POLITECNICO DI TORINO

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in Sustainable Nuclear Energy

Nuclear Fusion Reactor Engineering

HELIOS - Cryogenic Circuit Modeling

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Chapter 1

Introduction

Superconducting magnets are essential to confine plasma in fusion machines such as JT-60SA, ITER and other future fusion reactors. As they are based on LTS technologies, they must be cooled down with supercritical helium. The **HELIOS** experimental facility at CEA Grenoble, in France, aims to replicate, on a smaller scale, the cryogenic circuit of the Central Solenoid CS in the JT-60SA. Since the CS has an unsteady behaviour, the heat load removed by the refrigerator is pulsed. This may lead an over-sizing of the refrigerators to withstand the peak loads, so HELIOS is essential to investigate smoothing strategies to reduce the peaks, making a more uniform heat profile.

The purpose of this report is to develop on OpenModelica an analogous circuit that provides predictive simulation of HELIOS. At the end, to validate the numerical model, the results of the simulation will be compared with the experimental one gathered during HELIOS experimental campaigns.

Figure 1.1: HELIOS loop and the thermal buffer [1].

Chapter 2

Circuit Set-up

Modelica is an Object-Oriented language that allows to build complex system aggregating pre-defined objects. For this purpose, CryoModelica is used to model all the components of the loop, except for the valve implemented by ourself. Since helium at 4.5 K is not considerable an ideal gas, CryoModelica library, based on ThermoPower and ExternalMedia, accounts also for the cryogenic properties of the helium.

There are two circuits:

1. A primary loop in which the helium directly cool down the Central Solenoid, replaced with a test section, and release the heath to a liquid helium bath;
2. A secondary loop that refill the bath. In reality, this loop corresponds to the refrigerator, but for what concern our interest, this is just replaced by fixed boundary condition.

A more complete description of the different components is listed below:

2.0.1 Pipes

Pipes and heated pipes, representing the cryolines, are modelled as 1D finite-volume discretization of mass, momentum and energy balance.

In this model, pipes serve three different propose:

- **Heated Pipes** from C1 to C14 primarily serve to deliver helium and are assumed to have no friction. These pipes are subjected to an external static load due to the heat exchange with the external environment. Despite the strong, but not perfect, insulation, the small heat deposition cannot be neglected.
- **Heated Pipes** QL1, QL2 and QL3 replicated the section of the loop in which the helium is heated up by the CS pulsed heat load. In HELIOS, they are simulated with three electrical heaters, while in this model the pulsed behavior is taken into account by a Pulsed Source of Modelica library. Also these pipes are assumed with no friction. To achieve better results these tubes are discretized with 5 nodes instead of 2.

- **Pipes** HX1 and HX2 model the heat transfer with the liquid helium bath. In addition to the role of removing the heat load from the test section, they are essential to guarantee a sufficiently low inlet temperature in the circulator and to remove the heat produced by it. Each of them is composed by 12 parallel pipes in which the friction factor is defined by operating point. A component of CryoModelica is attached to model the convective heat transfer according to Dittus-Boelter correlation.

2.0.2 Helium Bath

The helium bath is filled with saturated helium and represent a crucial components for the smoothing operation. Since it works as a **thermal buffer** it stores a part of the pulsed loads during the transient and releases the energy progressively to the refrigerator until the next one, when it has to recover the initial condition in pressure and temperature.

2.0.3 Reservoir

Two ideal infinite reservoirs set the boundary condition of the problem. Since we are not focusing on the refrigerator loop, they are needed to impose the inlet pressure and temperature and the outlet pressure.

2.0.4 Circulator

The supercritical helium is driven by a cold circulator necessary to win the pressure losses along the circuit. To define the component, the flow and the efficiency characteristic are evaluated with the following graphics in Figure 2.1.

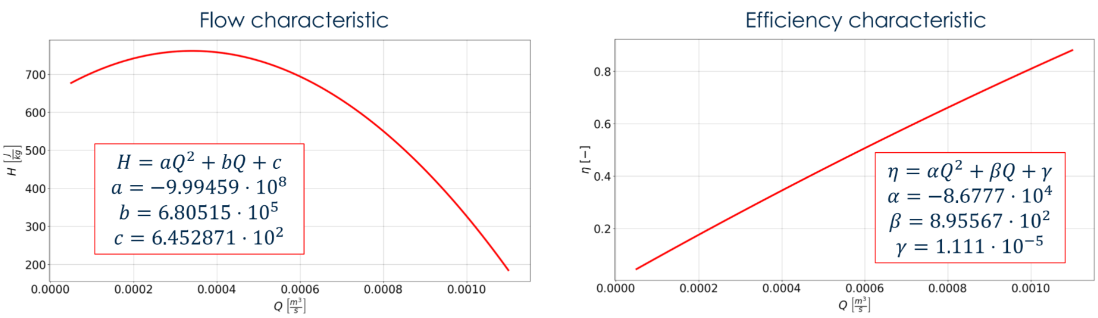

Figure 2.1: Circulator characteristics

2.0.5 Valve

The valve was the only component required to be developed. The equation governing the mass flow rate is the following:

$$w = \mathrm{char}(\theta) \cdot A_v \cdot Y \cdot \sqrt{\rho \cdot p_{\mathrm{in}} \cdot x} \tag{2.1}$$

Where:

- char(θ) is the percentage of the flow fraction represented by this characteristic:

$$\text{char}(\Theta) = \frac{1}{R} \cdot (\exp(\Theta \cdot \ln(R)) - (1 - \Theta)) \tag{2.2}$$

  where R is the valve rangeability. While Θ is the opening fraction of the valve and allows the regulation of the flow rate.

- A_v is the reduced area, given by:

$$A_v = C_v \cdot 2.4027 \times 10^{-5} \tag{2.3}$$

  where C_v is the flow coefficient (0.854USG min^{-1} psi$^{-1/2}$);

- ρ is the fluid density, evaluated through the replaceable package HeliumCoolProp that gives back the density value using in input the pressure and the enthalpy;

- p_{in} is the fluid inlet pressure provided by the ThermoPower connector;

- x is the pressure drop ratio defined as:

$$x = \begin{cases} \frac{\Delta p}{p_{in}} & \text{if } \frac{\Delta p}{p_{in}} < F_k x_T \\ F_k x_T & \text{if } \frac{\Delta p}{p_{\text{in}}} \geq F_k x_T \end{cases} \tag{2.4}$$

  where Δp is the pressure drop and $F_k x_T$ is the critical ratio, given by:

$$F_k x_T = \frac{\gamma}{1.4} F_k x_{T_{full}} \tag{2.5}$$

  where γ is the ratio of the specific heats (c_p/c_v), and $F_k x_{T_{full}}$ is the critical ratio at full opening (0.72).

- Y is the compressibility factor:

$$Y = 1 - \frac{x}{3F_k x_T} \tag{2.6}$$

Eventually, the mass flow rate is computed by the means of the homotopy operator, that allows to solve more easily non-linear equation.

These isenthalpic valves represent a relevant contribution of the pressure losses and their regulation is essential for the smoothing strategies we want to achive.

Chapter 3

Simulation

The HELIOS Loop consents to simulate different possible strategies to regulate the level of liquid helium in the thermal bath in different transient conditions as represented in Figure 3.1:

Scenario	Heating	Control
1a	Single synchronized [a] pulse	NO
1b	Single shifted [b] pulses	NO
2	3 synchronized pulses	V2 opening regulation (based on LHe bath liquid level)
3	3 synchronized pulses	V4 opening regulation (based on FE4 *dm*/*dt*)
4	3 synchronized pulses	Cold circulator speed regulation (based on FE4 *dm*/*dt*)

[a] The three heaters are simultaneously pulsed
[b] Each heater is on at different time

Figure 3.1: Features of operational scenario. [2]

In this report is analysed the scenario 3 of the previous list, varying the opening of the valves.

The transient is represented by a square waves with these characteristics:

- Amplitude of the pulse of 139.67 W;
- Period of 1200 s and a width of the pulse of 29.167% ;
- Different values for the Off-set according to the external static heat load.

The control strategy consists in two parts:

1. A first part, before the start of the transient (time<0), when the level of the helium bath is kept at the 70% of its maximum capacity by controlling the opening of the valve V2;
2. Then, when the transient begins, the control on V2 is switched off and it is activated a control on the valve V4 in order to have mass flow rate out of the bath of 26 g/s. The valves V6 and V7 are kept at a constant opening of 100% and 77% respectivly.

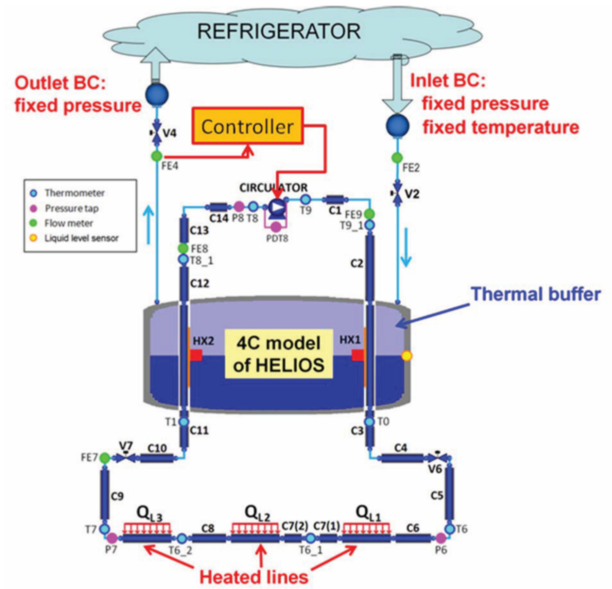

Figure 3.2: Sketch of the Modelica model of the HELIOS loop [2]

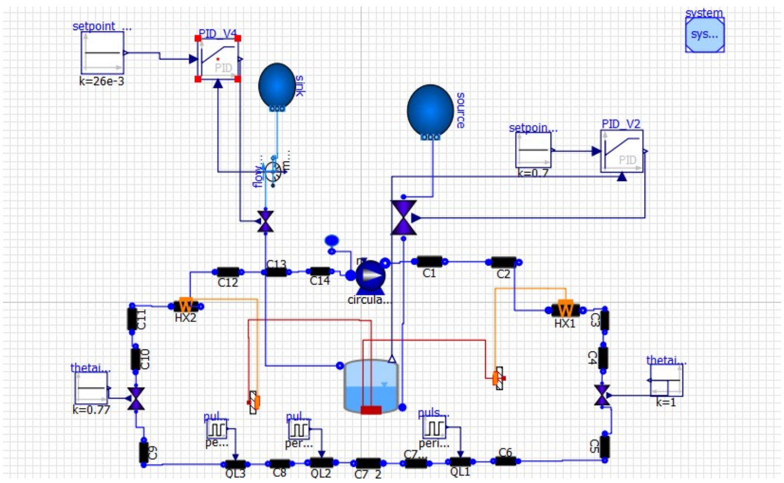

Figure 3.3: The Modelica set-up modeled for this report.

Chapter 4

Results

In this section are reported the comparison between the experimental data (dashed line) and the results obtain using the Modelica model. The graphs report the values between time -500 sec until the end of the last heat pulse.

4.0.1 Temperature

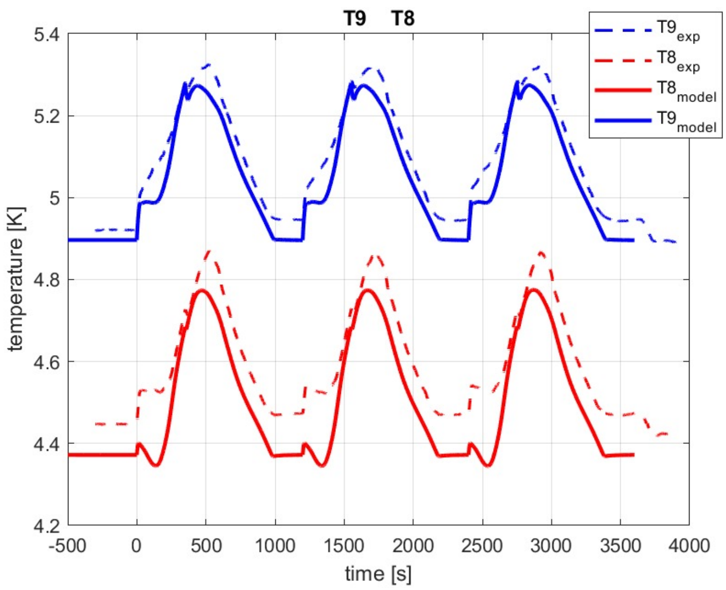

Figure 4.1: Temperature before (T8) and after (T9) the circulator.

In Figure 4.1 is shown the difference in temperature downstream and upstream of the circulator, it is evident that causes a non-negligible rise in the helium temperature. The model represents the temperatures with good accordance with the experimental data, however it slightly underestimates these values at all the time across the period considered.

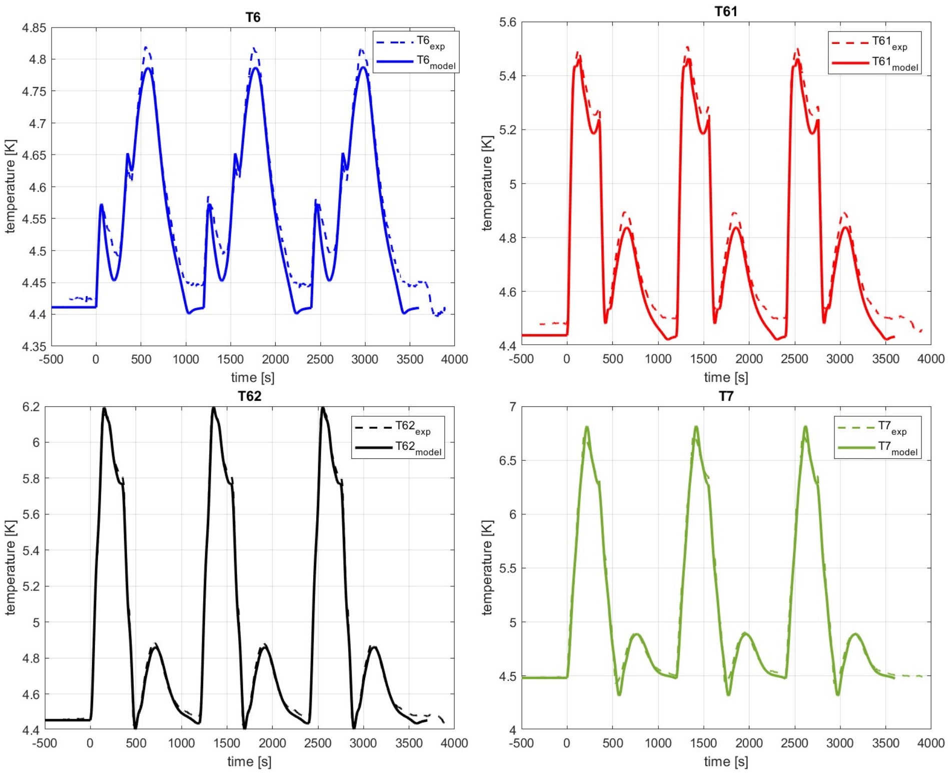

Figure 4.2: Temperature before QL1 (T6), before QL2 (T61), before QL3 (T62) and after QL3 (T7)

In these graphs of Figure 4.2, the temperature before and after each heated pipe is represented. It is evident that the profiles of the model have the same trend of the experimental results and how the temperature increases more and more as the helium flows across the heated pipes.

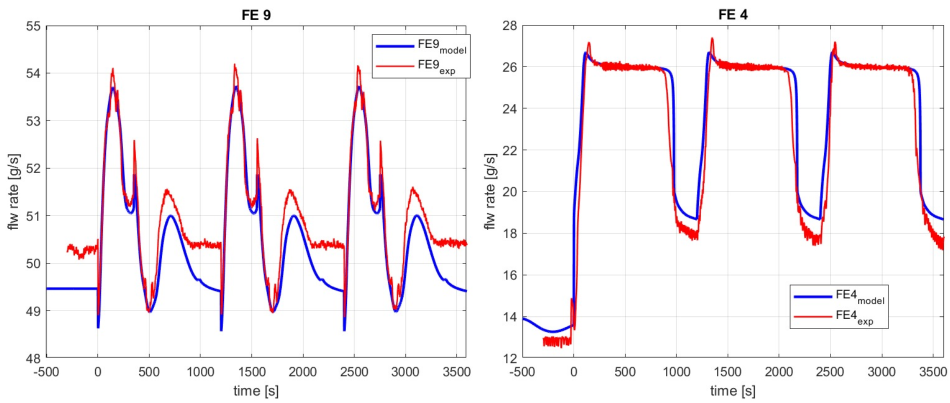

Figure 4.3: Flow rate in the primary (FE9) and in the secondary circuit (FE4).

In Figure 4.3, the plot on the left shows the mass flow rate in the primary circuit (FE9). The trend of the experimental result and ones of the model are similar, however the flow rate calculated with the model is lower than the one in the experiment. This discrepancy is consistent with the lower pressure losses obtained in the Modelica model with respect to the experiments.

At the beginning of each heat pulse it is interesting to note that the flow rate has a sudden drop, this happens because as the helium starts to expand and it pushes the flow in both directions. Then the flow rises to enhance the heat transfer of the fluid and to limit its increase of temperature. Finally, after some oscillation due to the complexity of the problem, it returns to its initial value.

The plot on the right shows the flow rate in the secondary circuit (FE4). Also here, there is good accordance between experimental data and simulated ones; it is also interesting to note that during the heat pulse the flow rate in the secondary arrives exactly to 26g/s which is the design value. The flow rate of the secondary is consistent with the value of the opening of the valve V4.

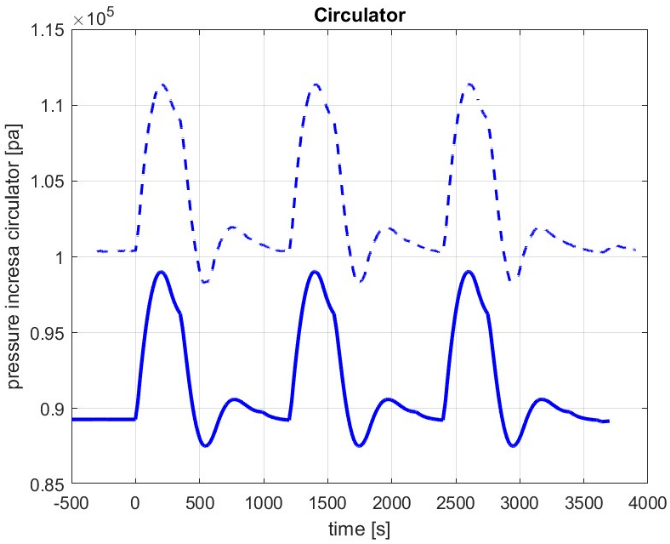

Figure 4.4: Pressure drop in circulator.

The Figure 4.4 above shows the pressure increase of the flow rate given by the circulator during the whole simulation. The trend of the two curves is the same but the simulated data are constantly about 0.1 bar lower than expected. This discrepancy affects other values such as the flow rate in the primary loop.

In Figure 4.5 below, the liquid level in the bath is reported as a percentage of the maximum level possible. Before the starting of the transient the level is exactly 70% as is imposed by the control on the valve V2. As the transient begins the liquid level varies in a similar way along the three heat pulses but the maximum value obtained in each pulse is lower than the peak obtained in the previous pulse. This means that the helium bath is not working in periodic conditions and that the helium bath could eventually dry out.

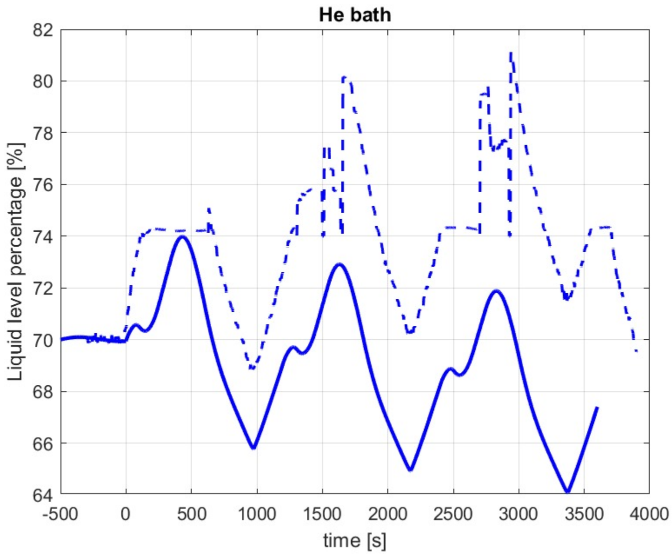

Figure 4.5: Liquid level percentage in the bath.

Chapter 5

Conclusion

To sum up, it has been modeled one of the smoothing strategies perused at HELIOS. Thanks to the control of the valves, a bath filled with helium at saturated condition serves as a thermal buffer.

All the quantities analysed followed a trend similar to the experimental data and most of them predict the magnitude of this values with great accuracy. Nevertheless, the model is really sensitive to initialisation of the problem and results could not be achieved if it is not set properly.

However, it turned out to be a powerful and useful method to predict and analyse different situation of interest, necessary for future development of nuclear fusion reactors.

Bibliography

[1] Christine Hoa et al. «Forced flow supercritical helium in a closed heat transfer loop subjected to pulsed heat loads». In: *AIP Conference Proceedings*. AIP, 2012. DOI: 10.1063/1.4707133. URL: http://dx.doi.org/10.1063/1.4707133.

[2] R. Zanino et al. «Verification of the predictive capabilities of the 4C code cryogenic circuit model». In: *AIP Conference Proceedings*. AIP Publishing LLC, 2014. DOI: 10.1063/1.4860896. URL: http://dx.doi.org/10.1063/1.4860896.