Introduction to Nuclear Engineering 2021/2022

Passive Safety System

Project Work - Experimental Facility Piacenza SIET Labs

Akzhol Almukhametov
William Oliveira
Lorenzo Meucci
Lorenzo Mazzocco
Patrik Shytaj
Daniele Timpano

Status update - Presentation

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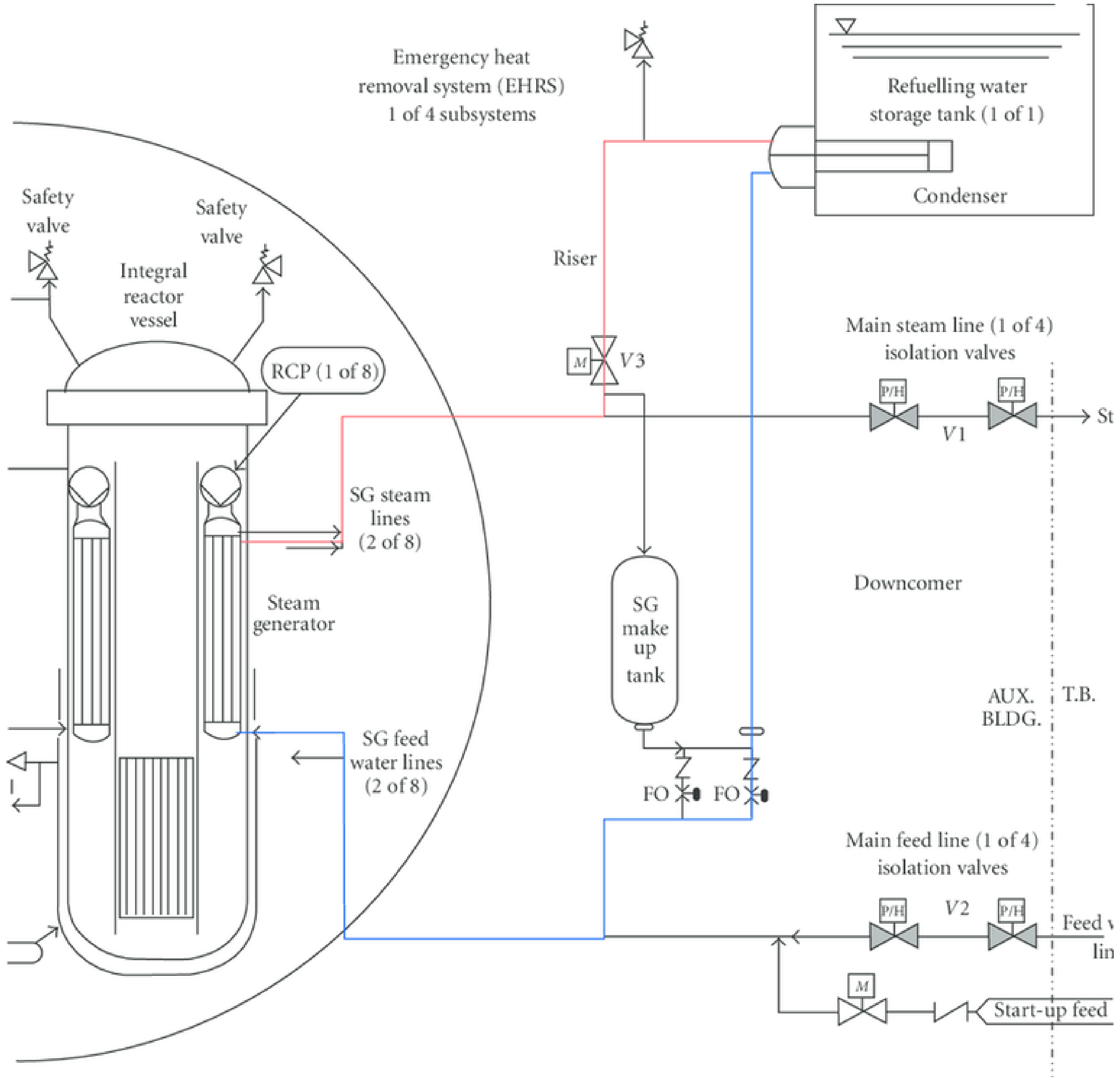
Project Work Focus

Why Passive Safety Systems?

Passive safety systems are based on natural laws, such as gravity and natural circulation. As opposed to active systems, the lack of mechanical moving parts or other active components should reduce the probability of hardware failure.

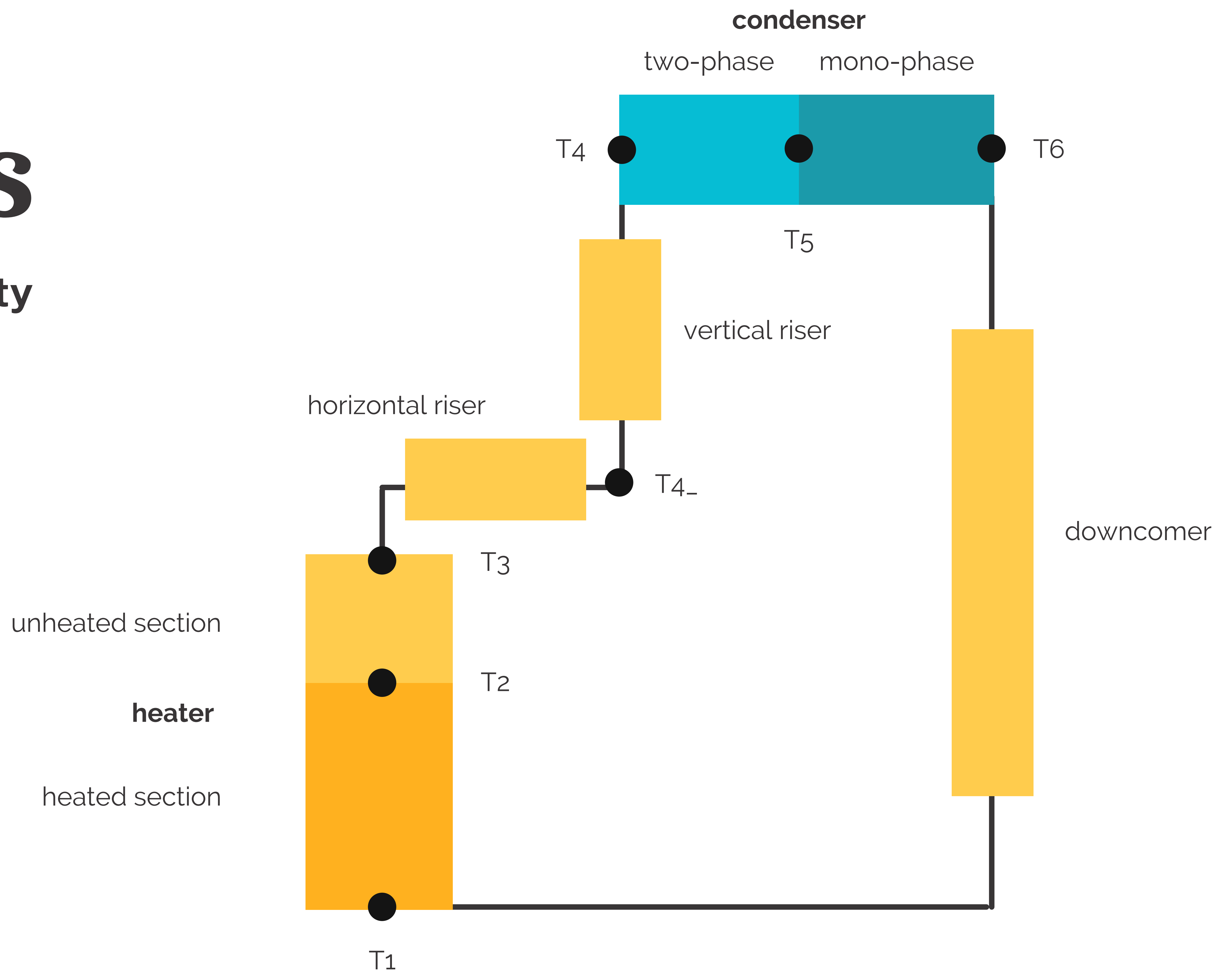
Goal and requirement

Remove decay heat using a natural circulation loop.



System Analysis

The experimental facility



Physical Model

Knowing the whole **geometry** and **characteristics** of the loop, the **inputs** necessary to run a simulation are the **thermodynamic coordinates** at the inlet of the heater (point 1), the **power exchanged** to the fluid by the **heater** and the **mass flow rate** of the fluid.

The two main **physical phenomena** to simulate around the loop are: **pressure drops** and **heat transfer** in the condenser.

Equations

Steady state **energy balance**

$$\dot{Q}_{heater} + \dot{Q}_{condenser} = \dot{m} \int_{loop} dh$$

Steady state **mass balance**

$$\dot{m} = cost$$

Steady state **momentum balance**

$$\int_{loop} \Phi_l^2 \frac{f_l(1-x)G_m^2}{2D\rho}\, dl \; + \; \sum_j K_j \frac{G^2}{2\rho} = \int_{downcomer} \rho g\, dz - \int_{riser} \rho g\, dz$$

Assumptions Made

- the system was considered **adiabatic**, with no **heat losses** along the loop;
- the frictional pressure drops in the condenser **are negligible** (1m length);
- the effect of **frictional pressure drops** on the **fluid temperature** was not considered;
- the **frictional pressure drops** for two-phase flow mixture are calculated with the separated fluid model by means of the **Lockhart-Martinelli correlations;**

Equations

Distributed and cocentrated **pressure drops module**

$$\Delta p = \Delta p_{friction} + \Delta p_{gravitational}$$

In case of **single-phase flow:**

$$\Delta p = -\frac{fLG^2}{2D\rho} - \rho g \Delta z$$

in case of **two-phase flow**

$$\Delta p = -\Phi_l^2 \frac{f_l L(1-x) G_m^2}{2D\rho} - \rho_m g \Delta z$$

$$with \;\; \Phi_l^2 = 1 + \frac{12}{X} + \frac{1}{X^2} \;, \quad X^2 = (\frac{1-x}{x})^{1.8} (\frac{\rho_v}{\rho_l})(\frac{\mu_l}{\mu_v})^{0.2}$$

Strategy for heat transfer

Heat transfer was modelled considering the thermal resistances of **convection** between the fluid and the innerpipe and the **conduction** of the pipe. The main assumption was that **the outer temperature of the pipe** was fixed at 100°C (no film boiling in the pool)**.**

In order to find **the heat transfer coefficient Chato** and **Dittus-Boelter** were employed.

Equations

Total thermal resistance

$$\dot{Q}_{cond} = \int_{condenser} \frac{T_{wall} - T_{sat}}{R_{th,tot}}, \ where \quad R_{th,tot} = \frac{1}{\alpha_{conv} A_{in}} + \frac{ln(\frac{R}{r})}{2\pi k L}$$

Condensation - Chato (Heat transfer coefficient)

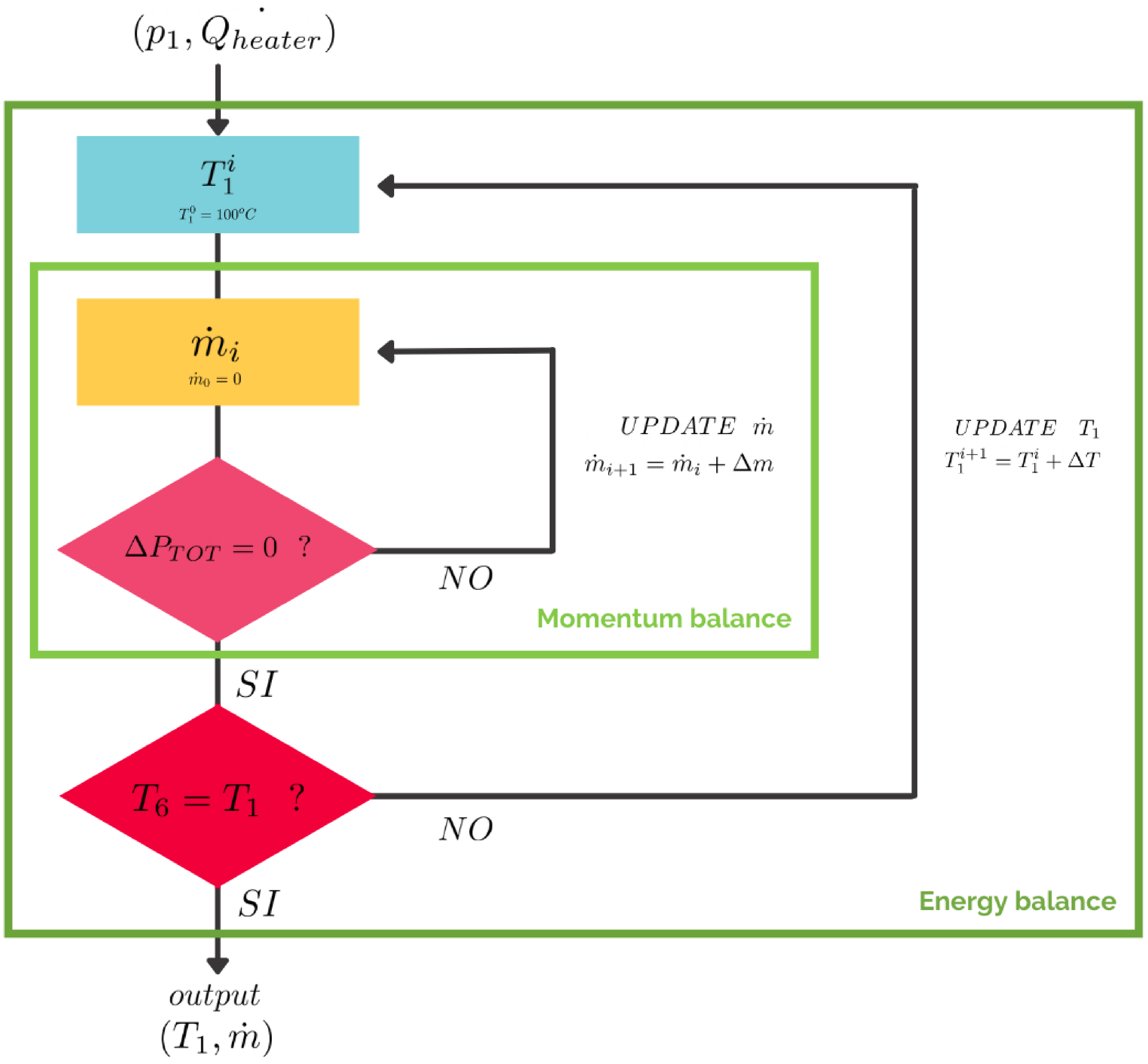
$$\alpha_{cond} = 0.555 [\frac{g(\rho_l - \rho_v)\rho_v K_V^3 h^*_{evap}}{D\mu_l (T_{sat} - T_{wall})}]^{\frac{1}{4}} \quad valid \quad for Re_v = \frac{G_v D}{\mu_v} < 35000$$

Subcooling - Dittus-Boelter

$$Nu = 0.023 Re^{0.8} Pr^{0.3} \quad valid \quad for \quad 0.7 < Pr < 100, Re > 10000$$

Two-loop structure

Two loop structure for computing thermodynamic properties in each point of interest



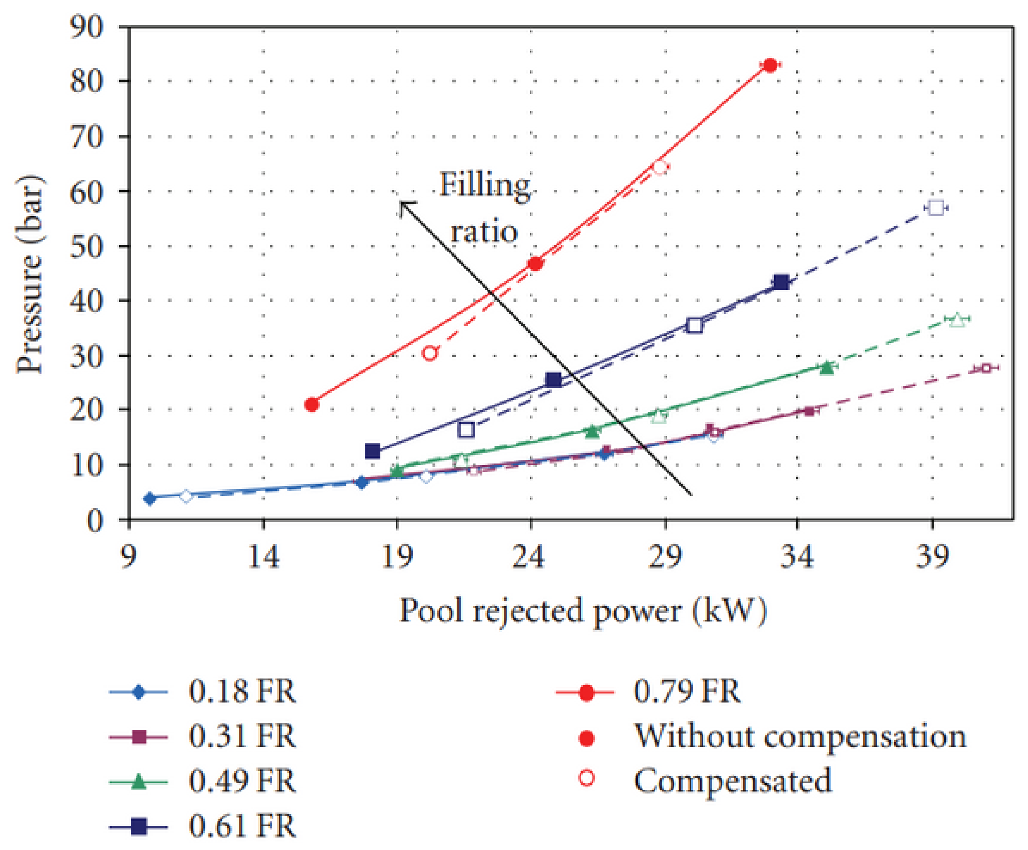
Specifics

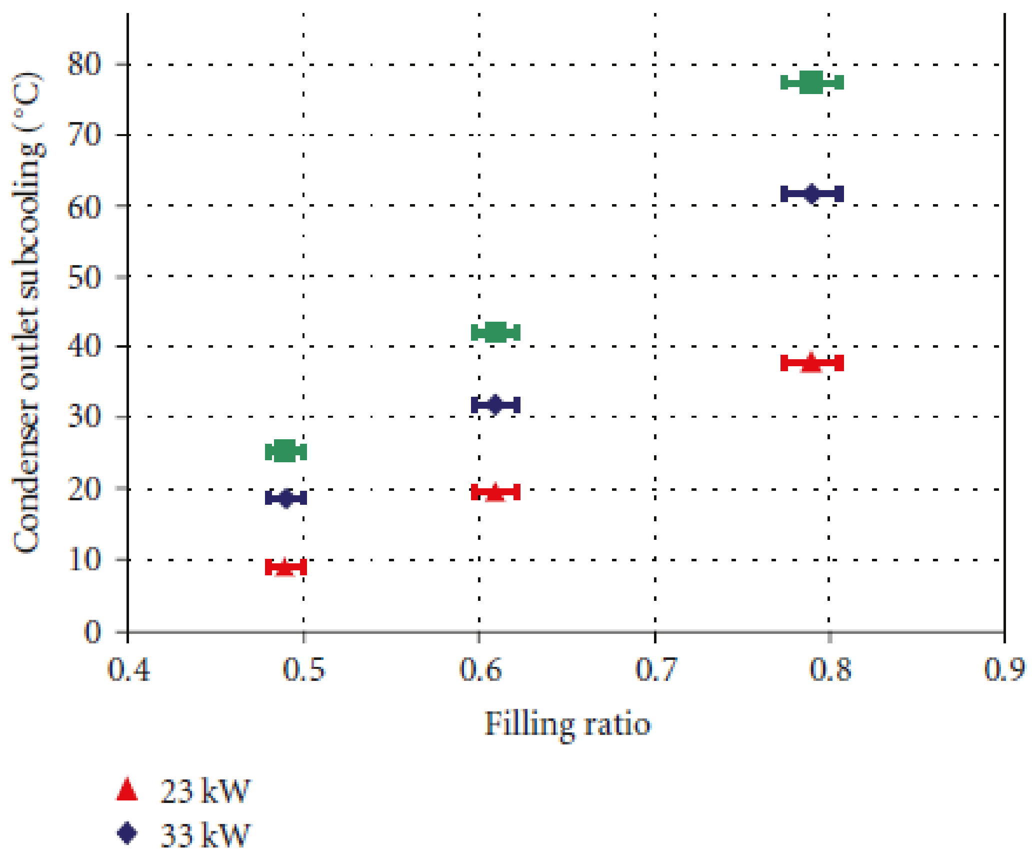
Two loop structure for computing thermodynamic properties in each point of interest

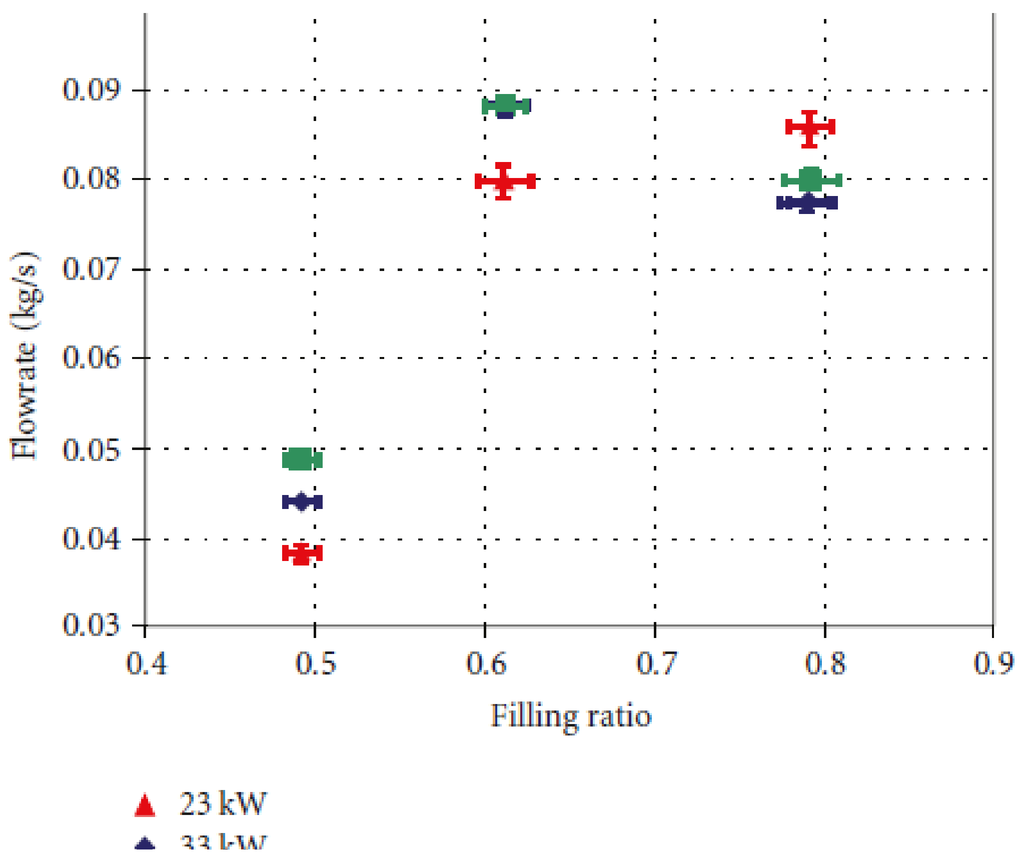
In order to run a simulation and characterize all the thermodynamic states of the fluid around the loop weneed the following inputs: **p1,T1, Qheater, m_dot**. Of those we can only control **p1** and **Qheater**, the other two are derived from the steady-state equilibrium that the loop reaches.

In order to find **T1** and m_dot that create a steady state equilibrium given **p1** and **Q heater** we need to iterate different values until we find the right ones. In particular a two nested loops **iterative routine** was created which verifies momentum and energy balance.
A schematic of such algorithm is given below.

Goal - Matching the experimental data

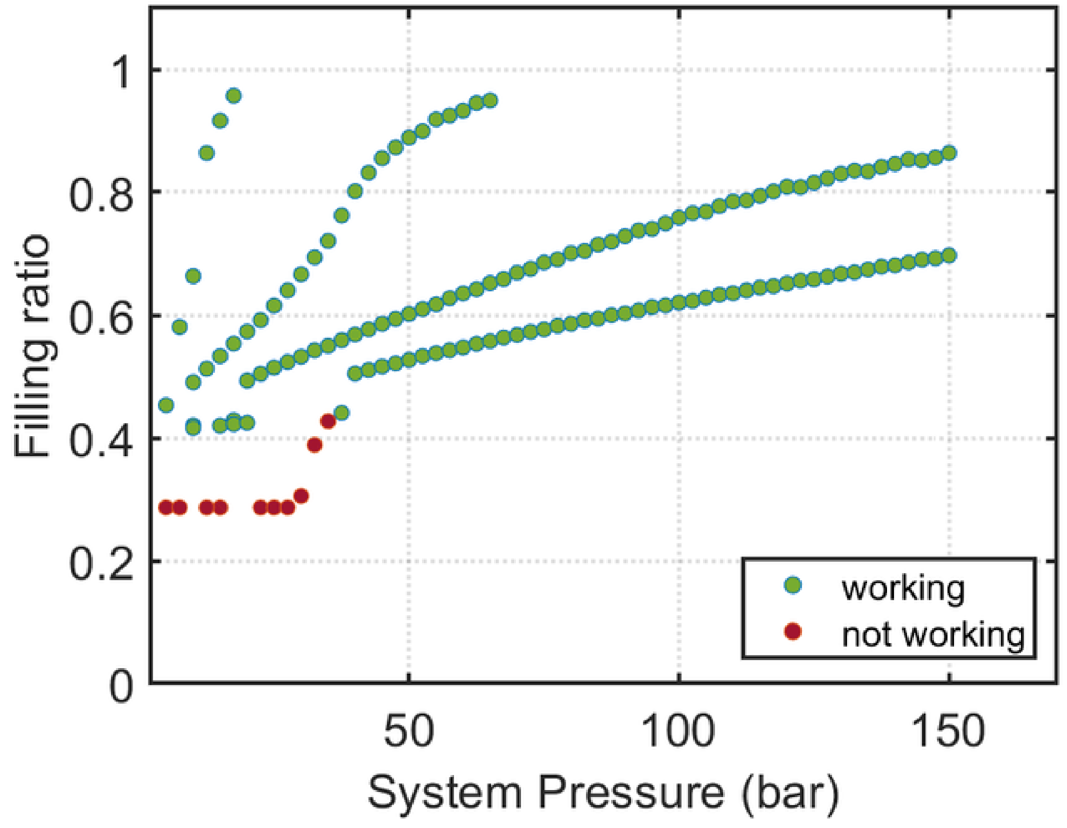


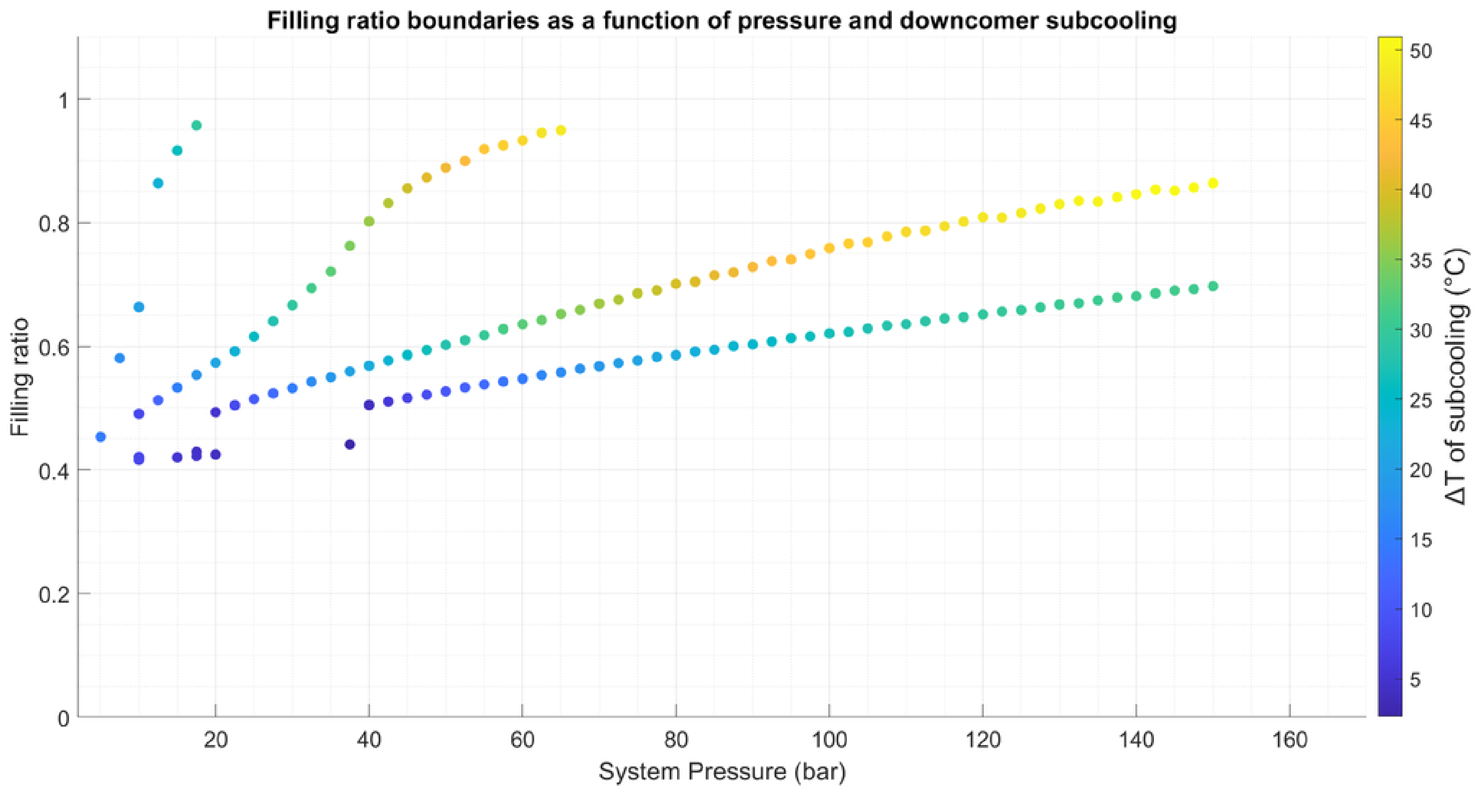




Results - Loop working region

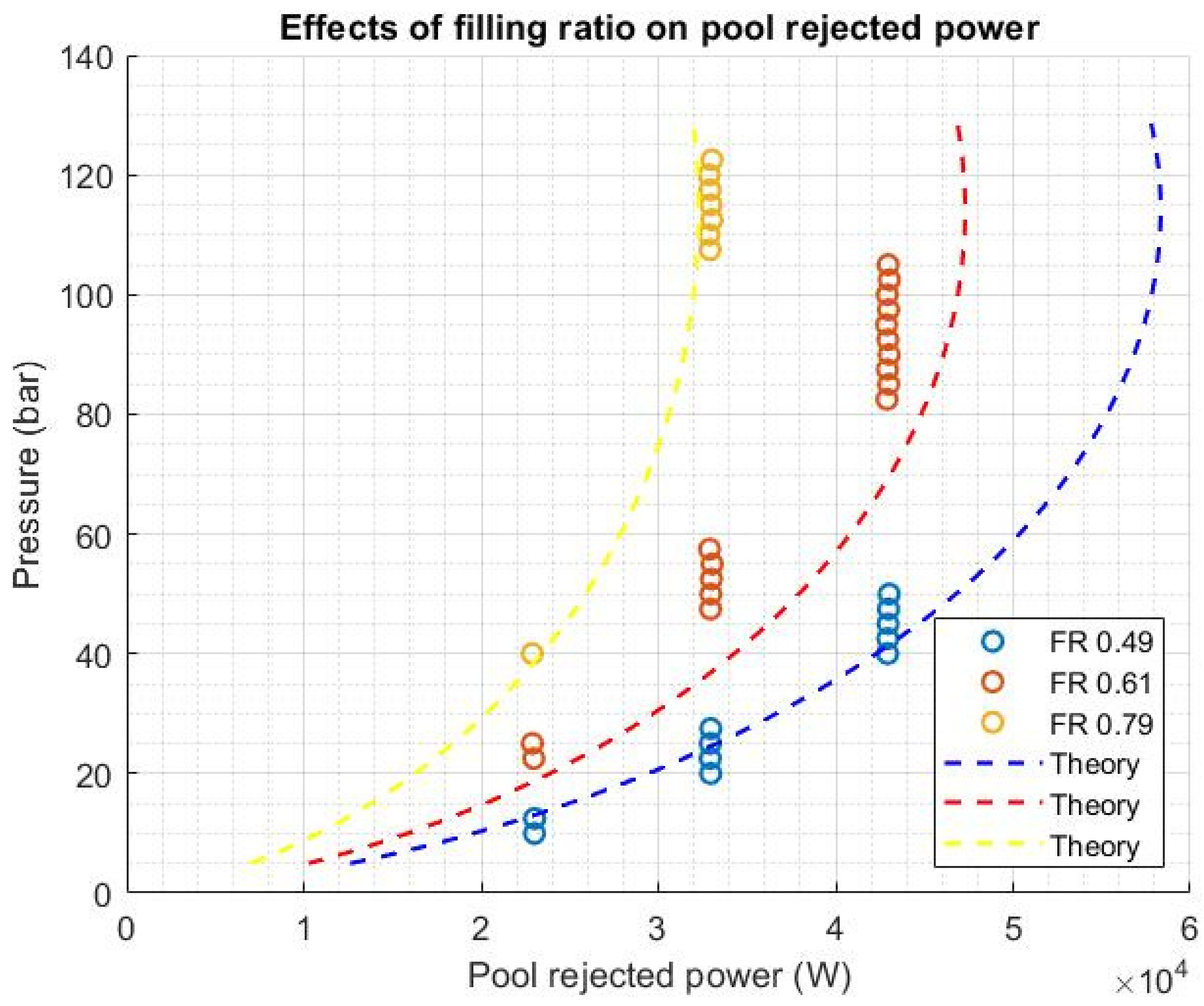
The charts identify the lower boundary of the working region as a filling ratio of around **0.4**. Also **higher filling ratios** are associated with **greater subcooling** of the water in the condenser. These results are in excellent agreement with the results obtained by Santini et al.



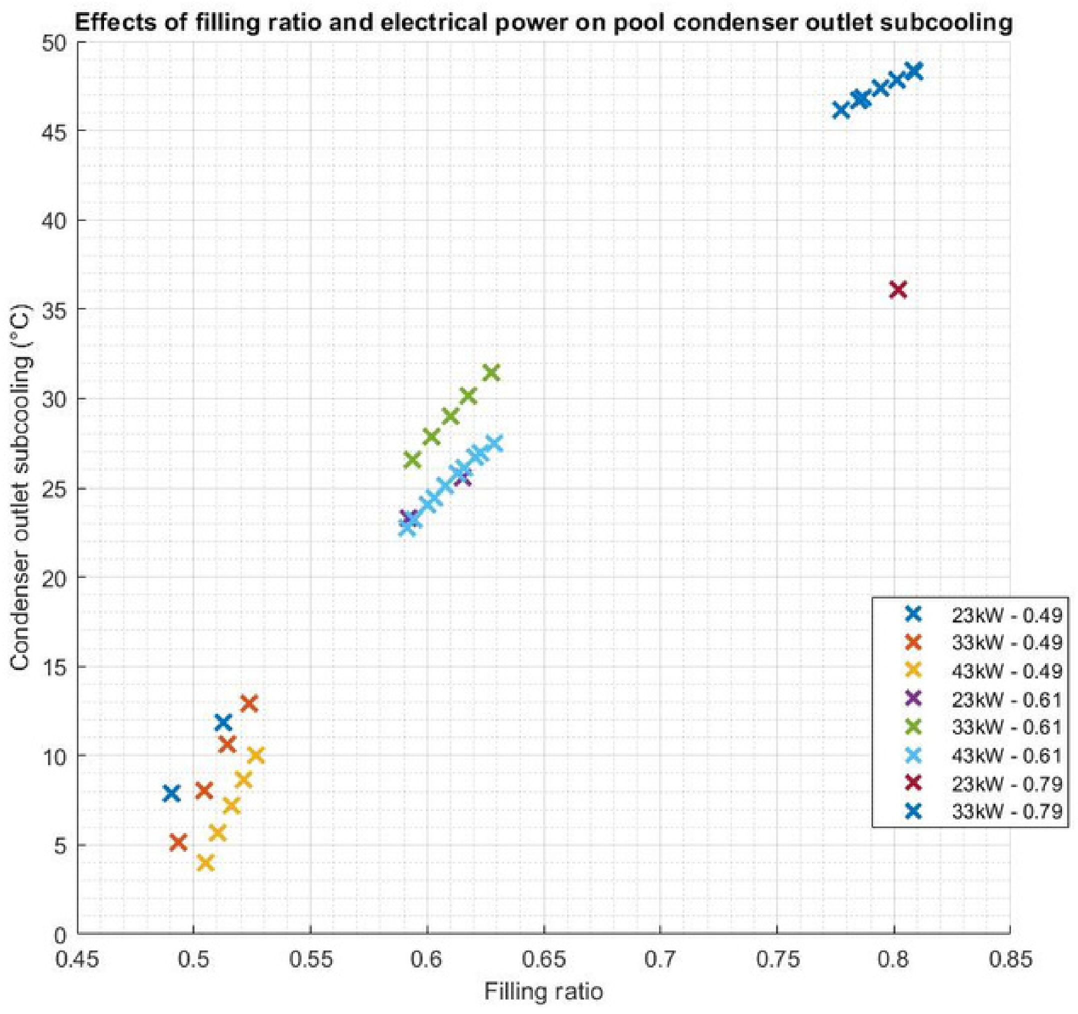


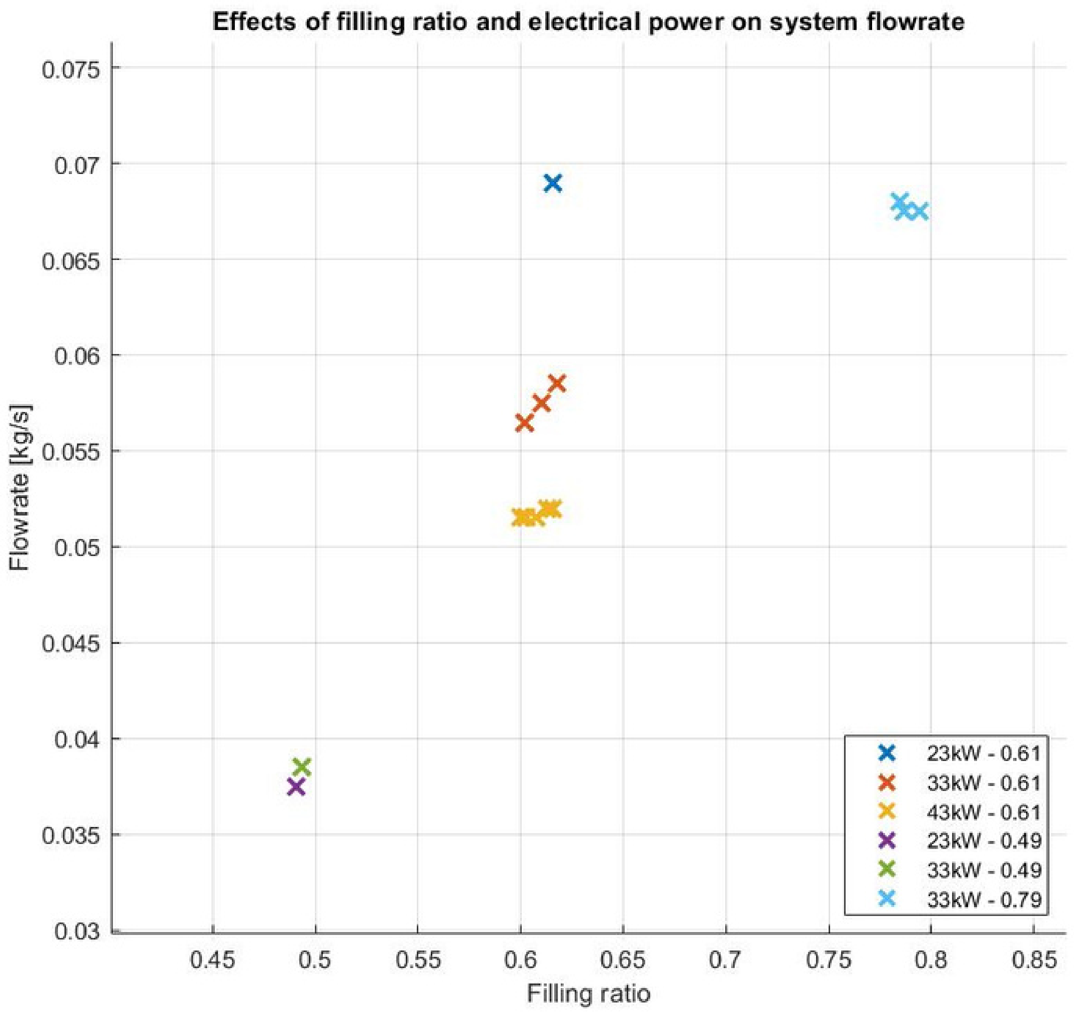
Results - Filling ratio - pressure

Our model is able to effectively reproduce **the relationship between Q, p and FR** for a wide range of initial conditions. The following chart plots the trends of pressure vs pool rejected power for different filling ratios (0.49, 0.61 and 0.79)



Results - Filling ratio - subcooling - flowrate



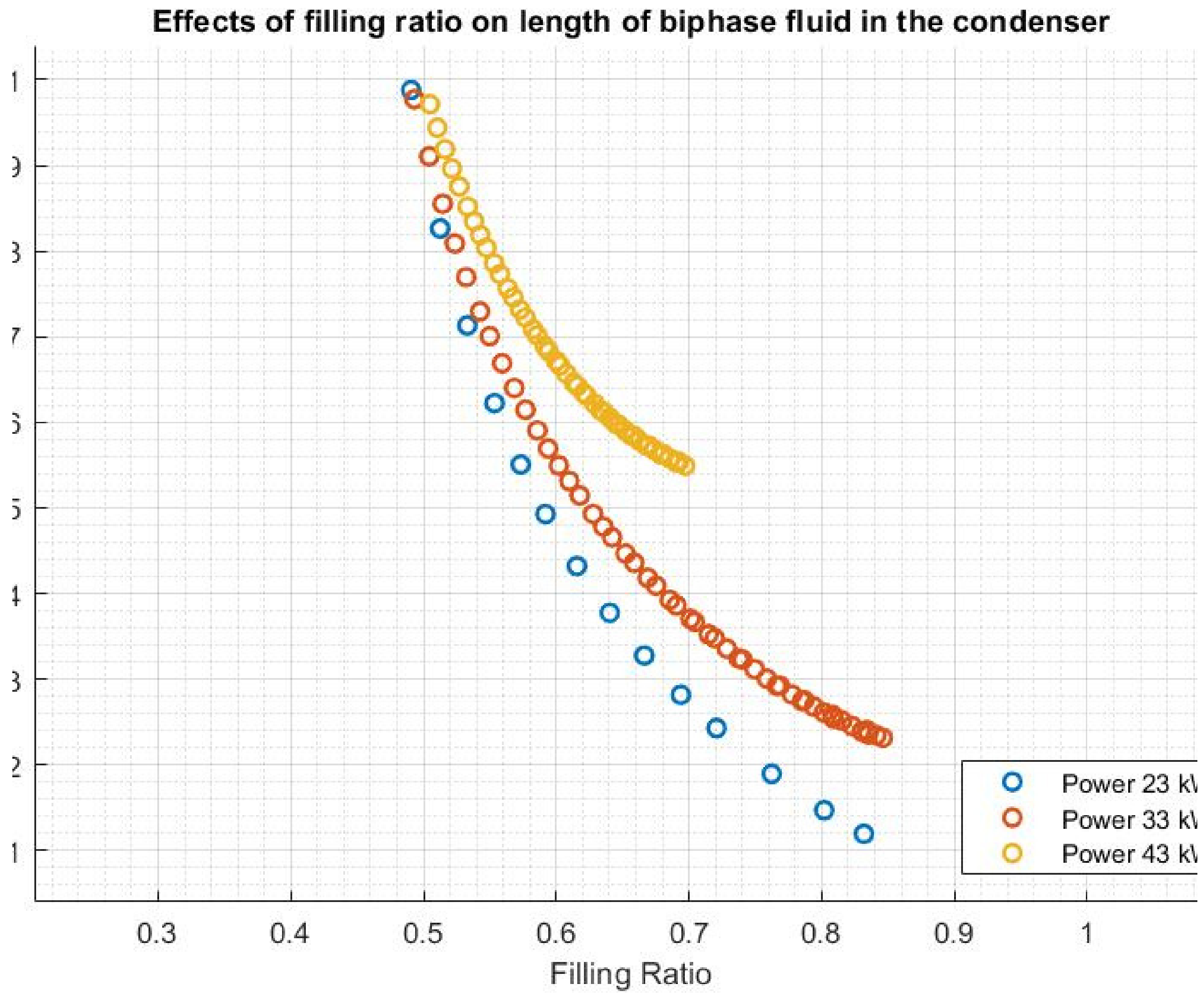


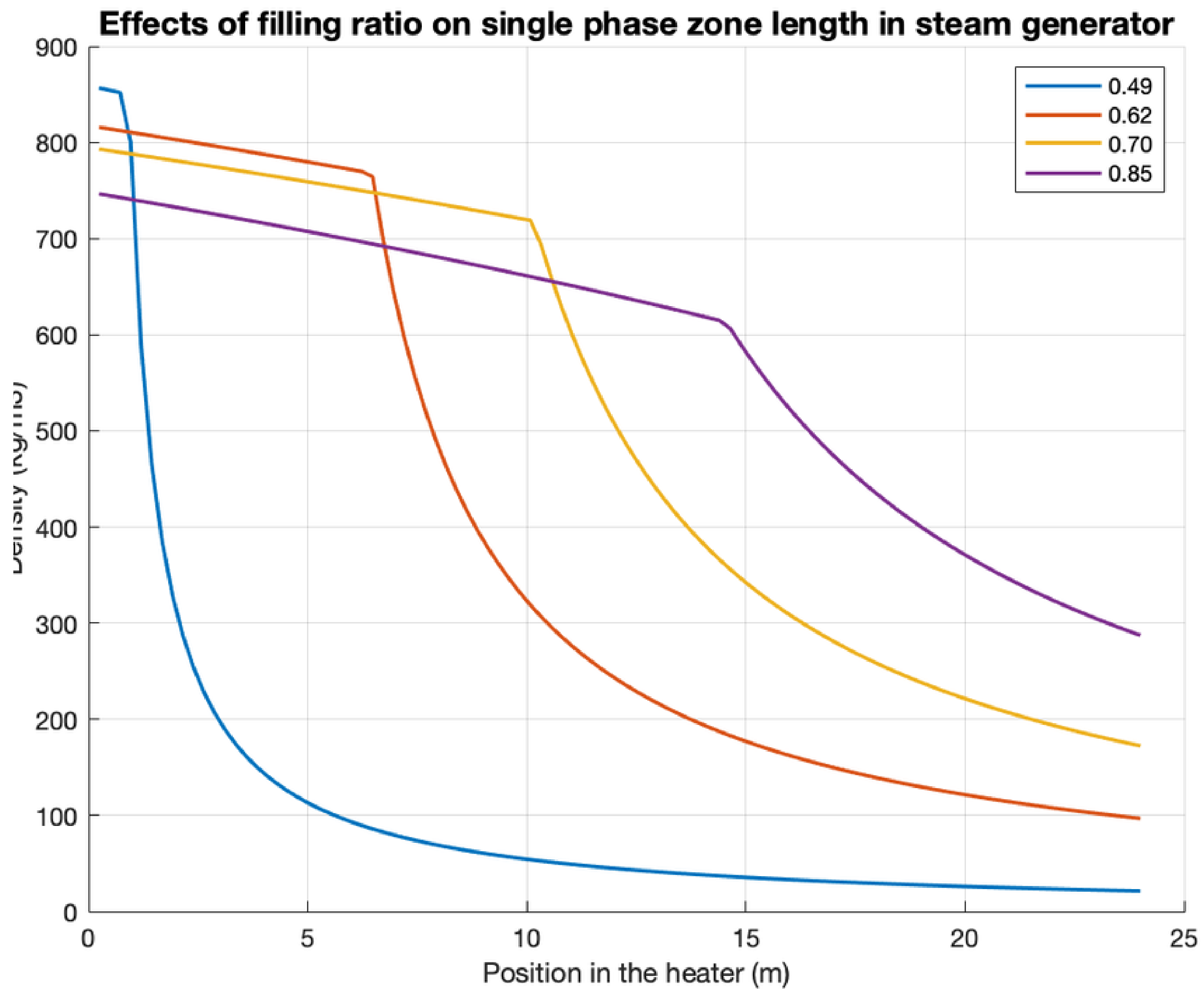
The trends of the condenser outlet subcooling increasing the FR follow the experimental results, however, compared to the paper, there is a reversal in the relation between **ΔT of subcooling and FR for different input powers**

The dependency of the **mass flow rate on filling ratio and power is not monotonic** and the reason of thisis to be found in the relationship between momentum balance and the single phase zone length of the steam generator

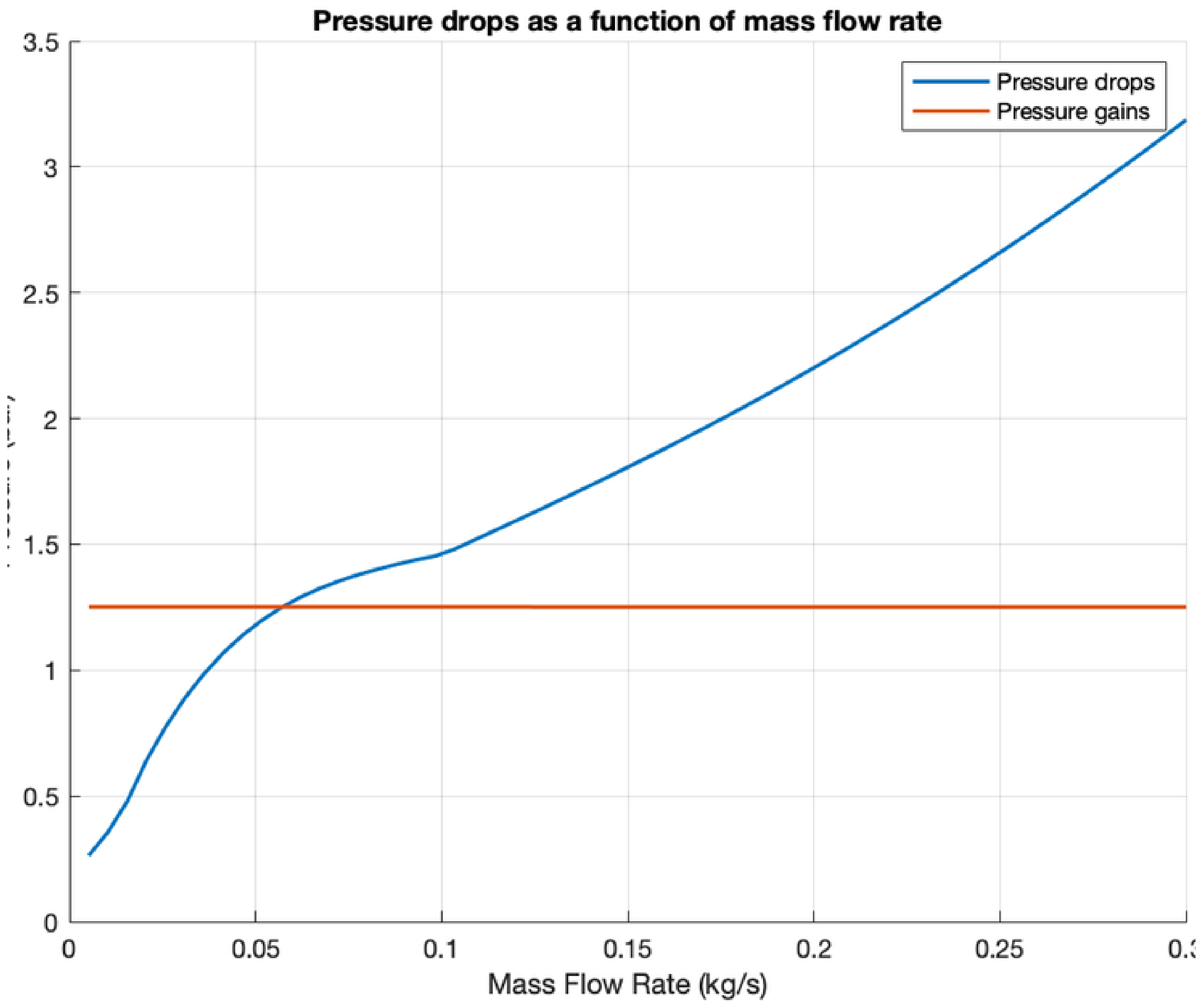
Results - Filling Ratio - two-phase zone length

Santini et al. explained how an increase of filling ratio, and thus of mass content of the loop, **brings the necessity to allocate the increase in mass** in the single phase zone lengths of the steam generator and con-denser. We are able to confirm these experimental results with the data from our simulations

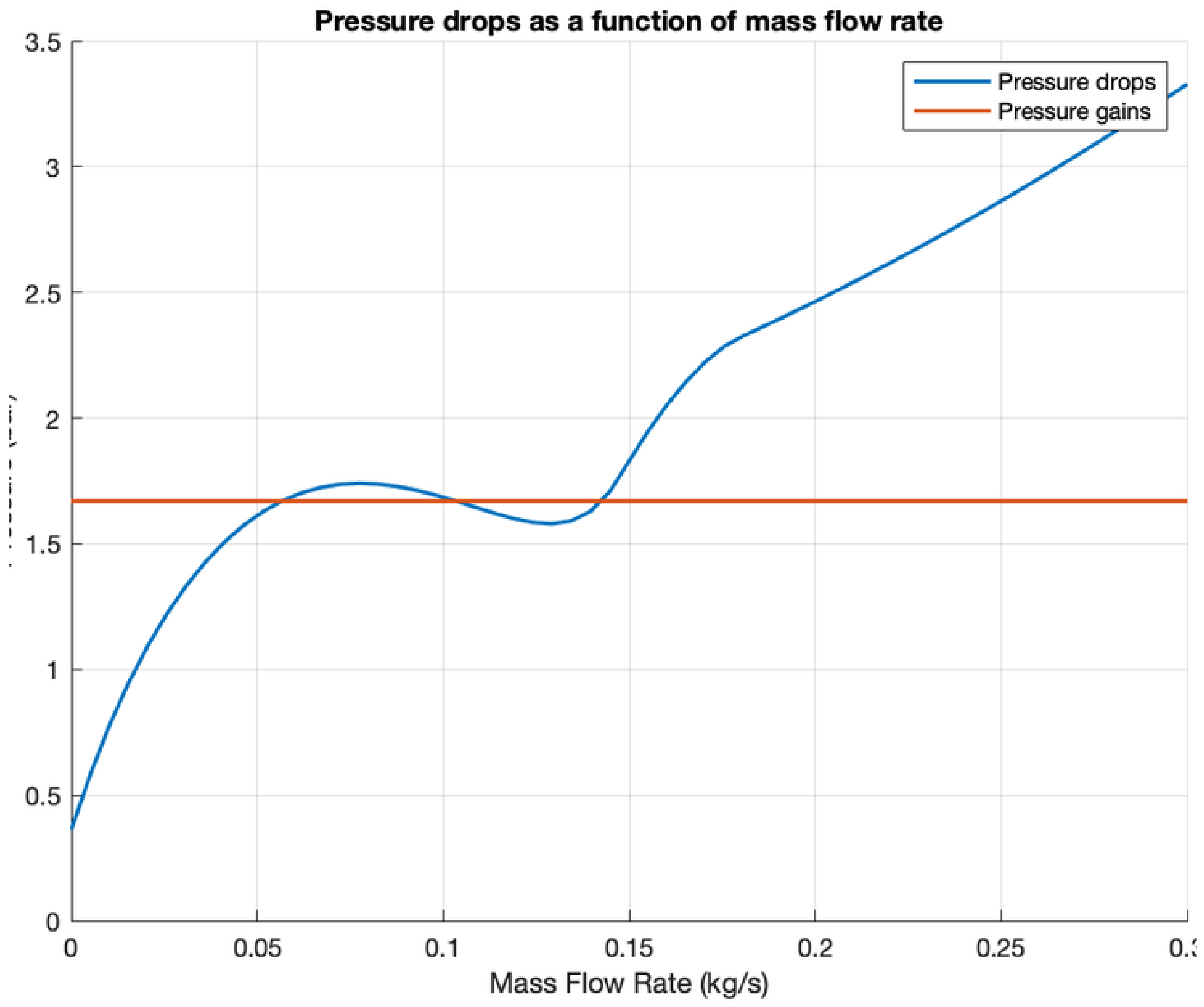




Results - Stability analysis and oscillations



The large majority of converged steady states that were simulated showed theoretical stability with characteristic curves similar to the one below (p1=145b, T1=289°C, Q=33 kW) with **just one intersection point** between pressure drops and positive head (pressure gains).



But we can see that under specific conditions (that do not correspond to converged steady state) like p1=10b,T1=140°C, Q=23kW we obtain **multiple mass flow rate values** that solve for momentum balance.

Future developments

The code may be easily adapted to limit the need for simplifying assumptions with regards to:

heat losses throughout the loop: further research concerning heat transfer relations in all the system's components could be integrated in the code, getting rid of the adiabatic assumptions made so far and predicting more coherent results. Experimental data concerning heat losses in the facility could guide this part of the modeling;

geometry accuracy: within the current model elbows and other geometrical peculiarities of the loop have been neglected thus causing an underestimation of the loop volume and concentrated pressure drops. While this version of the code has proven very effective in predicting physically meaningful results, including a complete enquiry on the geometrical features of the EHRS loop in Siet facilities could provide a further degree of accuracy;

noncondensable gases content: has been neglected so far. Further investigation on their influence on heat transfer and pressure drops could represent an interesting sensitivity analysis to be carried out;

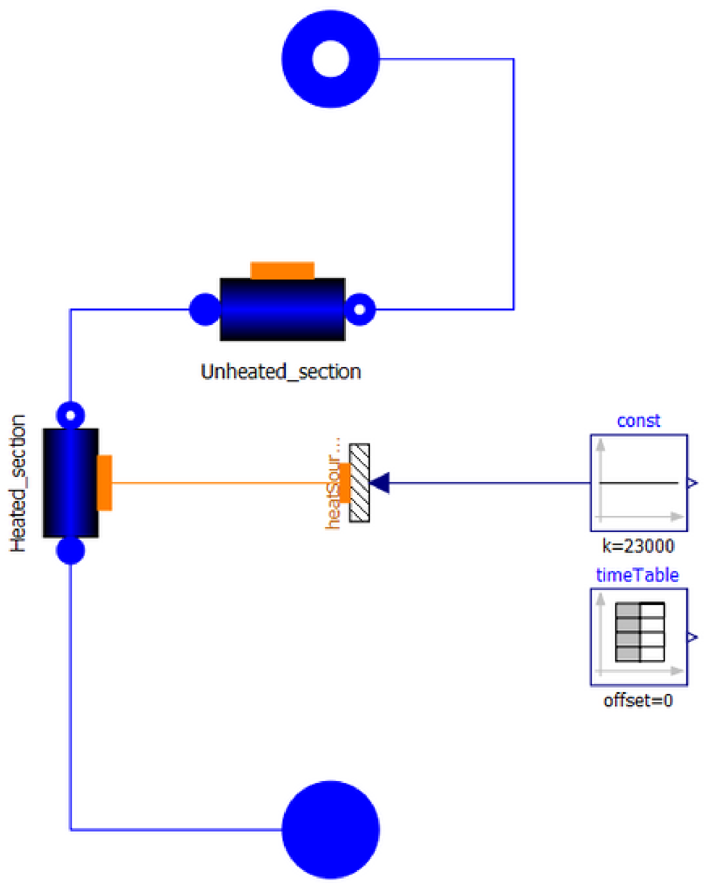
stability analysis and oscillations: the modeling of the dynamic behaviour of the loop has started using Modelica and it will eventually give us more information concerning loop transients.

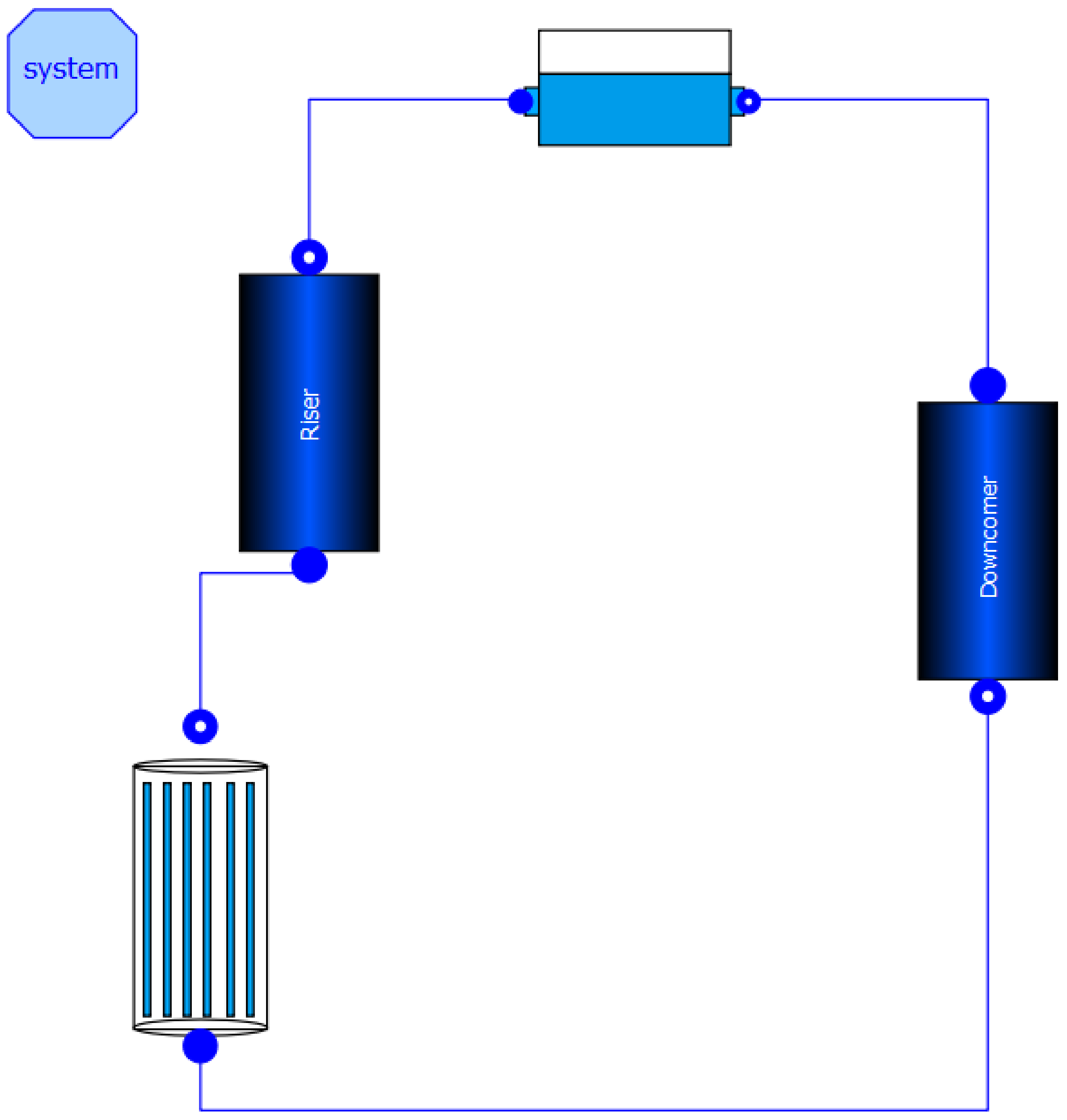
Notes on Dynamic Model

Wigner-Way formula:

$$P_d(t) = 0.0622\ P_o\left[t^{-0.2} - (t_o + t)^{-0.2}\right]$$

- $P_d(t)$ = thermal power generation due to beta and gamma rays,
- P_0 = thermal power before shutdown,
- t_0 = time, in seconds, of thermal power level before shutdown,
- t = time, in seconds, elapsed since shutdown.





Modelica model

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Thank you