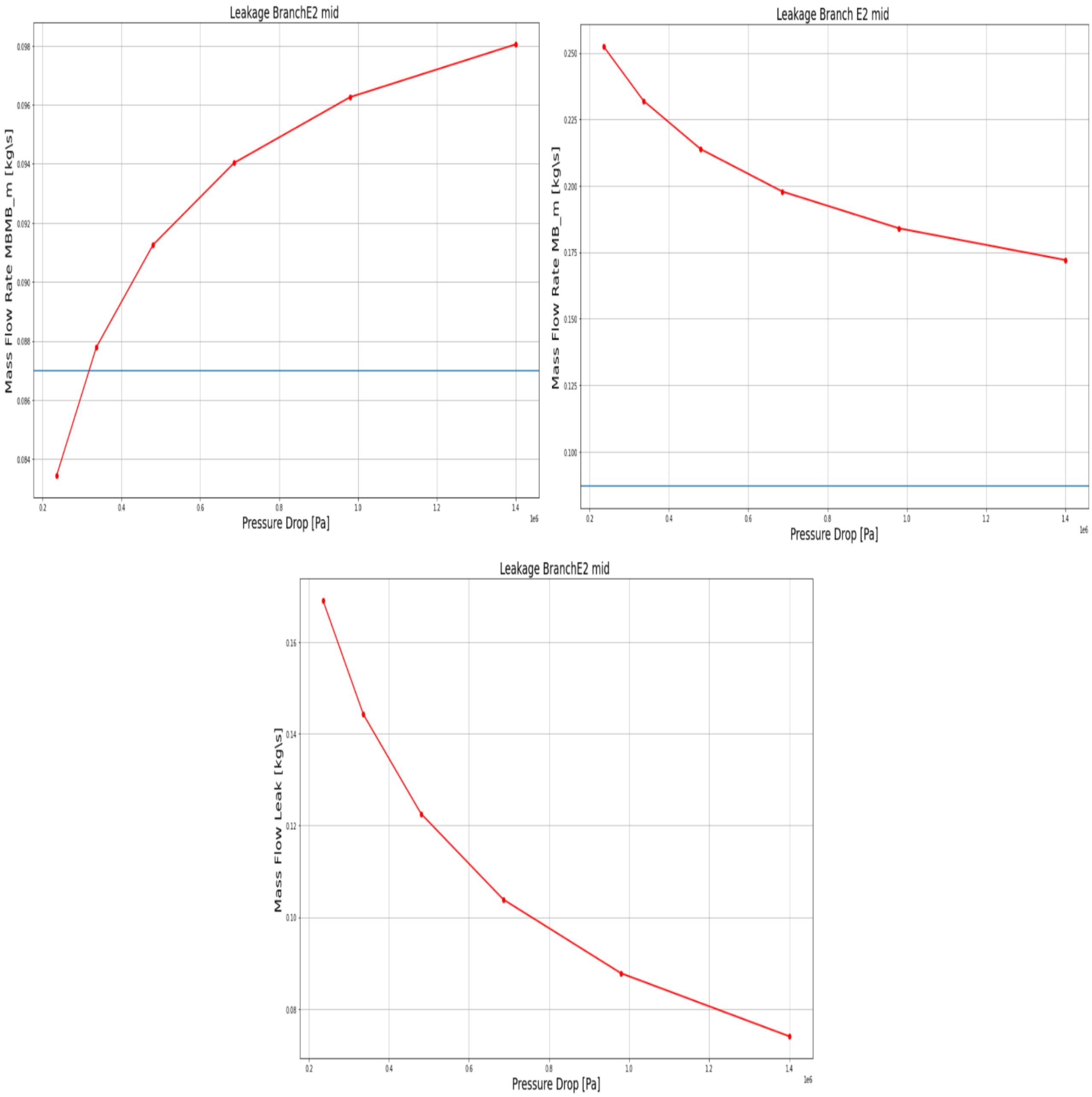
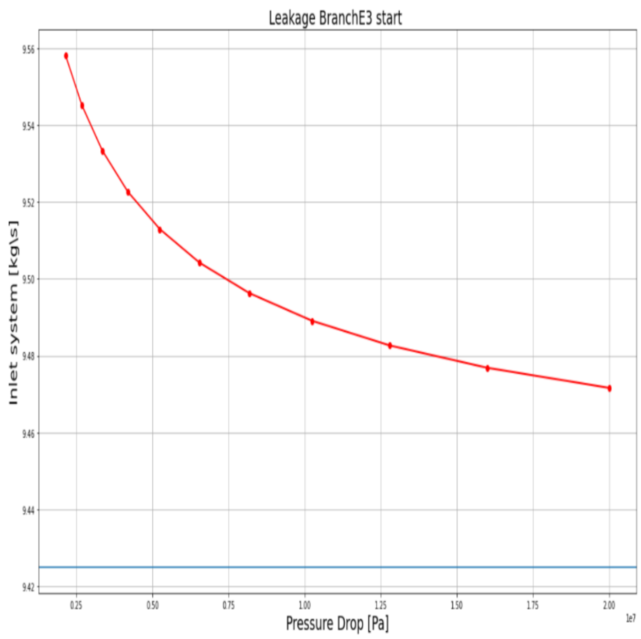
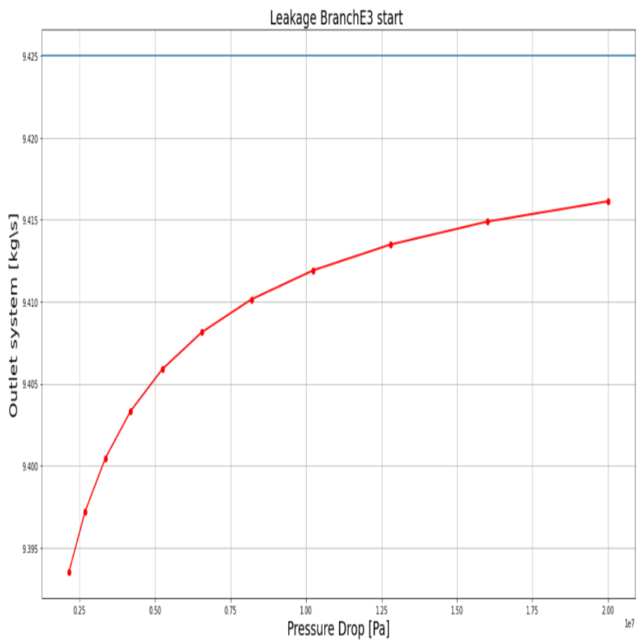
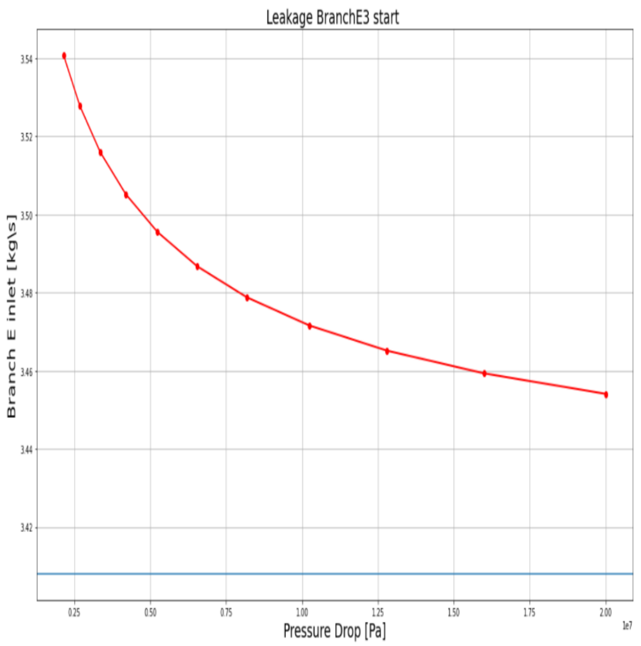
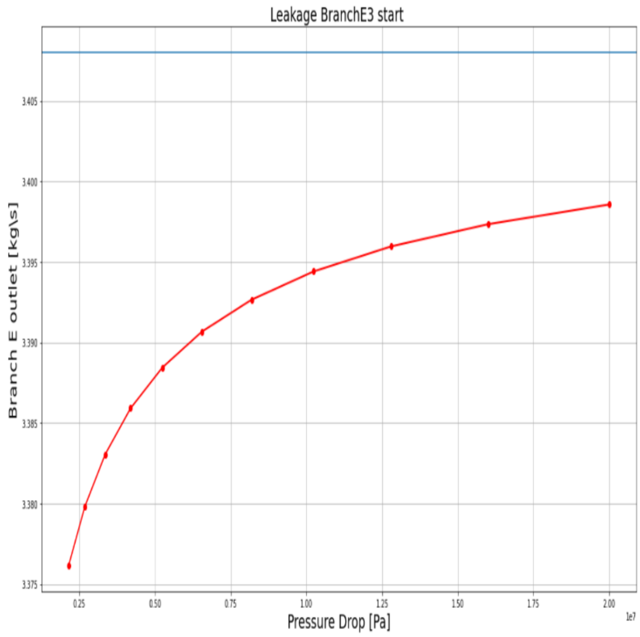


Figure 5.29 – Leakage Branch E2 middle


Leakage BranchE3 start
Inlet system [kg\s]
9.56
9.54
9.52
9.50
9.48
9.46
9.44
9.42
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e7
Pressure Drop [Pa]


Leakage BranchE3 start
Outlet system [kg\s]
9.425
9.420
9.415
9.410
9.405
9.400
9.395
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e7
Pressure Drop [Pa]


Leakage BranchE3 start
Branch E inlet [kg\s]
3.54
3.52
3.50
3.48
3.46
3.44
3.42
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e7
Pressure Drop [Pa]


Leakage BranchE3 start
Branch E outlet [kg\s]
3.405
3.400
3.395
3.390
3.385
3.380
3.375
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
1e7
Pressure Drop [Pa]

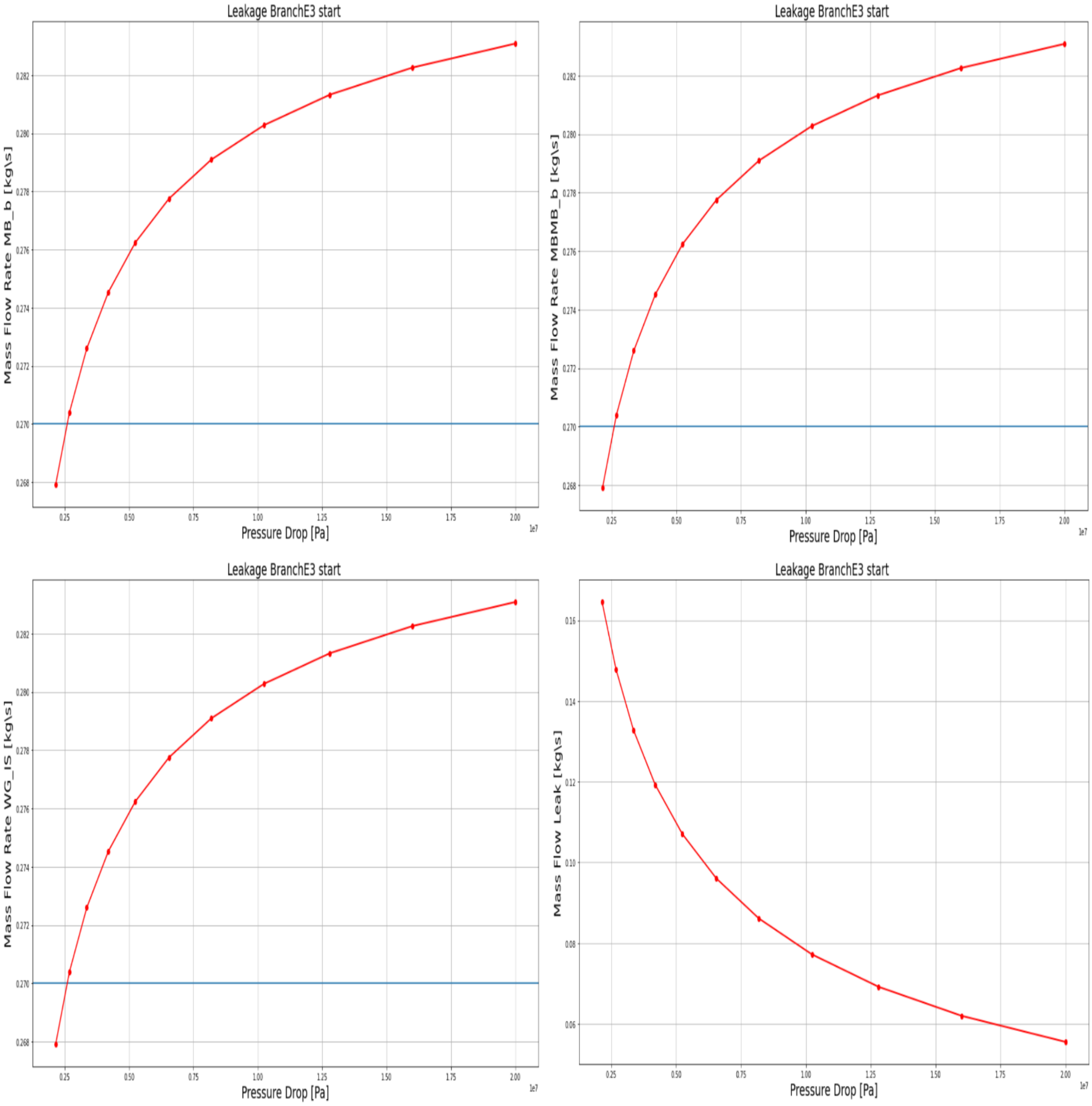
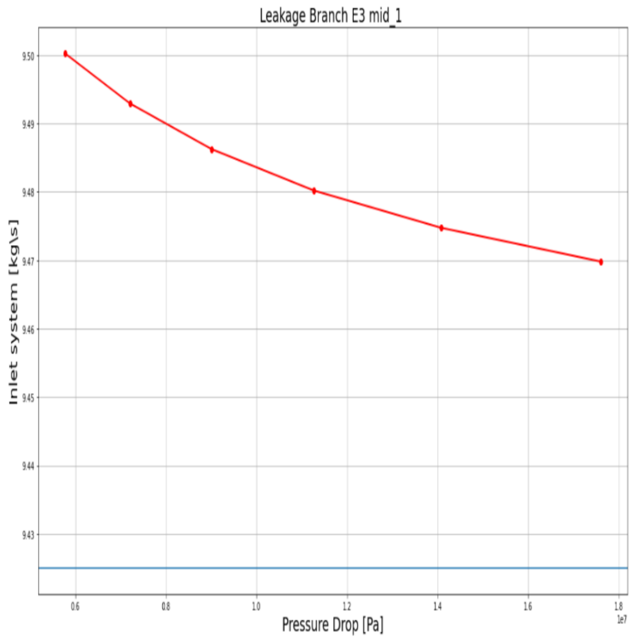
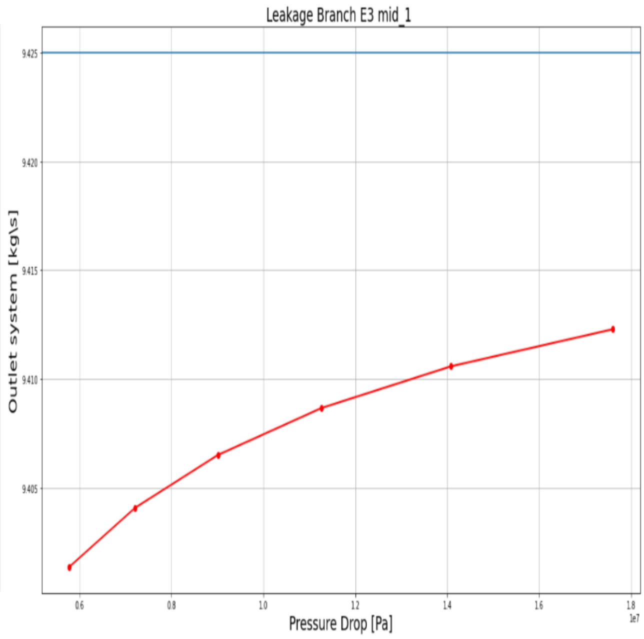
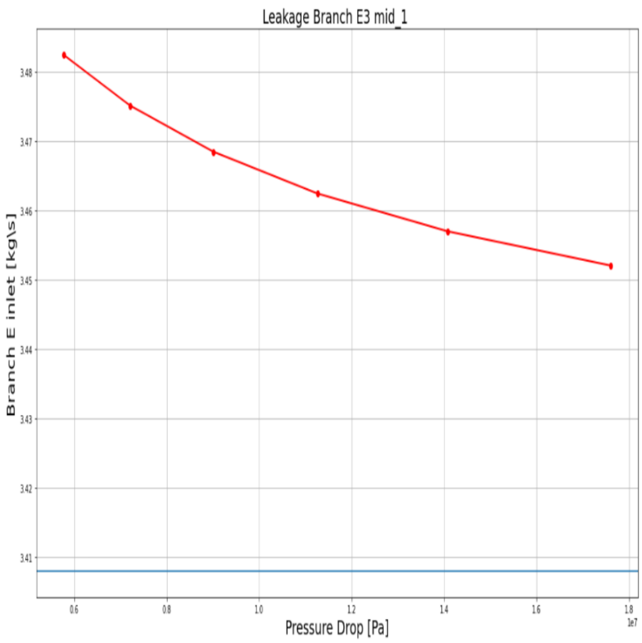
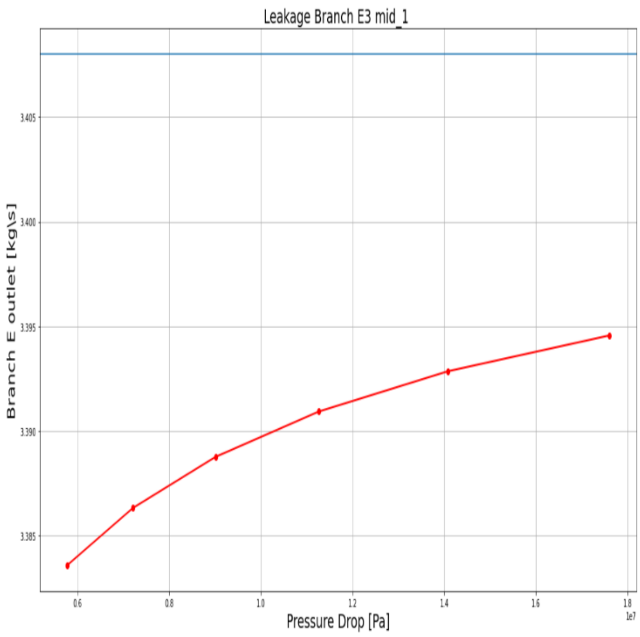


Figure 5.30 – Leakage Branch E3 start


Leakage Branch E3 mid_1
Inlet system [kg\s]
Pressure Drop [Pa]
1e7


Leakage Branch E3 mid_1
Outlet system [kg\s]
Pressure Drop [Pa]
1e7


Leakage Branch E3 mid_1
Branch E inlet [kg\s]
Pressure Drop [Pa]
1e7


Leakage Branch E3 mid_1
Branch E outlet [kg\s]
Pressure Drop [Pa]
1e7

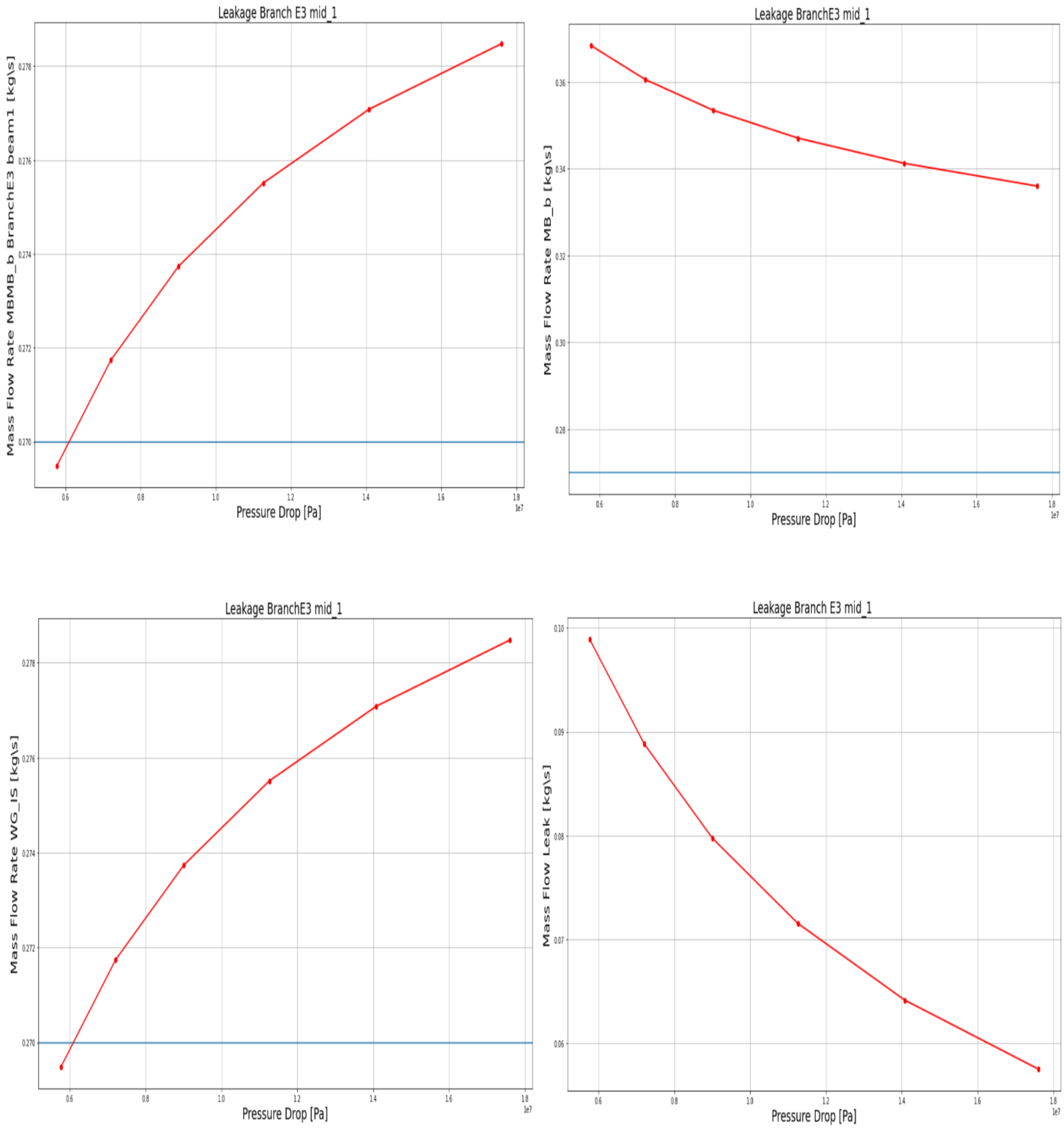
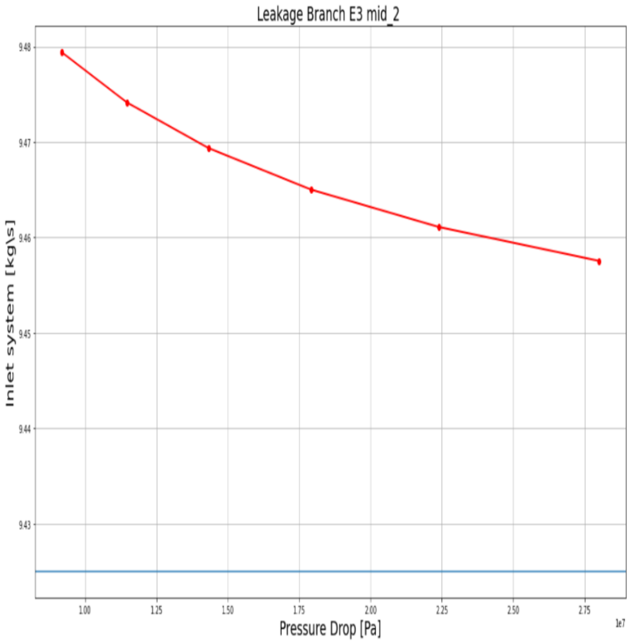
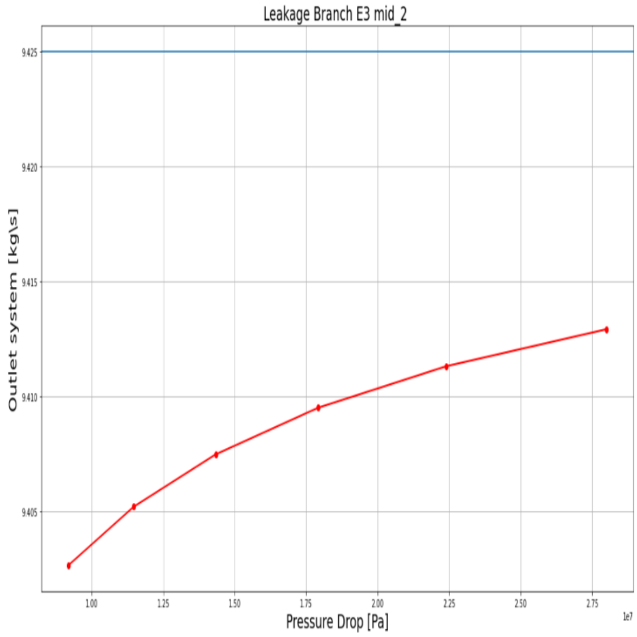
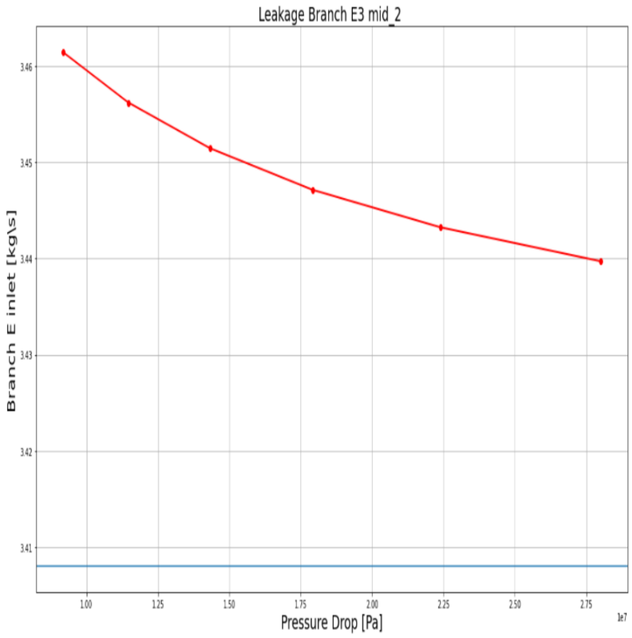
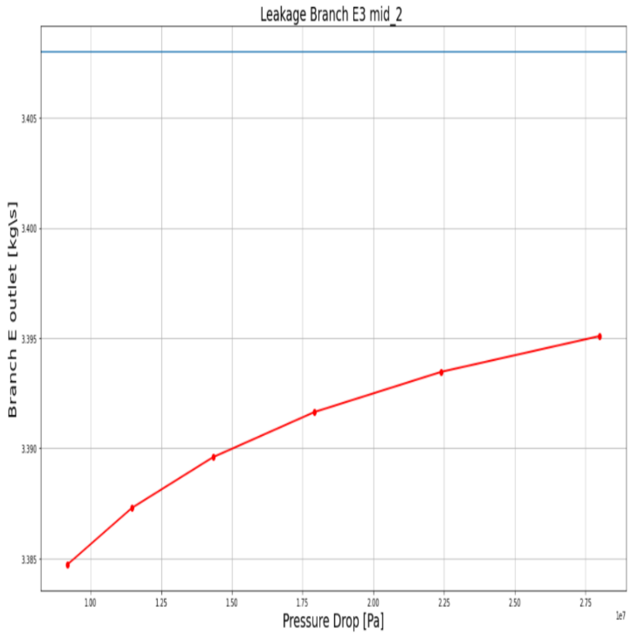


Figure 5.31 – Leakage Branch E3 middle_1


Leakage Branch E3 mid_2
Inlet system [kg\s]
Pressure Drop [Pa]
1e7


Leakage Branch E3 mid_2
Outlet system [kg\s]
Pressure Drop [Pa]
1e7


Leakage Branch E3 mid_2
Branch E inlet [kg\s]
Pressure Drop [Pa]
1e7


Leakage Branch E3 mid_2
Branch E outlet [kg\s]
Pressure Drop [Pa]
1e7

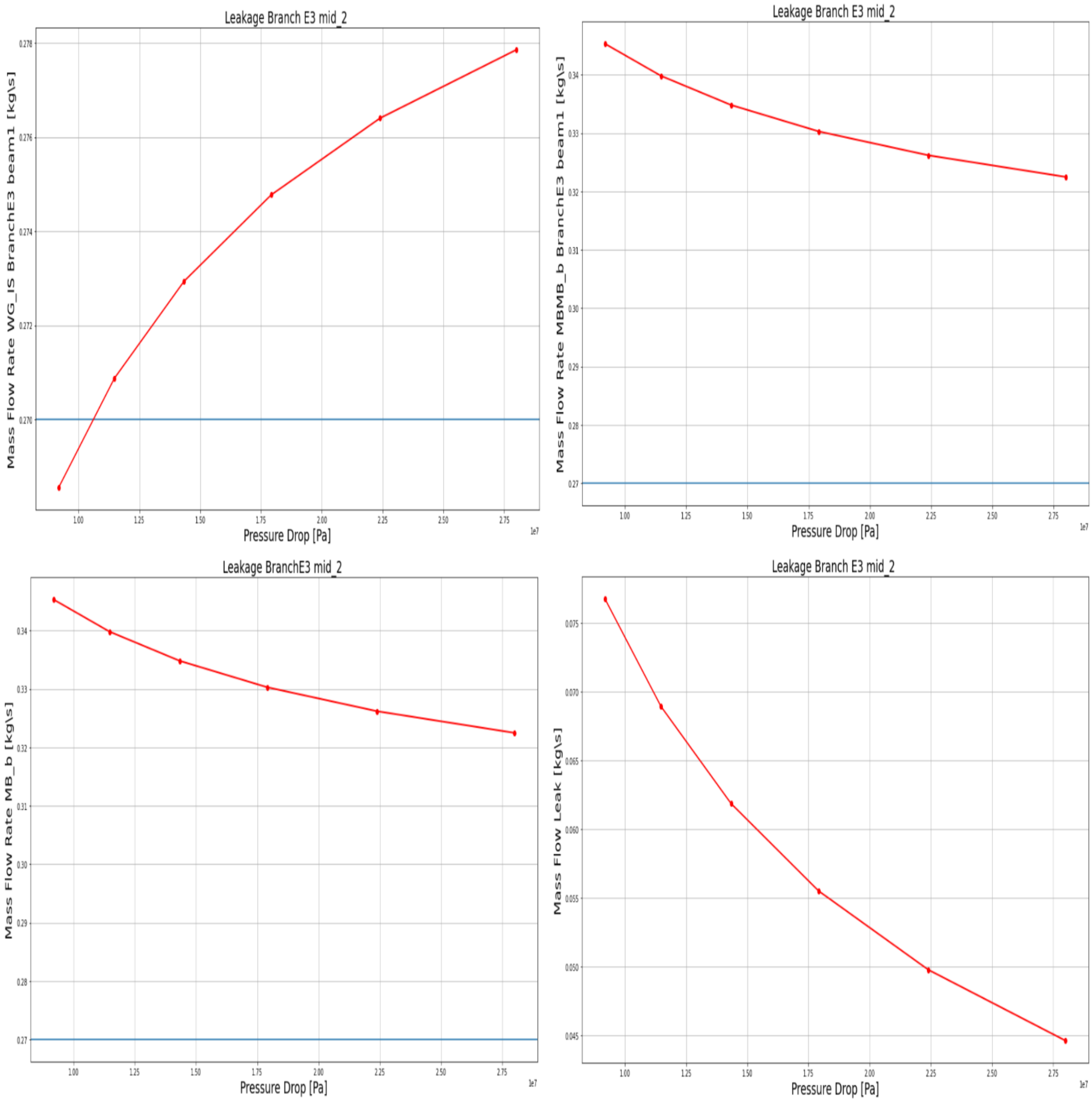


Figure 5.32 – Leakage Branch E3 middle_2

5.3 Outcomes for small break

The following figures represent the outcomes for small break. In particular, in each couple of Mass Flowmeters located in each branch, it was checked the ability to detect the loss of coolant due to the leakage.

- Leakage Branch A start

  - dp providing the minimum mass flow rate in the component = 335544.320 [Pa]

	Leakage BranchA start			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch A1	1,520642	0,332642	28,000%	✓
FlowMeter outlet Branch A1	1,087878	-0,100122	8,428%	✓
FlowMeter inlet Branch A2	1,211741	0,023741	1,998%	✓
FlowMeter outlet Branch A2	1,211741	0,023741	1,998%	✓
Mass Flow Rate FlowMeter inlet nominal = 1.188 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 1.188 [kg/s]				
Mass Flow Leak = 0,4818182028042231 [kg/s]				

Figure 5.33 – Detection Leakage Branch A start

- Leakage Branch A middle

  - dp providing the minimum mass flow rate in the component = 25418660.0 [Pa]

	Leakage BranchA middle			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch A1	1,2155	0,0275	2,315%	✓
FlowMeter outlet Branch A1	1,167436	-0,020564	1,731%	✓
FlowMeter inlet Branch A2	1,193403	0,005403	0,455%	×
FlowMeter outlet Branch A2	1,193403	0,005403	0,455%	×
Mass Flow Rate FlowMeter inlet nominal = 1.188 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 1.188 [kg/s]				
Mass Flow Leak = 0,04806405785731616 [kg/s]				

Figure 5.34 – Detection Leakage Branch A middle

- Leakage Branch B start

  - dp providing the minimum mass flow rate in the component = 114383.962275 [Pa]

	Leakage Branch B start			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch B1	0,137817	0,045817	49,801%	✓
FlowMeter outlet Branch B1	0,080011	-0,011989	13,031%	✓
FlowMeter inlet Branch B2	0,096497	0,004497	4,888%	✓
FlowMeter outlet Branch B2	0,096497	0,004497	4,888%	✓
Mass Flow Rate FlowMeter inlet nominal = 0,092 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,092 [kg/s]				
Mass Flow Leak = 0,05780534731204032 [kg/s]				

Figure 5.35 – Detection Leakage Branch B start

- Leakage Branch B middle

  - dp providing the minimum mass flow rate in the component = 137439.0 [Pa]

	Leakage Branch B middle			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch B1	0,134042	0,042042	45,697%	✓
FlowMeter outlet Branch B1	0,081146	-0,010854	11,798%	✓
FlowMeter inlet Branch B2	0,096084	0,004084	4,439%	✓
FlowMeter outlet Branch B2	0,096084	0,004084	4,439%	✓
Mass Flow Rate FlowMeter inlet nominal = 0,092 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,092 [kg/s]				
Mass Flow Leak = 0,05882281058479268 [kg/s]				

Figure 5.36 – Detection Leakage Branch B middle

- Leakage Branch C start

  - dp providing the minimum mass flow rate in the component = 140737.5 [Pa]

	Leakage Branch C start			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch C1	0,590906	0,166906	39,365%	✓
FlowMeter outlet Branch C1	0,350844	-0,073156	17,254%	✓
FlowMeter inlet Branch C2	0,462391	0,038391	9,055%	✓
FlowMeter outlet Branch C2	0,462391	0,038391	9,055%	✓
Mass Flow Rate FlowMeter inlet nominal = 0,424 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,424 [kg/s]				
Mass Flow Leak = 0,2670921597738475 [kg/s]				

Figure 5.37 – Detection Leakage Branch C start

- Leakage Branch C middle

  - dp providing the minimum mass flow rate in the component = 2541866.0 [Pa]

	Leakage Branch C middle			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch C1	0,463621	0,039621	9,345%	✓
FlowMeter outlet Branch C1	0,405979	-0,018021	4,250%	✓
FlowMeter inlet Branch C2	0,433689	0,009689	2,285%	✓
FlowMeter outlet Branch C2	0,433689	0,009689	2,285%	✓
Mass Flow Rate FlowMeter inlet nominal = 0,424 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,424 [kg/s]				
Mass Flow Leak = 0,05764206156085827 [kg/s]				

Figure 5.38 – Detection Leakage Branch C middle

- Leakage Branch E1 start

  - dp providing the minimum mass flow rate in the component = 0.01717986918 [Pa]

	Leakage Branch E1 start			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,822476	0,396476	93,069%	✓
FlowMeter outlet Branch E0 beam 1	0,287535	-0,138465	32,504%	✓
FlowMeter inlet Branch E0 beam 2	0,426001	0,000001	0,0003%	×
FlowMeter outlet Branch E0 beam2	0,426001	0,000001	0,0003%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426 [kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				
Mass Flow Leak = 0,5747578452218567 [kg/s]				

Figure 5.39 – Detection Leakage Branch E1 start

- Leakage Branch E1 middle

  - dp providing the minimum mass flow rate in the component = 0.0335544320 [Pa]

	Leakage Branch E1 middle			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0.720098	0,294098	69,037%	✓
FlowMeter outlet Branch E0 beam 1	0,335425	-0,090575	21,262%	✓
FlowMeter inlet Branch E0 beam 2	0,425974	-0,000026	0,0062%	×
FlowMeter outlet Branch E0 beam 2	0,425974	-0,000026	0,0062%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426[kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				
Mass Flow Leak = 0,4205699154089425 [kg/s]				

Figure 5.40 – Detection Leakage Branch E_1 middle

- Leakage Branch E2 start

  - dp providing the minimum mass flow rate in the component = 0.62914560 [Pa]

	Leakage Branch E2 start			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,684524	0,258524	60,686%	✓
FlowMeter outlet Branch E0 beam 1	0,351935	-0,074065	17,386%	✓
FlowMeter inlet Branch E0 beam 2	0,425964	-0,000036	0,0085%	×
FlowMeter outlet Branch E0 beam 2	0,425964	-0,000036	0,0085%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426[kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				
Mass Flow Leak = 0,3670619341256454 [kg/s]				

Figure 5.41 – Detection Leakage Branch E2 start

- Leakage Branch E2 middle

  - dp providing the minimum mass flow rate in the component = 336140.0 [Pa]

	Leakage Branch E2 mid			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,534675	0,108675	25,511%	✓
FlowMeter outlet Branch E0 beam 1	0,390512	-0,035488	8,331%	✓
FlowMeter inlet Branch E0 beam 2	0,426	-1,85E-07	0,00004%	×
FlowMeter outlet Branch E0 beam 2	0,426	-1,85E-07	0,00004%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426[kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				
Mass Flow Leak = 0,168979665088865 [kg/s]				

Figure 5.42 – Detection Leakage Branch E2 middle

- Leakage Branch E3 start

  - dp providing the minimum mass flow rate in the component = 2684354.56 [Pa]

	Leakage Branch E3 start			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,545932	0,119932	28,153%	✓
FlowMeter outlet Branch E0 beam 1	0,398019	-0,027981	6,568%	✓
FlowMeter inlet Branch E0 beam 2	0,425971	-0,000029	0,0069%	×
FlowMeter outlet Branch E0 beam 2	0,425971	-0,000029	0,0069%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426[kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				
Mass Flow Leak = 0,1479129450537463 [kg/s]				

Figure 5.43 – Detection Leakage Branch E3 start

- Leakage Branch E3 middle_1

  - dp providing the minimum mass flow rate in the component = 7208960.0 [Pa]

	Leakage Branch E3 mid_1			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,49314	0,067140	15,761%	✓
FlowMeter outlet Branch E0 beam 1	0,404323	-0,021677	5,088%	✓
FlowMeter inlet Branch E0 beam 2	0,426001	1,33E-06	0,0003%	×
FlowMeter outlet Branch E0 beam 2	0,426001	1,33E-06	0,0003%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426[kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				
Mass Flow Leak = 0,09889953492212067 [kg/s]				

Figure 5.44 – Detection Leakage Branch E3 middle_1

- Leakage Branch E3 middle_2

  - dp providing the minimum mass flow rate in the component = 11468800.0 [Pa]

	Leakage Branch E3 mid_2			
	Mass Flow	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
FlowMeter inlet Branch E0 beam 1	0,474095	0,048095	11,290%	✓
FlowMeter outlet Branch E0 beam 1	0,405184	-0,020816	4,886%	✓
FlowMeter inlet Branch E0 beam 2	0,426016	1,60E-05	0,0036%	×
FlowMeter outlet Branch E0 beam 2	0,426016	1,60E-05	0,0036%	×
Mass Flow Rate FlowMeter inlet nominal = 0,426[kg/s]				
Mass Flow Rate FlowMeter outlet nominal = 0,426 [kg/s]				
Mass Flow Leak = 0,06891014917083321 [kg/s]				

Figure 5.45 – Detection Leakage Branch E3 middle_2

5.4 Double ended guillotine

The beam affected by the leak was directly collected to ambient for the modelling of the double ended guillotine, without any resistance given by the orifice: a model for each location of the leak was implemented. These leakages could cause a flow reversal in certain sections of the system.

In the following figures the models implemented through OpenModelica will be introduced:

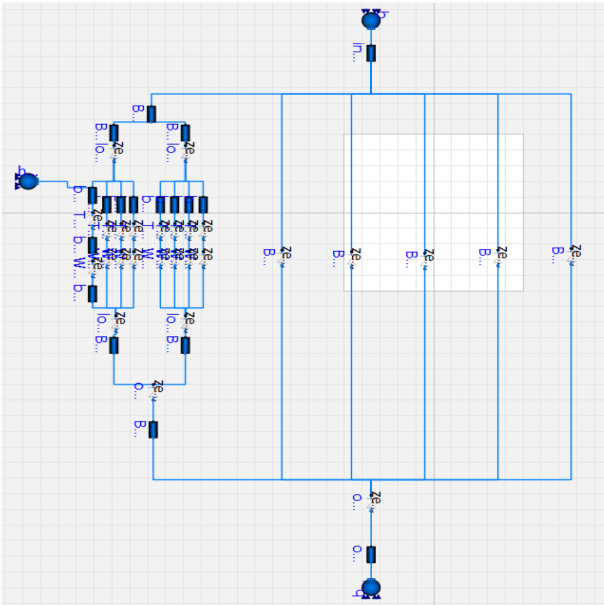


Figure 5.46 – Double Ended Guillotine Branch A start

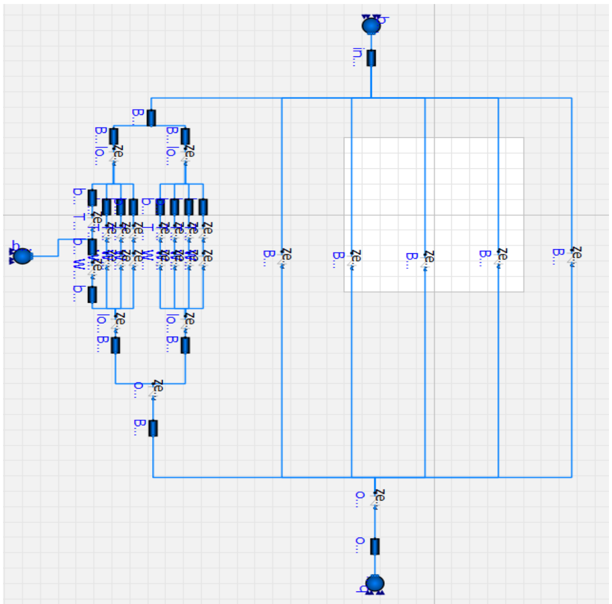


Figure 5.47 – Double Ended Guillotine Branch A middle

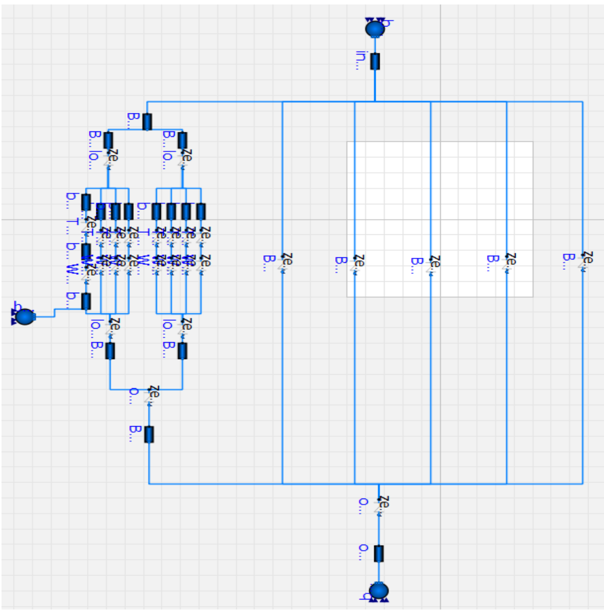


Figure 5.48 – Double Ended Guillotine Branch A end

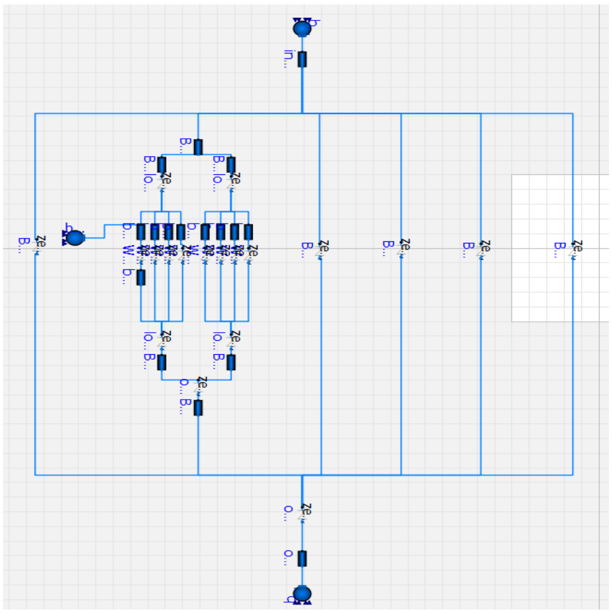


Figure 5.49 – Double Ended Guillotine Branch B start

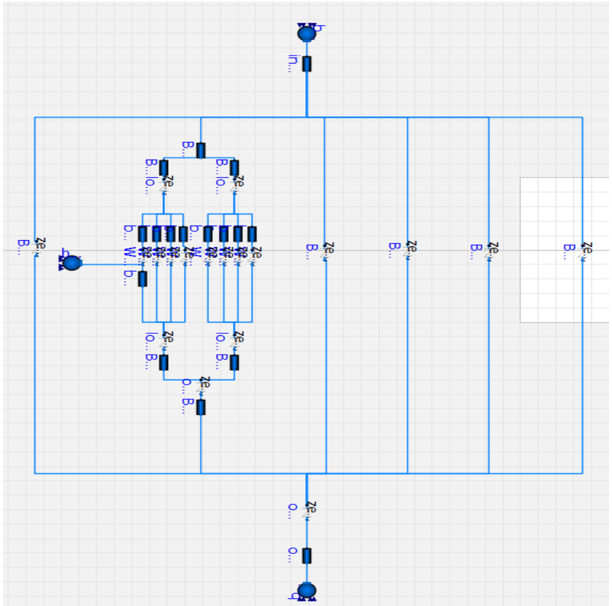


Figure 5.50 – Double Ended Guillotine Branch B middle

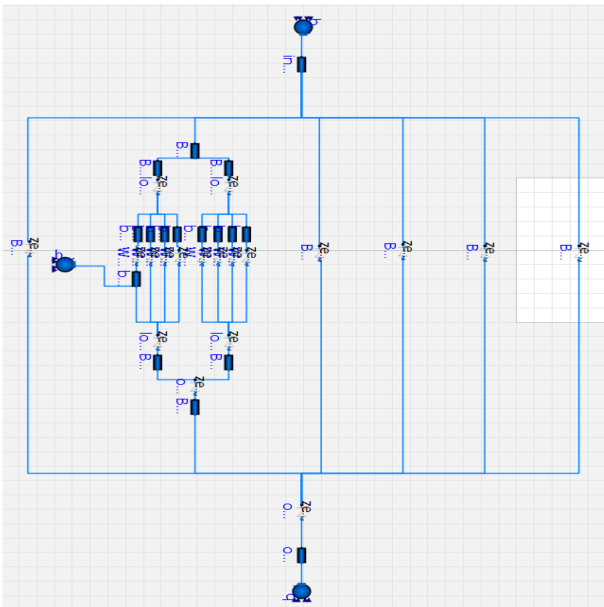


Figure 5.51 – Double Ended Guillotine Branch B end

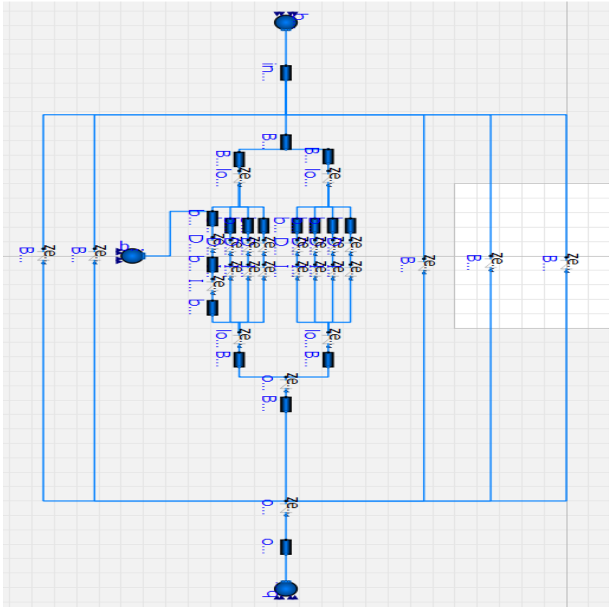


Figure 5.52 – Double Ended Guillotine Branch C start

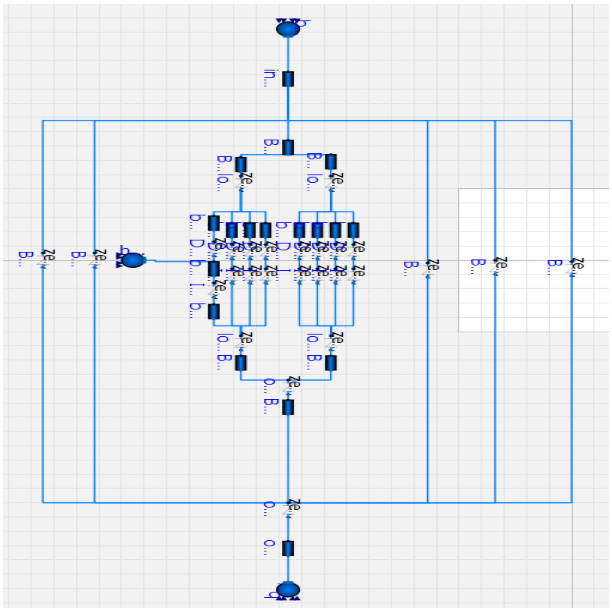


Figure 5.53 – Double Ended Guillotine Branch C middle

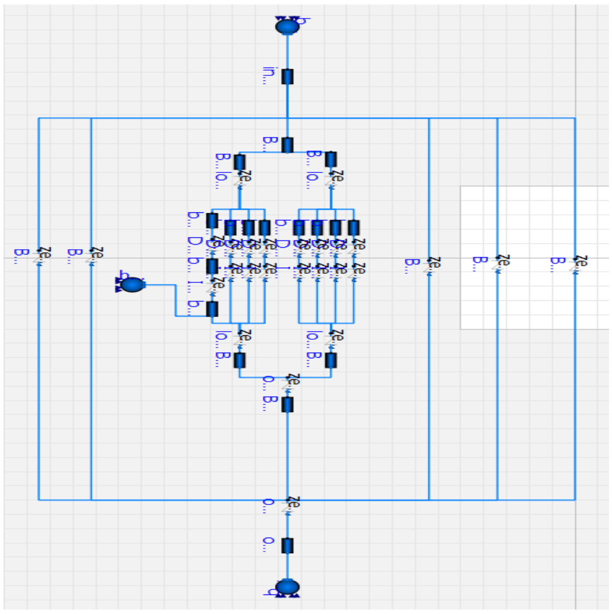


Figure 5.54 – Double Ended Guillotine Branch C end

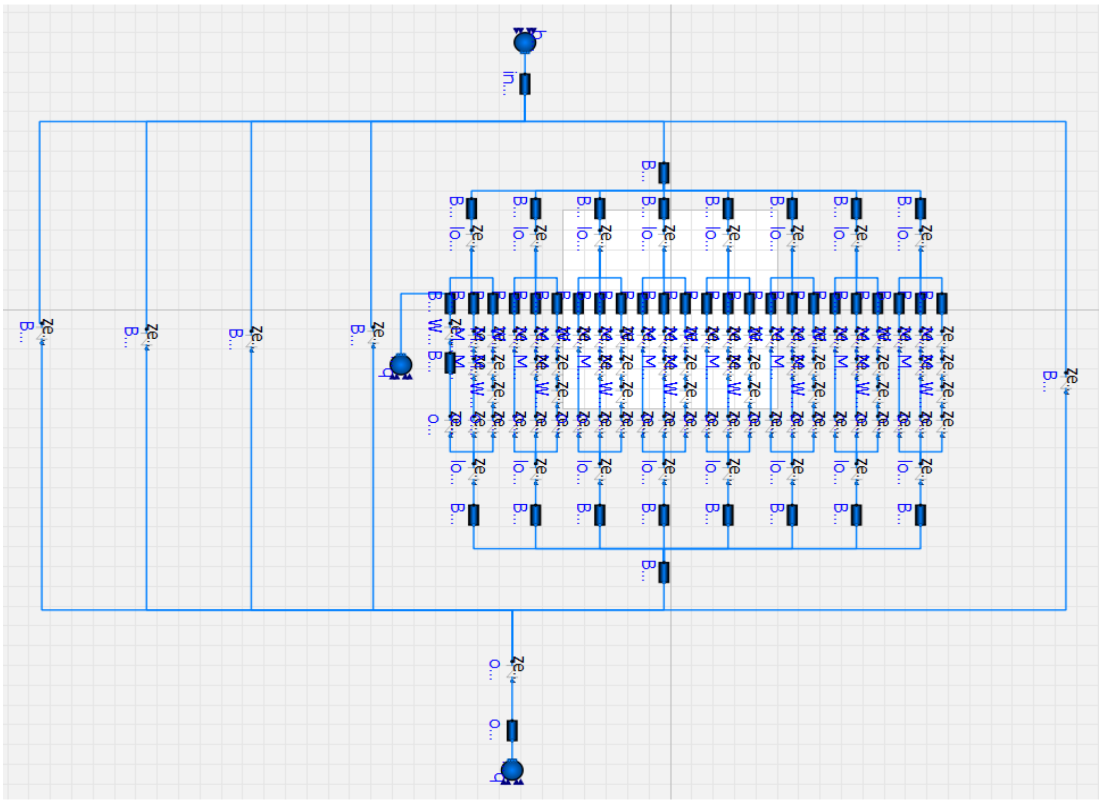


Figure 5.55 – Double Ended Guillotine Branch E1 start

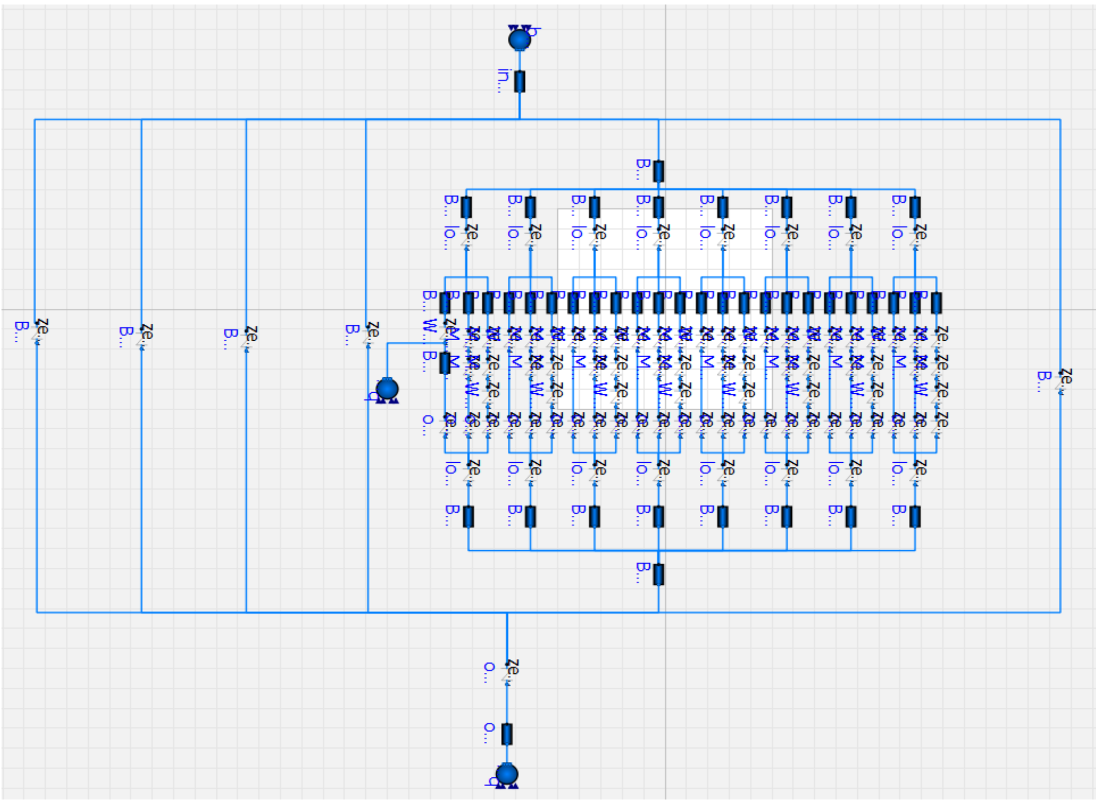


Figure 5.56 – Double Ended Guillotine Branch E1 middle

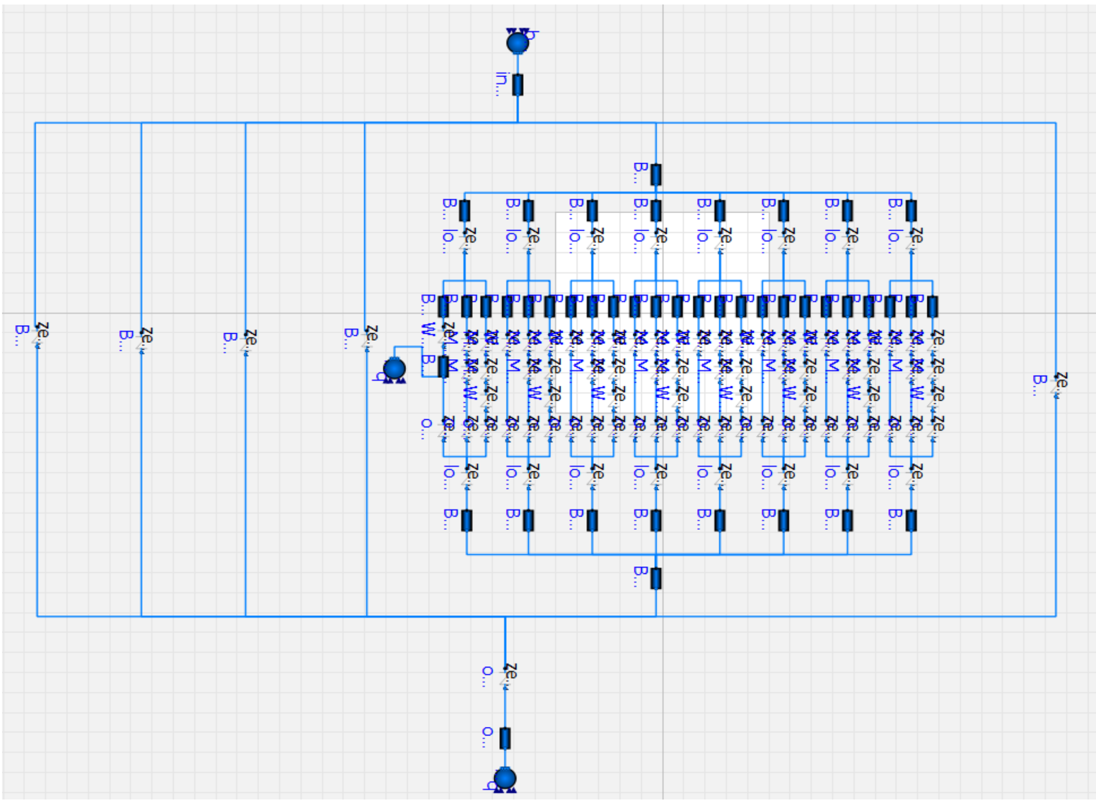


Figure 5.57 – Double Ended Guillotine Branch E1 end

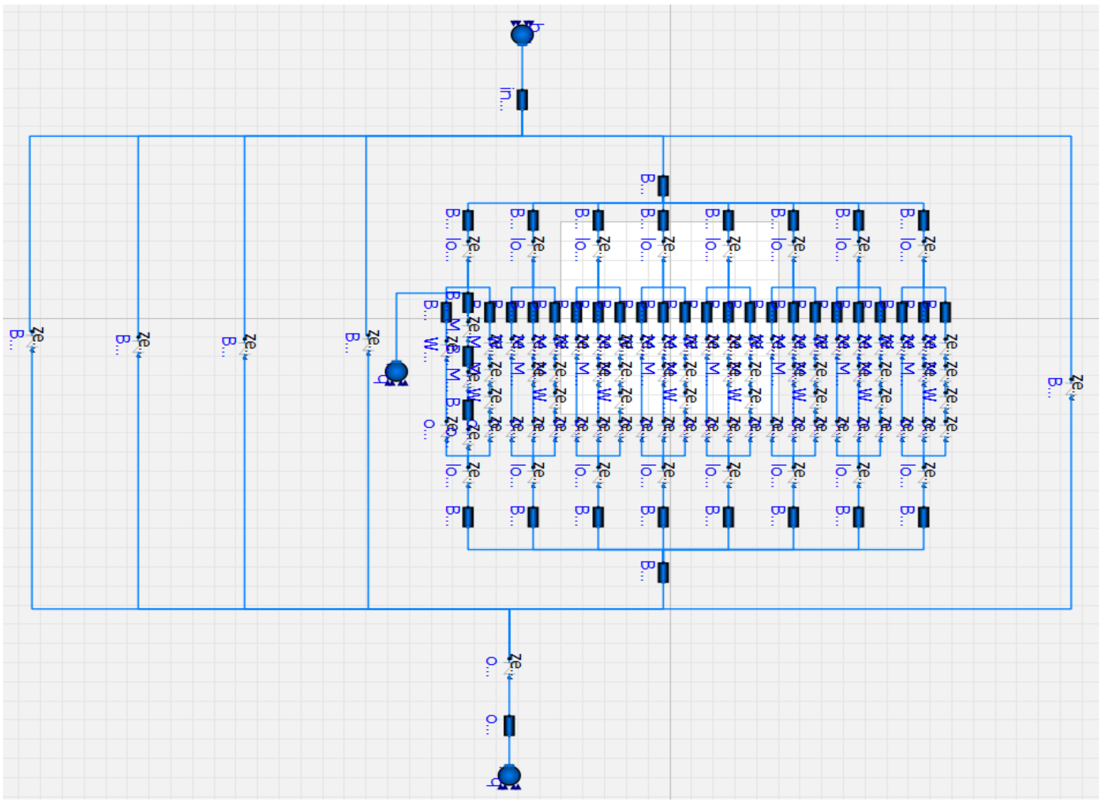


Figure 5.58 – Double Ended Guillotine Branch E2 start

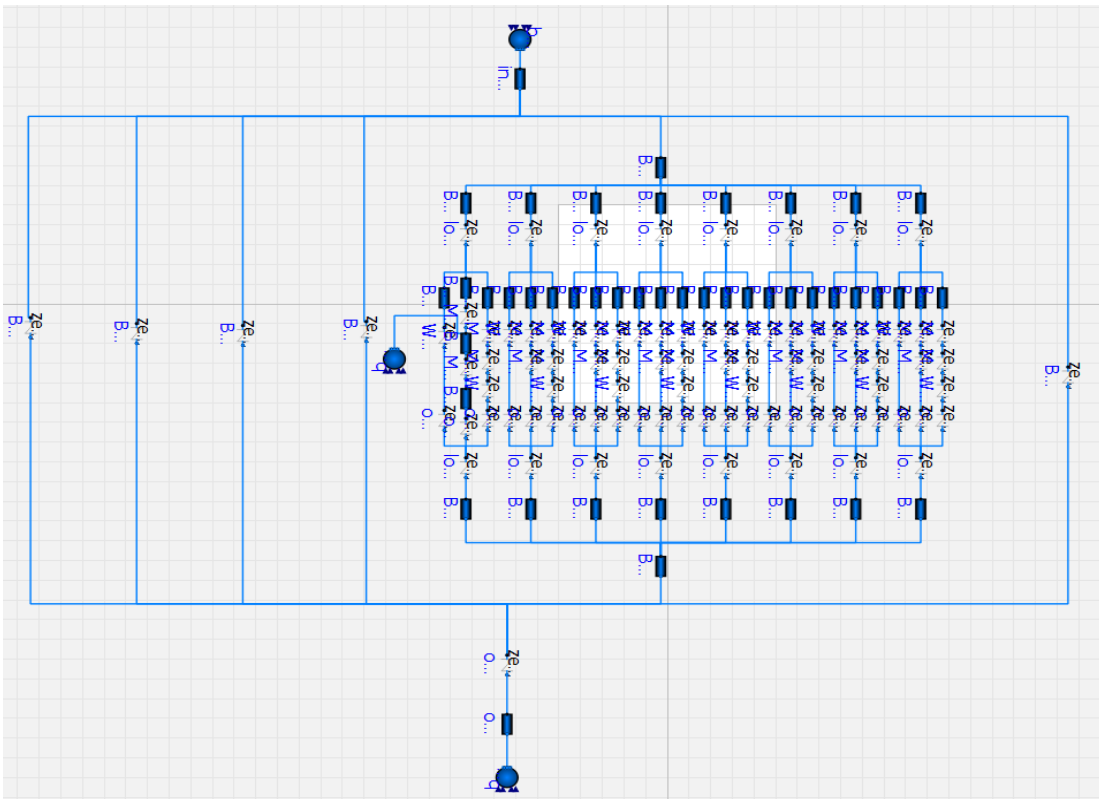


Figure 5.59 – Double Ended Guillotine Branch E2 middle

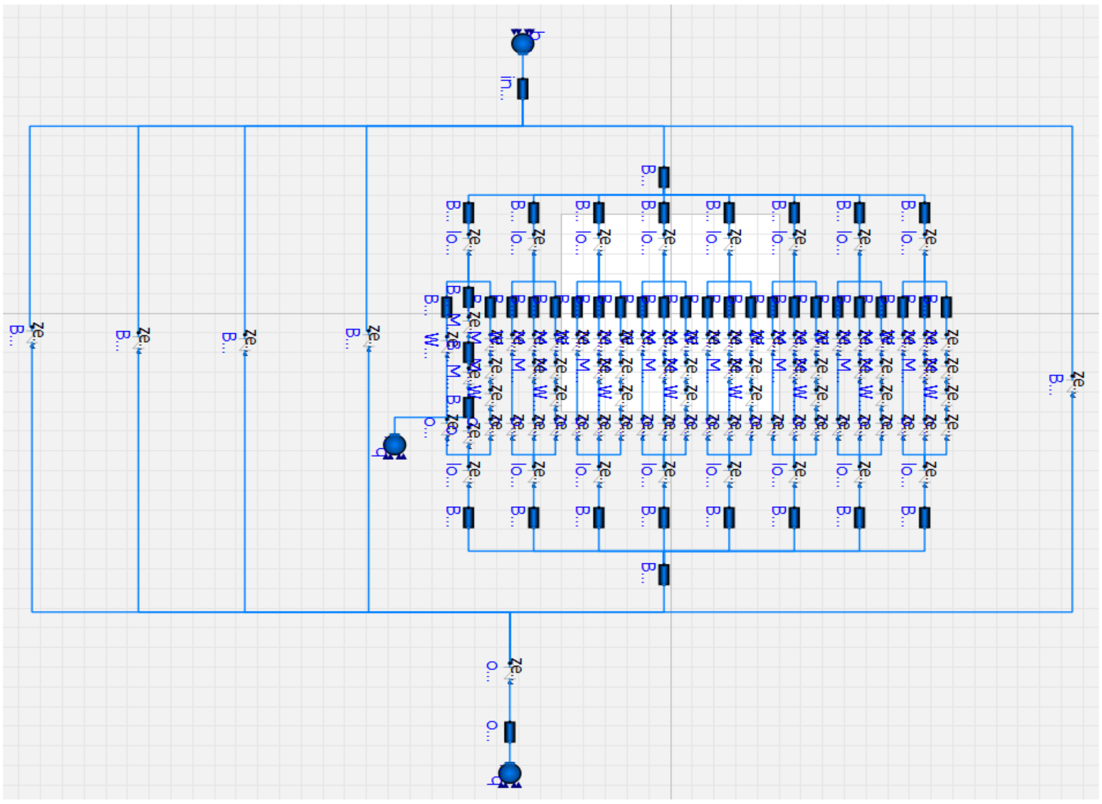


Figure 5.60 – Double Ended Guillotine Branch E2 end

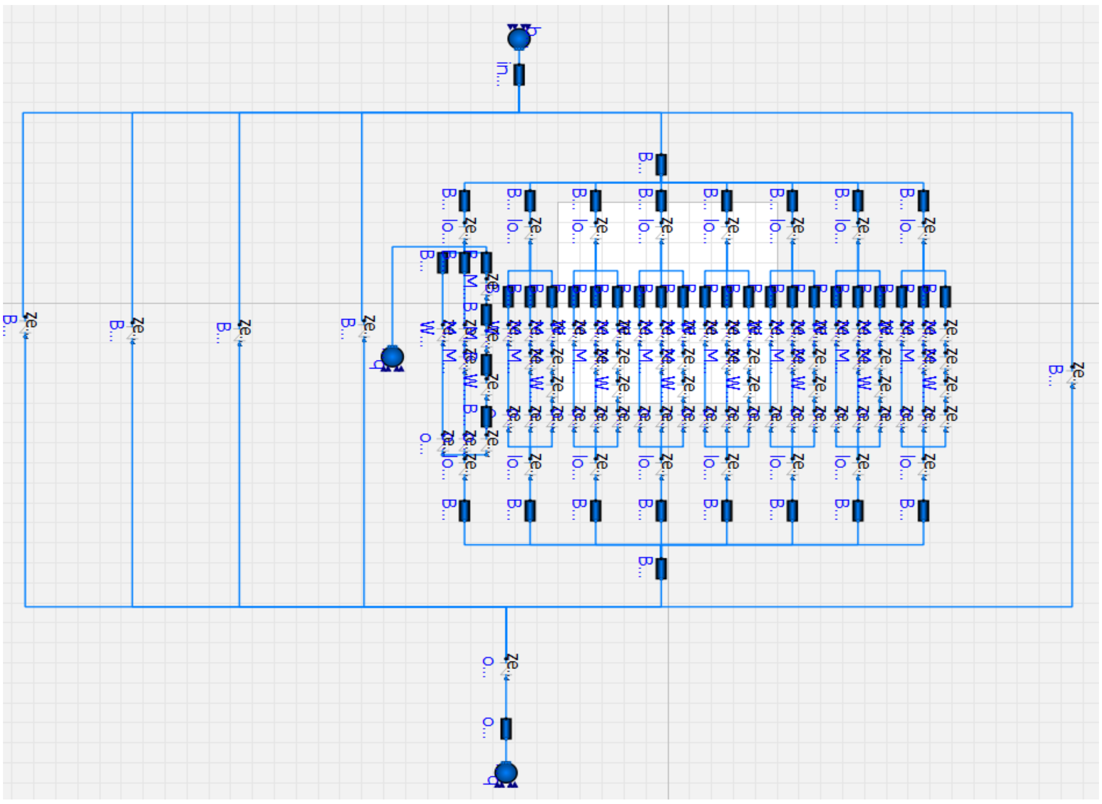


Figure 5.61 – Double Ended Guillotine Branch E3 start

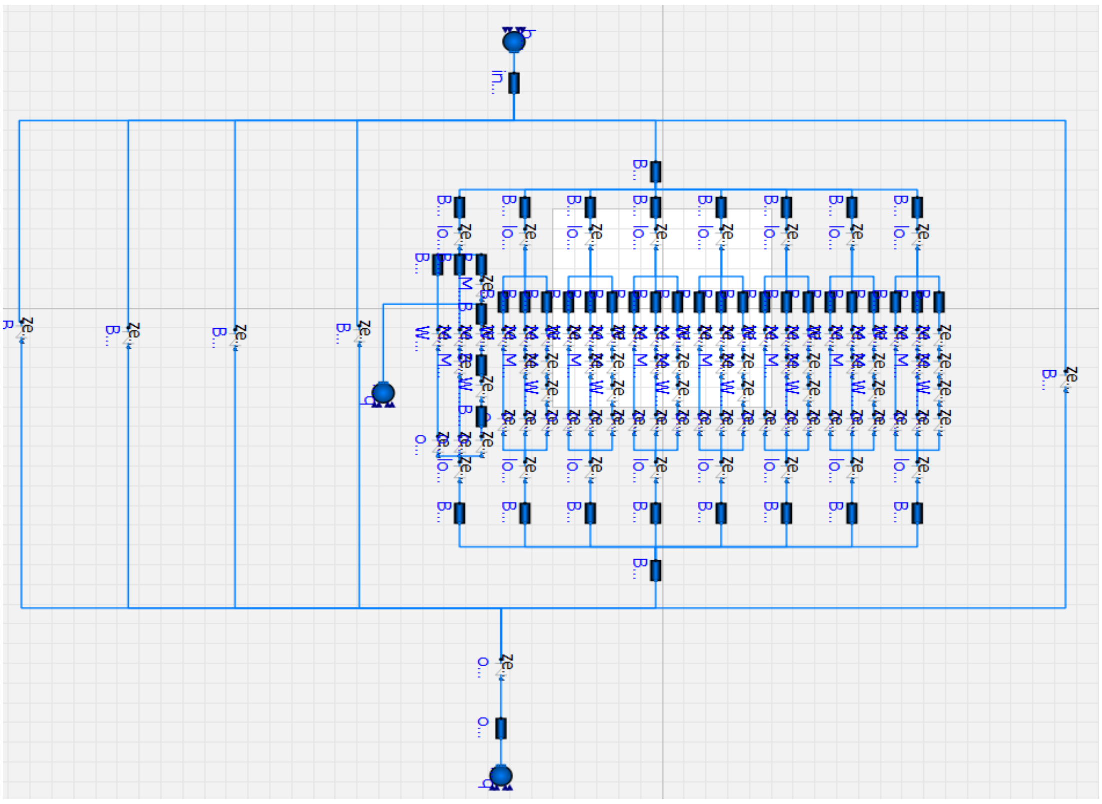


Figure 5.62 – Double Ended Guillotine Branch E3 middle_1

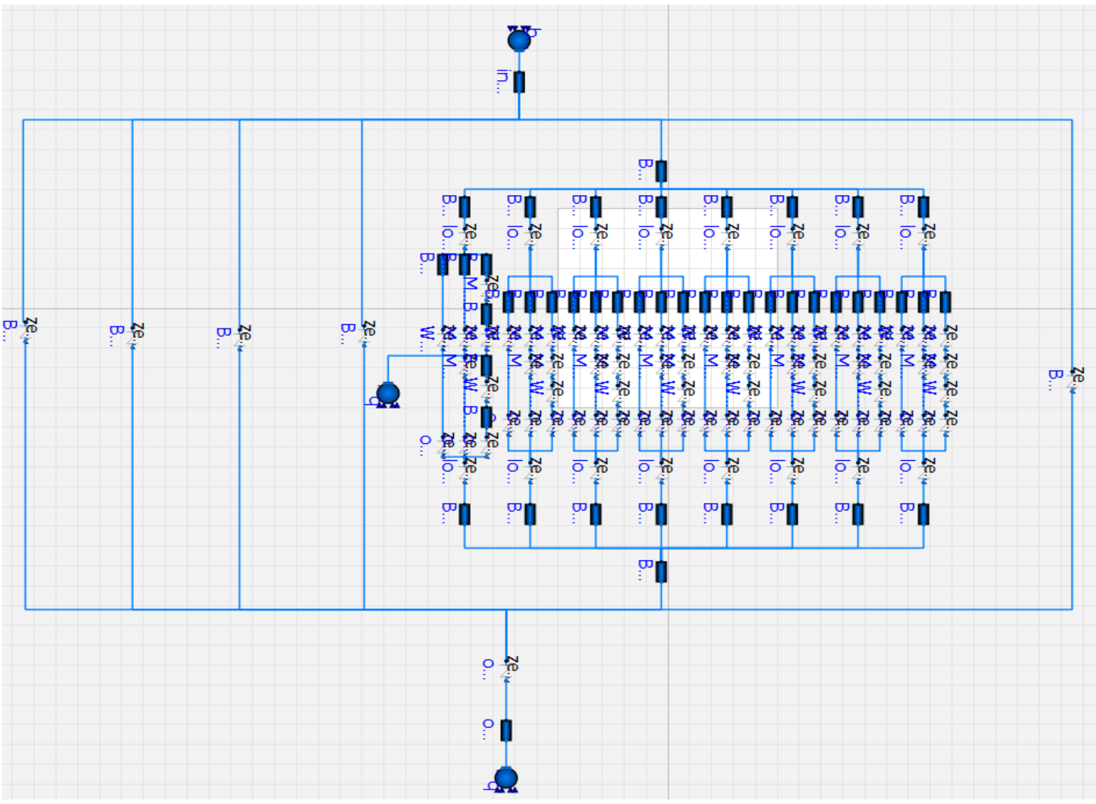


Figure 5.63 – Double Ended Guillotine Branch E3 middle_2

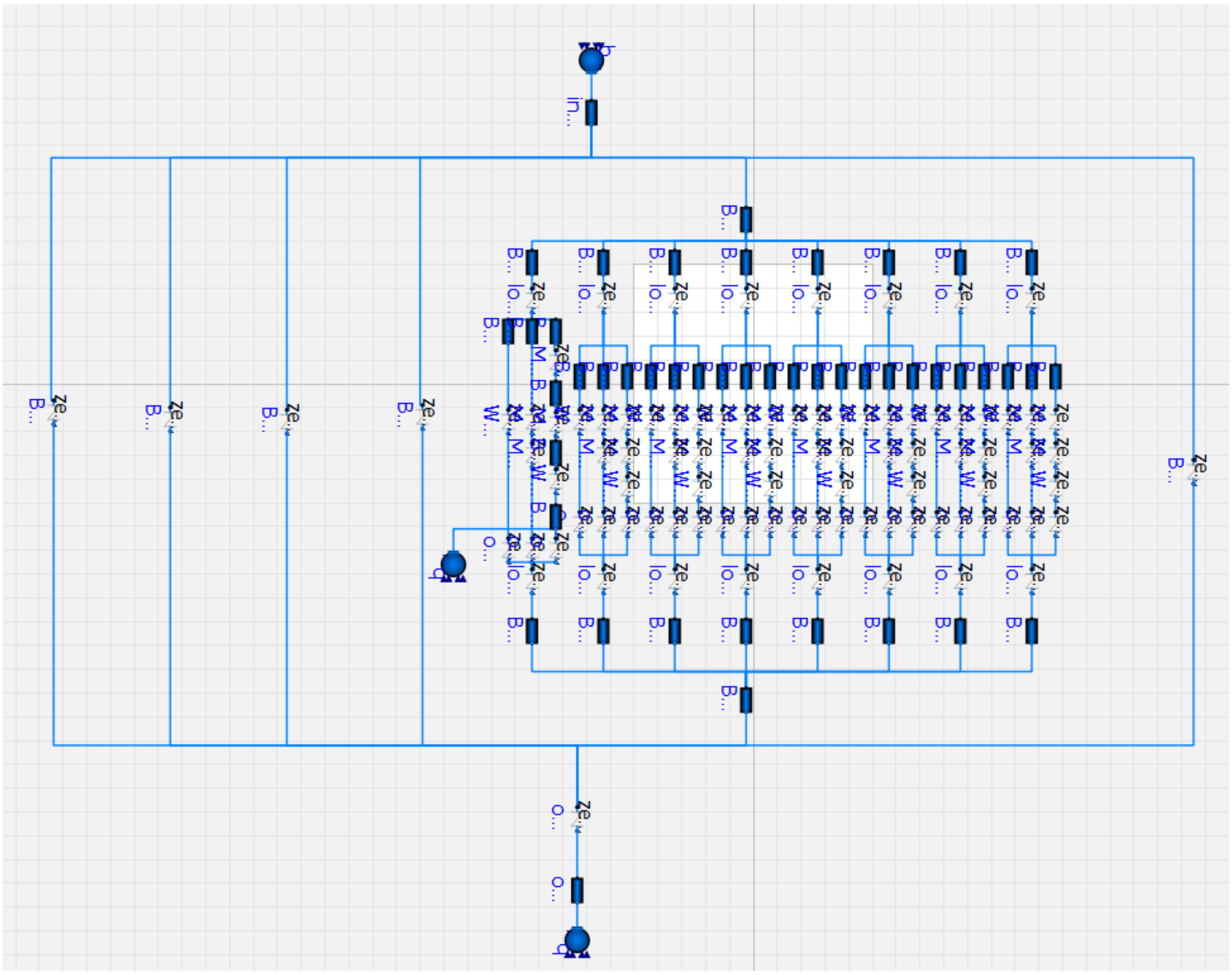


Figure 5.64 – Double Ended Guillotine Branch E3 end

The simulation was carried out through OMPython, because it made the post processing easier. The following script refers to the double ended guillotine at the beginning of Branch A. The same script was adopted for the simulation of other leaks, changing model path, model name and the name of the components.

```
# creation of mod, using Model path and Model name
mod = ModelicaSystem("C:/Users/loren/Documents/OpenModelica/LeakageBranchA_start_guillotine.mo",
                     "LeakageBranchA_start_guillotine")

mod.simulate() # simulation of the model

# getting the mass flow rate of which I'm interested in
Inlet_system = mod.getSolutions(["inlet_system.port_a.m_flow"])
Outlet_system = mod.getSolutions(["outlet_system.port_a.m_flow"])
BranchA_inlet = mod.getSolutions(["BranchA_inlet.port_a.m_flow"])
```

```
BranchA_outlet = mod.getSolutions(["BranchA_outlet.port_a.m_flow"])
BranchB = mod.getSolutions(["BranchB.m_flow"])
BranchC = mod.getSolutions(["BranchC.m_flow"])
BranchD = mod.getSolutions(["BranchD.m_flow"])
BranchE = mod.getSolutions(["BranchE.m_flow"])
BranchF = mod.getSolutions(["BranchF.m_flow"])
mass_flow_reader_inlet_A1 = mod.getSolutions(["loss_massFlowRate_branchA1_inlet.port_a.m_flow"])
mass_flow_reader_outlet_A1 = mod.getSolutions(["loss_massFlowRate_branchA1_outlet.port_a.m_flow"])
mass_flow_reader_inlet_A2 = mod.getSolutions(["loss_massFlowRate_branchA2_inlet.port_a.m_flow"])
mass_flow_reader_outlet_A2 = mod.getSolutions(["loss_massFlowRate_branchA2_outlet.port_a.m_flow"])
flow_after_leak = mod.getSolutions(["TL_PC_ISV_BranchA1_beam1.port_a.m_flow"])
mass_flow_BranchA1_beam2 = mod.getSolutions(["beam2_BranchA1.port_a.m_flow"])
mass_flow_BranchA1_beam3 = mod.getSolutions(["beam3_BranchA1.port_a.m_flow"])
mass_flow_BranchA1_beam4 = mod.getSolutions(["beam4_BranchA1.port_a.m_flow"])
mass_flow_leak = mod.getSolutions(["boundary.ports[1].m_flow"])

# extraction of one element from the numpy arrays
Inlet_system = Inlet_system.flat[0]
Outlet_system = Outlet_system.flat[0]
BranchA_inlet = BranchA_inlet.flat[0]
BranchA_outlet = BranchA_outlet.flat[0]
BranchB = BranchB.flat[0]
BranchC = BranchC.flat[0]
BranchD = BranchD.flat[0]
BranchE = BranchE.flat[0]
BranchF = BranchF.flat[0]
mass_flow_reader_inlet_A1 = mass_flow_reader_inlet_A1.flat[0]
mass_flow_reader_outlet_A1 = mass_flow_reader_outlet_A1.flat[0]
mass_flow_reader_inlet_A2 = mass_flow_reader_inlet_A2.flat[0]
mass_flow_reader_outlet_A2 = mass_flow_reader_outlet_A2.flat[0]
flow_before_leak = flow_before_leak.flat[0]
flow_after_leak = flow_after_leak.flat[0]
mass_flow_BranchA1_beam2 = mass_flow_BranchA1_beam2.flat[0]
mass_flow_BranchA1_beam3 = mass_flow_BranchA1_beam3.flat[0]
mass_flow_BranchA1_beam4 = mass_flow_BranchA1_beam4.flat[0]
mass_flow_leak = mass_flow_leak.flat[0]
unaffected_Branch = BranchB+BranchC+BranchD+BranchE+BranchF
```

```
beam_sum = mass_flow_BranchA1_beam2+mass_flow_BranchA1_beam3+mass_flow_BranchA1_beam4
flow_before_leak = mass_flow_reader_inlet_A1-(mass_flow_BranchA1_beam2+mass_flow_BranchA1_beam3+mass_flow_BranchA1_beam4)

print("\n")
print("Inlet system =", Inlet_system, "[kg/s]")
print("\n")
print("Outlet system =", Outlet_system, "[kg/s]")
print("\n")
print("Branch A inlet =", BranchA_inlet, "[kg/s]")
print("\n")
print("Branch A outlet =", BranchA_outlet, "[kg/s]")
print("\n")
print("Branch B =", BranchB, "[kg/s]")
print("\n")
print("Branch C =", BranchC, "[kg/s]")
print("\n")
print("Branch D =", BranchD, "[kg/s]")
print("\n")
print("Branch E =", BranchE, "[kg/s]")
print("\n")
print("Branch F =", BranchF, "[kg/s]")
print("\n")
print("Unaffected Branch =", unaffected_Branch, "[kg/s]")
print("\n")
print("Mass flow beams Branch A1 =", beam_sum, "[kg/s]")
print("\n")
print("Mass flow preceding leak =", flow_before_leak, "[kg/s]")
print("\n")
print("Mass flow following leak =", flow_after_leak, "[kg/s]")
print("\n")
print("Mass Flow Rate Meter Branch A1 inlet =", mass_flow_reader_inlet_A1, "[kg/s]")
print("\n")
print("Mass Flow Rate Meter Branch A1 outlet =", mass_flow_reader_outlet_A1, "[kg/s]")
print("\n")
print("Mass Flow Rate Meter Branch A2 inlet =", mass_flow_reader_inlet_A2, "[kg/s]")
print("\n")
```

```
print("Mass Flow Rate Meter Branch A2 outlet =", mass_flow_reader_outlet_A2, "[kg/s]")
print("\n")
print("Mass Flow leak =", mass_flow_leak, "[kg/s]")
```

Script 5.2 – Double Ended Guillotine Branch A start

For the validation of the double ended guillotine model, a new one was specifically implemented by using as input data those linked with version 4.1 of the hydraulic model [2], given that the data which has been made available by NIER were linked with that version.

In the following table the comparison between the model created on OpenModelica and the one realised on PyLoca [4] is shown.

	Model output data	Output data report	Difference [kg/s]	Difference [%]
Inlet system	11,73715259	11,6575	0,079652589	0,683%
Unaffected Branch (B+C+D+E+F)	7,13486003	7,1353	-0,00043997	0,006%
Outlet system	6,827477271	6,8215	0,005977271	0,088%
Branch A inlet	4,60229256	4,5222	0,08009256	1,771%
Branch A2 inlet	1,140885717	1,1276	0,013285717	1,178%
Branch A outlet	**-0,307382759**	**-0,3137**	0,006317241	2,014%
Branch A1 inlet	3,461406842	3,3946	0,066806842	1,968%
Mass Flow sum unaffected beam Branch A1	**-1,086185319**	**-1,081**	-0,005185319	0,480%
Branch A1 outlet	**-1,448268476**	**-1,4413**	-0,006968476	0,483%
Flow preceding leak	4,547592161	4,4756	0,071992161	1,609%
Flow following leak	**-0,362083157**	**-0,3603**	-0,001783157	0,495%

Figure 5.65 – Double Ended Guillotine Branch A start, Validation

The small percentages differences are due to a greater refinement in the model implemented on OpenModelica, which by consequence can be validated. After the validation of the model, several configurations were explored, as described in the following paragraph.

5.5 Outcomes for Double Ended Guillotine

After the validation, the double ended guillotine could be simulated for every other branch (input data version 4.2 hydraulic model [3]), getting the following results:

	Nominal MFR	Model output data
Inlet system	9,425	10,37192196
Unaffected Branch	7,049	7,065144709
Outlet system	9,425	8,731092978
Branch A inlet	2,376	3,30677725
Branch A2 inlet	1,188	1,391183442
Branch A outlet	2,376	1,665948269
Branch A1 inlet	1,188	1,915593809
Mass Flow sum unaffected beam Branch A1	0,891	1,06501141
Branch A1 outlet	1,188	0,274764827
Flow preceding leak	0,297	0,850582399
Flow following leak	0,297	**-0,790246583**
Total Loss Mass Flow Rate = 1.640828981455268 [kg/s]		

Figure 5.66 – Double Ended Guillotine Branch A middle, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	11,08460175
Unaffected Branch	7,049	7,136054727
Outlet system	9,425	6,360523725
Branch A inlet	2,376	3,948547026
Branch A2 inlet	1,188	1,613041226
Branch A outlet	2,376	**-0,775531002**
Branch A1 inlet	1,188	2,3355058
Mass Flow sum unaffected beam Branch A1	0,891	1,751628208
Branch A1 outlet	1,188	**-2,388572229**
Flow preceding leak	0,297	0,583877592
Flow following leak	0,297	**-4,140200437**
Total Loss Mass Flow Rate = 4.724078028718994 [kg/s]		

Figure 5.67 – Double Ended Guillotine Branch A end, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,753751625
Unaffected Branch	9,241	9,245621105
Outlet system	9,425	9,256510518
Branch B inlet	0,184	0,50813052
Branch B2 inlet	0,092	0,138135325
Branch B outlet	0,184	0,010889413
Branch B1 inlet	0,092	0,369995195
Mass Flow sum unaffected beam Branch B1	0,069	**-0,095434434**
Branch B1 outlet	0,092	**-0,127245912**
Flow preceding leak	0,023	0,465429629
Flow following leak	0,023	**-0,031811478**
Total Loss Mass Flow Rate = 0.4972411067723574 [kg/s]		

Figure 5.68 – Double Ended Guillotine Branch B start, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,59519061
Unaffected Branch	9,241	9,252294779
Outlet system	9,425	9,189210949
Branch B inlet	0,184	0,342895831
Branch B2 inlet	0,092	0,143122534
Branch B outlet	0,184	**-0,06308383**
Branch B1 inlet	0,092	0,199773297
Mass Flow sum unaffected beam Branch B1	0,069	0,148663155
Branch B1 outlet	0,092	**-0,206206364**
Flow preceding leak	0,023	0,051110142
Flow following leak	0,023	**-0,354869519**
Total Loss Mass Flow Rate = 0.4059796613910954 [kg/s]		

Figure 5.69 – Double Ended Guillotine Branch B middle, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,599955385
Unaffected Branch	9,241	9,252653926
Outlet system	9,425	9,181122618
Branch B inlet	0,184	0,347301459
Branch B2 inlet	0,092	0,144380007
Branch B outlet	0,184	**-0,071531307**
Branch B1 inlet	0,092	0,202921452
Mass Flow sum unaffected beam Branch B1	0,069	0,152191089
Branch B1 outlet	0,092	**-0,215911314**
Flow preceding leak	0,023	0,050730363
Flow following leak	0,023	**-0,368102403**
Total Loss Mass Flow Rate = 0.4188327662647077 [kg/s]		

Figure 5.70 – Double Ended Guillotine Branch B end, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	10,97118245
Unaffected Branch	8,577	8,593754149
Outlet system	9,425	8,557100943
Branch C inlet	0,848	2,377428305
Branch C2 inlet	0,424	0,782699787
Branch C outlet	0,848	**-0,036653207**
Branch C1 inlet	0,424	1,594728518
Mass Flow sum unaffected beam Branch C1	0,318	**-0,614514459**
Branch C1 outlet	0,424	**-0,819352993**
Flow preceding leak	0,106	2,209242977
Flow following leak	0,106	**-0,204838534**
Total Loss Mass Flow Rate = 2.414081511333647 [kg/s]		

Figure 5.71 – Double Ended Guillotine Branch C start, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	10,35718884
Unaffected Branch	8,577	8,580763849
Outlet system	9,425	9,056236041
Branch C inlet	0,848	1,776424996
Branch C2 inlet	0,424	0,691161887
Branch C outlet	0,848	0,475472192
Branch C1 inlet	0,424	1,085263108
Mass Flow sum unaffected beam Branch C1	0,318	0,273281814
Branch C1 outlet	0,424	-0,215689695
Flow preceding leak	0,106	0,811981294
Flow following leak	0,106	-0,488971509
Total Loss Mass Flow Rate = 1.300952803524489 [kg/s]		

Figure 5.72 – Double Ended Guillotine Branch C middle, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	10,71537576
Unaffected Branch	8,577	8,604765883
Outlet system	9,425	8,428008486
Branch C inlet	0,848	2,110609877
Branch C2 inlet	0,424	0,798398995
Branch C outlet	0,848	-0,176757397
Branch C1 inlet	0,424	1,312210881
Mass Flow sum unaffected beam Branch C1	0,318	0,984157726
Branch C1 outlet	0,424	-0,975156393
Flow preceding leak	0,106	0,328053155
Flow following leak	0,106	-1,959314119
Total Loss Mass Flow Rate = 2.287367274169668 [kg/s]		

Figure 5.73 – Double Ended Guillotine Branch C end, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	10,37384321
Unaffected Branch	6,017	5,799882258
Outlet system	9,425	8,649818895
Branch E inlet	3,408	4,340321157
Branch E0 beam2 inlet	0,426	0,427108889
Branch E outlet	3,408	2,616296844
Branch E0 beam 1 inlet	0,426	1,350558934
Mass Flow sum unaffected beam Branch E0 beam1	0,396	-0,347139898
Branch E0 beam 1 outlet	0,426	-0,373465379
Flow preceding leak	0,03	1,697698832
Flow following leak	0,03	-0,026325481
Total Loss Mass Flow Rate = 1.724024313283169 [kg/s]		

Figure 5.74 – Double Ended Guillotine Branch E1 start, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,482487901
Unaffected Branch	6,017	5,786353336
Outlet system	9,425	9,361223798
Branch E inlet	3,408	3,463039765
Branch E0 beam2 inlet	0,426	0,426128414
Branch E outlet	3,408	3,341775661
Branch E0 beam 1 inlet	0,426	0,480140869
Mass Flow sum unaffected beam Branch E0 beam1	0,396	0,397259648
Branch E0 beam 1 outlet	0,426	0,358876766
Flow preceding leak	0,03	0,082881222
Flow following leak	0,03	**-0,038382882**
Total Loss Mass Flow Rate = 0.1212641037493807 [kg/s]		

Figure 5.75 – Double Ended Guillotine Branch E1 middle, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,482385588
Unaffected Branch	6,017	5,786354498
Outlet system	9,425	9,361223889
Branch E inlet	3,408	3,462936242
Branch E0 beam2 inlet	0,426	0,42612851
Branch E outlet	3,408	3,341774543
Branch E0 beam 1 inlet	0,426	0,480036672
Mass Flow sum unaffected beam Branch E0 beam1	0,396	0,397287693
Branch E0 beam 1 outlet	0,426	0,358874974
Flow preceding leak	0,03	0,082748979
Flow following leak	0,03	**-0,038412719**
Total Loss Mass Flow Rate = 0.1211616986453406 [kg/s]		

Figure 5.76 – Double Ended Guillotine Branch E1 end, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	10,37384321
Unaffected Branch	6,017	5,799882258
Outlet system	9,425	8,649818883
Branch E inlet	3,408	4,340321158
Branch E0 beam2 inlet	0,426	0,427108889
Branch E outlet	3,408	2,616296831
Branch E0 beam 1 inlet	0,426	1,350558934
Mass Flow sum unaffected beam Branch E0 beam1	0,396	**-0,28048255**
Branch E0 beam 1 outlet	0,426	**-0,373465392**
Flow preceding leak	0,03	1,631041484
Flow following leak	0,03	**-0,092982843**
Total Loss Mass Flow Rate = 1.724024326385067 [kg/s]		

Figure 5.77 – Double Ended Guillotine Branch E2 start, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,833046012
Unaffected Branch	6,017	5,790136932
Outlet system	9,425	9,135945703
Branch E inlet	3,408	3,809661863
Branch E0 beam2 inlet	0,426	0,426398008
Branch E outlet	3,408	3,112561554
Branch E0 beam 1 inlet	0,426	0,82487581
Mass Flow sum unaffected beam Branch E0 beam1	0,396	0,236930595
Branch E0 beam 1 outlet	0,426	0,1277755
Flow preceding leak	0,03	0,587945215
Flow following leak	0,03	**-0,109155095**
Total Loss Mass Flow Rate = 0.6971003092997097 [kg/s]		

Figure 5.78 – Double Ended Guillotine Branch E2 middle, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,721295638
Unaffected Branch	6,017	5,790106753
Outlet system	9,425	9,174805653
Branch E inlet	3,408	3,697942883
Branch E0 beam2 inlet	0,426	0,426403364
Branch E outlet	3,408	3,151452899
Branch E0 beam 1 inlet	0,426	0,713119338
Mass Flow sum unaffected beam Branch E0 beam1	0,396	0,280353999
Branch E0 beam 1 outlet	0,426	0,166629353
Flow preceding leak	0,03	0,432765339
Flow following leak	0,03	**-0,113724646**
Total Loss Mass Flow Rate = 0.5464899847789895 [kg/s]		

Figure 5.79 – Double Ended Guillotine Branch E2 end, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	10,37387025
Unaffected Branch	6,017	5,799899413
Outlet system	9,425	8,649281627
Branch E inlet	3,408	4,340330349
Branch E0 beam2 inlet	0,426	0,427110209
Branch E outlet	3,408	2,615741728
Branch E0 beam 1 inlet	0,426	1,350558884
Mass Flow sum unaffected beam Branch E0 beam1	0,396	**-0,119972579**
Branch E0 beam 1 outlet	0,426	**-0,374029737**
Flow preceding leak	0,03	1,470531463
Flow following leak	0,03	**-0,254057158**
Total Loss Mass Flow Rate = 1.724588620810456 [kg/s]		

Figure 5.80 – Double Ended Guillotine Branch E3 start, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	10,0561914
Unaffected Branch	6,017	5,799293731
Outlet system	9,425	8,78576243
Branch E inlet	3,408	4,023281583
Branch E0 beam2 inlet	0,426	0,427088902
Branch E outlet	3,408	2,752852613
Branch E0 beam 1 inlet	0,426	1,033659269
Mass Flow sum unaffected beam Branch E0 beam1	0,396	0,050461375
Branch E0 beam 1 outlet	0,426	**-0,236769701**
Flow preceding leak	0,03	0,983197893
Flow following leak	0,03	**-0,287231076**
Total Loss Mass Flow Rate = 1.270428969601614 [kg/s]		

Figure 5.81 – Double Ended Guillotine Branch E3 middle_1, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,922781464
Unaffected Branch	6,017	5,800020392
Outlet system	9,425	8,811910206
Branch E inlet	3,408	3,889115714
Branch E0 beam2 inlet	0,426	0,427154947
Branch E outlet	3,408	2,778244456
Branch E0 beam 1 inlet	0,426	0,899031088
Mass Flow sum unaffected beam Branch E0 beam1	0,396	0,0942299
Branch E0 beam 1 outlet	0,426	**-0,21184017**
Flow preceding leak	0,03	0,804801188
Flow following leak	0,03	**-0,30607007**
Total Loss Mass Flow Rate = 1.110871257907232 [kg/s]		

Figure 5.82 – Double Ended Guillotine Branch E3 middle_2, outcomes

	Nominal MFR	Model output data
Inlet system	9,425	9,790903355
Unaffected Branch	6,017	5,801786151
Outlet system	9,425	8,805521749
Branch E inlet	3,408	3,755400715
Branch E0 beam2 inlet	0,426	0,427300667
Branch E outlet	3,408	2,770019109
Branch E0 beam 1 inlet	0,426	0,764296048
Mass Flow sum unaffected beam Branch E0 beam1	0,396	0,121366225
Branch E0 beam 1 outlet	0,426	**-0,221085558**
Flow preceding leak	0,03	0,642929823
Flow following leak	0,03	**-0,342451783**
Total Loss Mass Flow Rate = 0.9853816061018691 [kg/s]		

Figure 5.83 – Double Ended Guillotine Branch E3 end, outcomes

6 CONCLUSIONS

Three different requirements must be carried out:

- *design requirement*: mass flow rates must be redistributed as shown in Figure 3.2;
- *minimum mass flow rate requirement*: a minimum mass flow rate must be provided in all the different components within the system;
- *detection requirement*: mass flow rate variations must be detected through the use of mass flow rate meters, in particular if the mass flow rate in a component dropped below its minimum.

Thanks to the hydraulic modelling through OpenModelica of the EVCS in normal and off-normal (in presence of obstructions or leakages) operativity conditions, an independent evaluation of the Excel file implemented by NIER [3] was carried out, validating the design requirement.
Both in the event of an obstruction or a leakage, it has been demonstrated that flow meters must be able to detect mass flow rate variations; in particular, flow meters must be able to detect when the minimum admissible mass flow rate is reached in one of the components. The perturbation must be higher than the minimum detectable variation by the flowmeter in order to satisfy the detection requirement.
Moreover, it can be observed that the mass flow rate drop in the flowmeters is always higher than the admissible variation detectable by the Venturi (as shown in Table 4.13).
With regards to the system's modelling in case of leakage, the results on which NIER based its analysis [4] were validated, certifying the working methodology in just one case.
This study shows that, in case of a small-break loss of coolant from a beam line of a given branch, the coolant flow rate through the components of that beam line either increase or decrease (depending on the location of the break, as indicated in Paragraph 5.2).
The analyses performed for small-break scenarios also showed that, while an appreciable flow redistribution occurs in the affected branch, the rest of the circuit is perturbed to a negligible extent (as shown in Paragraph 5.3). The minimum mass flow rate requirement in presence of obstruction or leakage was verified by assigning a pressure drop to the orifice, so that the minimum mass flow rate was provided in the components (it was checked in presence of a break that the minimum mass flow rate was supplied in the component following the leak). The detection requirement was finally satisfied: in particular, in case of obstruction it is always possible to detect mass flow rate variations in the couple of flowmeters (both feed and return) located in the perturbed sub-branch, whereas it is not possible in the unperturbed one (as shown in Figure 6.1). In case of leakage, it is always possible to detect loss of coolant in the beam affected by the leak, whereas for some locations it is not possible in the parallel one (Figure 6.2).

Location	Flowmeter	Mass Flow	Mass Flow Nominal	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
Branch A	Inlet Branch A1	1,175898	1,188	-0,012102	1,019%	✓
	Outlet Branch A1	1,175898	1,188	-0,012102	1,019%	✓
	Inlet Branch A2	1,191466	1,188	0,003466	0,292%	×
	Outlet Branch A2	1,191466	1,188	0,003466	0,292%	×
Branch B	Inlet Branch B1	0,090862	0,092	-0,001138	1,237%	✓
	Outlet Branch B1	0,090862	0,092	-0,001138	1,237%	✓
	Inlet Branch B2	0,092457	0,092	0,000457	0,497%	×
	Outlet Branch B2	0,092457	0,092	0,000457	0,497%	×
Branch C	Inlet Branch C1	0,420891	0,424	-0,003109	0,733%	✓
	Outlet Branch C1	0,420891	0,424	-0,003109	0,733%	✓
	Inlet Branch C2	0,425727	0,424	0,001727	0,407%	×
	Outlet Branch C2	0,425727	0,424	0,001727	0,407%	×
Branch E1	Inlet Branch E0 beam 1	0,419772	0,426	-0,006228	1,462%	✓
	Outlet Branch E0 beam 1	0,419772	0,426	-0,006228	1,462%	✓
	Inlet Branch E0 beam 2	0,426026	0,426	0,000026	0,006%	×
	Outlet Branch E0 beam 2	0,426026	0,426	0,000026	0,006%	×
Branch E2	Inlet Branch E0 beam 1	0,412545	0,426	-0,013455	3,158%	✓
	Outlet Branch E0 beam 1	0,412545	0,426	-0,013455	3,158%	✓
	Inlet Branch E0 beam 2	0,426051	0,426	0,000051	0,0120%	×
	Outlet Branch E0 beam 2	0,426051	0,426	0,000051	0,0120%	×
Branch E3	Inlet Branch E0 beam 1	0,410057	0,426	-0,015943	3,742%	✓
	Outlet Branch E0 beam 1	0,410057	0,426	-0,015943	3,742%	✓
	Inlet Branch E0 beam 2	0,426060	0,426	0,00006	0,0140%	×
	Outlet Branch E0 beam 2	0,426060	0,426	0,00006	0,0140%	×
Branch F	Inlet Branch F	0,200343	0,233	-0,032657	14,016%	✓
	Outlet Branch F	0,200343	0,233	-0,032657	14,016%	✓

Figure 6.1 - Obstructions

Location	Flowmeter	Mass Flow	Mass Flow Nominal	Difference [kg/s]	Difference [%]	Detection (>= 0.63)
Leakage Branch A start	Inlet Branch A1	1,520642	1,188	0,332642	28,000%	✓
	Outlet Branch A1	1,087878	1,188	-0,100122	8,428%	✓
	Inlet Branch A2	1,211741	1,188	0,023741	1,998%	✓
	Outlet Branch A2	1,211741	1,188	0,023741	1,998%	✓
Leakage Branch A middle	Inlet Branch A1	1,2155	1,188	0,0275	2,315%	✓
	Outlet Branch A1	1,167436	1,188	-0,020564	1,731%	✓
	Inlet Branch A2	1,193403	1,188	0,005403	0,455%	×
	Outlet Branch A2	1,193403	1,188	0,005403	0,455%	×
Leakage Branch B start	Inlet Branch B1	0,137817	0,092	0,045817	49,801%	✓
	Outlet Branch B1	0,080011	0,092	-0,011989	13,031%	✓
	Inlet Branch B2	0,096497	0,092	0,004497	4,888%	✓
	Outlet Branch B2	0,096497	0,092	0,004497	4,888%	✓
Leakage Branch B middle	Inlet Branch B1	0,134042	0,092	0,042042	45,697%	✓
	Outlet Branch B1	0,081146	0,092	-0,010854	11,798%	✓
	Inlet Branch B2	0,096084	0,092	0,004084	4,439%	✓
	Outlet Branch B2	0,096084	0,092	0,004084	4,439%	✓
Leakage Branch C start	Inlet Branch C1	0,590906	0,424	0,166906	39,365%	✓
	Outlet Branch C1	0,350844	0,424	-0,073156	17,254%	✓
	Inlet Branch C2	0,462391	0,424	0,038391	9,055%	✓
	Outlet Branch C2	0,462391	0,424	0,038391	9,055%	✓
Leakage Branch C middle	Inlet Branch C1	0,463621	0,424	0,039621	9,345%	✓
	Outlet Branch C1	0,405979	0,424	-0,018021	4,250%	✓
	Inlet Branch C2	0,433689	0,424	0,009689	2,285%	✓
	Outlet Branch C2	0,433689	0,424	0,009689	2,285%	✓
Leakage Branch E1 start	Inlet Branch E0 beam 1	0,822476	0,426	0,396476	93,069%	✓
	Outlet Branch E0 beam 1	0,287535	0,426	-0,138465	32,504%	✓
	Inlet Branch E0 beam 2	0,426001	0,426	0,000001	0,0003%	×
	Outlet Branch E0 beam 2	0,426001	0,426	0,000001	0,0003%	×
Leakage Branch E1 middle	Inlet Branch E0 beam 1	0.720098	0,426	0,294098	69,037%	✓
	Outlet Branch E0 beam 1	0,335425	0,426	-0,090575	21,262%	✓
	Inlet Branch E0 beam 2	0,425974	0,426	-0,000026	0,0062%	×
	Outlet Branch E0 beam 2	0,425974	0,426	-0,000026	0,0062%	×
Leakage Branch E2 start	Inlet Branch E0 beam 1	0,684524	0,426	0,258524	60,686%	✓
	Outlet Branch E0 beam 1	0,351935	0,426	-0,074065	17,386%	✓
	Inlet Branch E0 beam 2	0,425964	0,426	-0,000036	0,0085%	×
	Outlet Branch E0 beam 2	0,425964	0,426	-0,000036	0,0085%	×
Leakage Branch E2 middle	Inlet Branch E0 beam 1	0,534675	0,426	0,108675	25,511%	✓
	Outlet Branch E0 beam 1	0,390512	0,426	-0,035488	8,331%	✓
	Inlet Branch E0 beam 2	0,426	0,426	-1,85E-07	0,00004%	×
	Outlet Branch E0 beam 2	0,426	0,426	-1,85E-07	0,00004%	×
Leakage Branch E3 start	Inlet Branch E0 beam 1	0,545932	0,426	0,119932	28,153%	✓
	Outlet Branch E0 beam 1	0,398019	0,426	-0,027981	6,568%	✓
	Inlet Branch E0 beam 2	0,425971	0,426	-0,000029	0,0069%	×
	Outlet Branch E0 beam 2	0,425971	0,426	-0,000029	0,0069%	×
Leakage Branch E3 middle_1	Inlet Branch E0 beam 1	0,49314	0,426	0,067140	15,761%	✓
	Outlet Branch E0 beam 1	0,404323	0,426	-0,021677	5,088%	✓
	Inlet Branch E0 beam 2	0,426001	0,426	1,33E-06	0,0003%	×
	Outlet Branch E0 beam 2	0,426001	0,426	1,33E-06	0,0003%	×
Leakage Branch E3 middle_2	Inlet Branch E0 beam 1	0,474095	0,426	0,048095	11,290%	✓
	Outlet Branch E0 beam 1	0,405184	0,426	-0,020816	4,886%	✓
	Inlet Branch E0 beam 2	0,426016	0,426	1,60E-05	0,0036%	×
	Outlet Branch E0 beam 2	0,426016	0,426	1,60E-05	0,0036%	×

Figure 6.2 – Small Breaks

On the other hand, in case of a double-ended guillotine, considerable flow rate and pressure variations take place throughout the entire system, with flow inversion at several locations and with leak flow rates being as large as (or even larger than) the total nominal flow rate through the affected branch (as shown in Paragraph 5.5).

To conclude the design fulfils the defined requirements.

This publication reflects only the author's point of view and Fusion for Energy cannot be held responsible for any use of the information contained therein.

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