Example of cryogenic process simulation using EcosimPro: LHC beam screen cooling circuits

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Abstract

CERN has developed a dedicated library to model helium cryogenic plants with a commercial software called EcosimPro. The aim of such a library is to provide a simple way to model small and large scale cryogenic systems performing dynamic simulations in an acceptable timescale to assist both control and operation teams in the optimal commissioning and operation of cryogenic plants. Moreover, the tool allows users to easily develop models related to their specific components such as cryogenic transfer lines or superconducting magnets. During the last few years, this library has been used to model several CERN cryogenic systems. The models have been used for different purposes, e.g. operator training, virtual commissioning of control systems and control optimization. This paper briefly presents EcosimPro with the cryogenic library developed at CERN and gives an example of modeling the LHC beam screen cooling circuits showing simulation results compared with experimental data.

Keywords: Helium, Heat transfer, Fluid Dynamics, Numerical Simulation

1. Introduction

In the last few years, the interest in dynamic simulations of cryogenic systems was increased significantly [1, 2, 3, 4, 5] for several reasons. First of all, the dynamic cryogenic simulations need significant computation power due to the high temperature ranges and non-linearities and nowadays, computational tools are much more powerful and efficient than before. Secondly, large-scale cryogenic plants are more and more complex and consume a large

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amount of energy. Dynamic simulations are well adapted to perform control optimizations on these complex cryogenic plants ensuring a better stability and allowing one to save energy. Finally, new cryogenic plants are being designed to operate under pulsed heat loads for superconductor tokamaks such as EAST, ITER, JT60SA and KSTAR, hence cryogenic plants cannot only be designed for steady-state but need also dynamic simulations to optimize transient responses. In this context, the European Organization for Nuclear Research (CERN) developed a real-time dynamic simulator for cryogenic systems using the modeling and simulation software EcosimPro [5].

In the first section of this paper, the software EcosimPro is briefly presented and the cryogenic library developed at CERN is described in the second section. Then, an example of modeling of the Large Hadron Collider (LHC) beam screen cooling circuits is presented with some simulation results compared to experimental data.

2. EcosimPro

EcosimPro is a commercial modelling software to simulate 0D or 1D multidisciplinary continuous-discrete systems[6]. It can be used to simulate any kind of system based on Differential Algebraic Equations (DAE) such as thermo-hydraulic processes like cryogenic systems. It provides a graphical user interface to develop models, build complex systems and perform dynamic simulations, parametric studies or steady-state computations. EcosimPro generates C++ code to run simulations (transparent for the users) and then, this code can be used to link the model to other applications.

Other modeling and simulation software exists on the market with similar capabilities but one of the reasons why EcosimPro was chosen is because of the ease of integration of its well documented C++ code with other environments. This type of feature was mandatory to develop operator training platform.

EcosimPro provides its own object oriented programing language (*EL* language) to model components. This language is non-causal where the relationship among algebraic and differential variables has to be specified and the final mathematical model is automatically generated with the boundary conditions selected by the user.

3. Cryogenic Library

A cryogenic library has been developed to perform simulation of helium cryogenic plants (liquefier, refrigerator, distribution box, etc.) using common cryogenic equipments such as valves, heat exchangers, turbines, etc. The cryogenic library directly embeds functions to compute the main thermodynamic properties of helium from interpolation tables extracted from HEPAK [7] and material properties at cryogenic temperatures such as heat conductivity or heat capacity for Stainless Steel 304, aluminum T6 or copper. The cryogenic library is divided into different types of equipment represented in Figure 1:

a) **Hydraulic components**: compute a mass-flow as a function of a pressure drop and the accumulation of mass in these components is neglected: Control valve, On/Off valve, screw compressor, turbine, cold compressor, pump, hydraulic resistance.
b) **Storage components**: compute an internal pressure as a function of input and output massflows and have a thermal inertia: pipe, different mixing volumes, adsorber, tank, phase separator, phase separator integrating a heat exchanger in the bath, 1D transfer line, filter.
c) **Heat Exchangers (HX)**: perform an energetic balance between different 1D streams (parallel flow or counter flow) and have a thermal inertia and a pressure drop: HX with 1 cold stream and 1 hot stream, HX with 2 hot streams and 1 cold stream, HX with 2 cold streams and 1 hot streams.
d) **Instrumentation**: basic analog and digital cryogenic instrumentation: temperature sensor, pressure sensor, flowmeter, level sensor, pressure switch, temperature switch, level switch.
e) **Sources and Sinks**: Ideal sources and sinks to force boundary conditions: input pressure/temperature, input massflow/temperature, output pressure, output massflow.

All the components are based on classical thermo-hydraulic equations. The *hydraulic components* are 0D models using algebraic equations since the aim of this library is to provide simulations in terms of general process behavior where the very fast flow dynamics can be neglected. The *storage components* and *heat exchangers* are based on differential algebraic equations defining mass and energy balances. *Transfer lines* and *HX* are modeled in 1D by means of a spatial discretization whereas all other models are 0D. Heat transfer coefficients and pressure drops are computed from algebraic

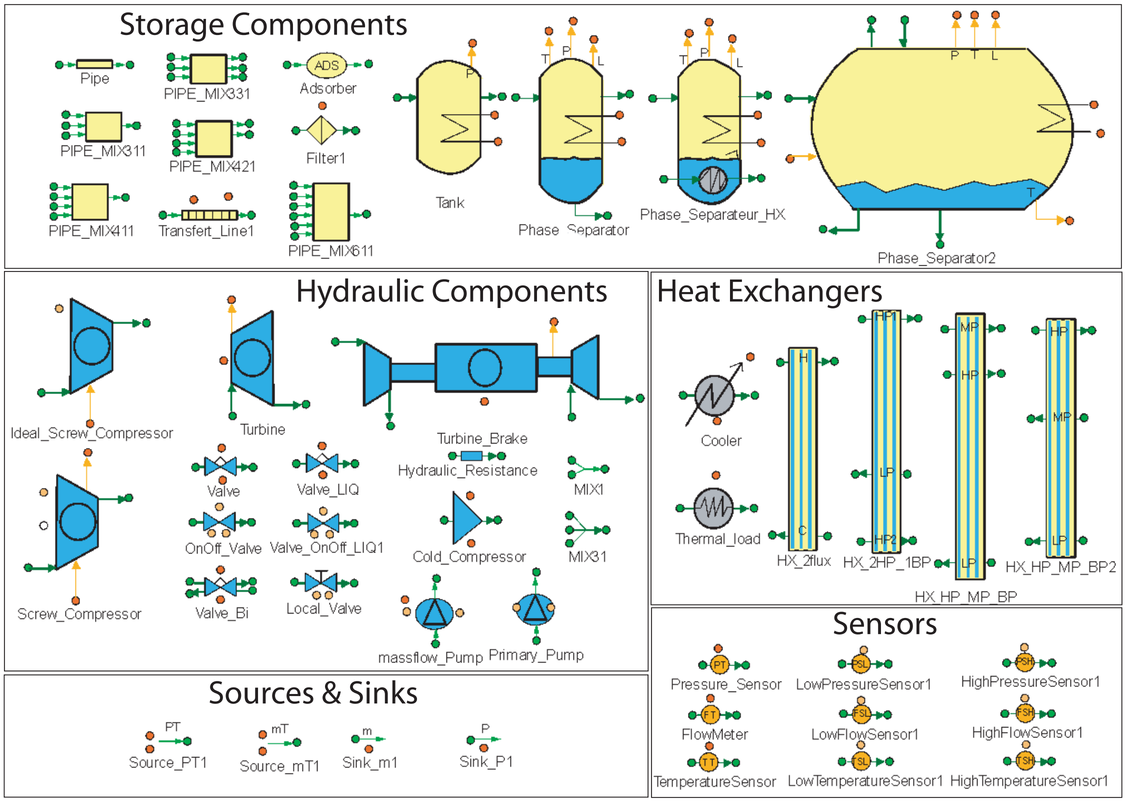

Figure 1: Different cryogenic equipments modeled in the Ecosimpro cryogenic library

correlations appropriate to the components and the flow regimes. For more details on the component modeling, see [5].

It is worth noting that the source code for libraries is entirely open, this allows new properties or new materials to be easily added or modified in the library. For the same reason, equations or correlations used by default in the different components can be also modified. This flexibility gives a real advantage to this tool where the user knows exactly what equations are used and can change them according to the requirements.

4. LHC beam screen

The LHC beam screen is located inside cold-bore beam pipes of the LHC, see Figure 2: it minimizes heat losses between 4.6 K and 20 K, it removes the resistive wall power losses dissipated by the beam and it intercepts synchrotron radiation and molecules in order to increase the quality of the beam vacuum [8]. Each beam screen is cooled by conduction through two small cooling pipes, supplied by supercritical helium coming from the Cryogenic Distribution Line of the LHC (QRL) at 3 bar and 4.6 K to avoid two-phase flow regime. One beam screen is installed on each beam pipe in a half-cell of the LHC corresponding to three superconducting dipoles and one superconducting quadrupole for a total length of 53 m.

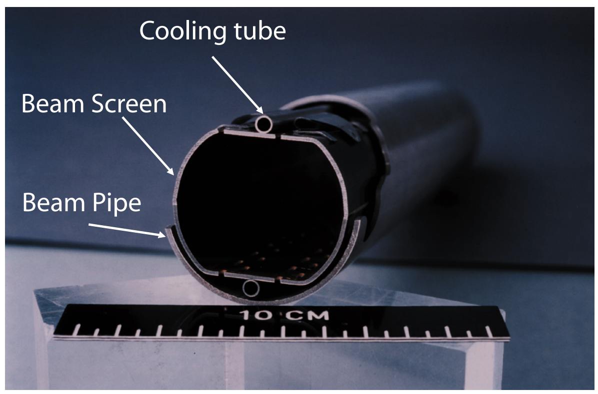

Figure 2: LHC beam screen cooled by its two small cooling tubes

The initial cryogenic library provides only 0-D pipe models or very simplified 1-D models where the ideal gas law is used. Hence, to model this specific supercritical helium flow cooling the LHC beam screen, a new model had to be developed reusing the facilities of the Ecosimpro cryogenic library. This kind of approach was already used previously to simulate a heat wave propagation along the LHC cryogenic distribution line after a quench [9] but in this last paper, the model was based on simplifications for very low pressure helium flows which are not valid for supercritical helium flows.

The following section describes the model of a supercritical helium flow though small cooling pipes which will be then embedded in a larger system with other components from the cryogenic library in order to simulate the complete beam screen cooling circuits.

4.1. Modeling of a supercritical helium flow

A one dimensional compressible flow according to the x axis has to be considered as the isothermal compressibility is very high for supercritical helium. In this case, the three Euler equations defining mass, momentum and energy balances can be defined as follow to describe a supercritical helium flow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \dot{M}}{\partial x} = 0 \tag{1}$$

$$\frac{\partial \dot{M}}{\partial t} + \frac{\partial P}{\partial x} + \frac{fr}{2D\rho} \cdot \dot{M}^2 - \frac{\rho g z}{100} = 0 \tag{2}$$

$$\rho \cdot \frac{\partial h}{\partial t} + \dot{M} \cdot \frac{\partial h}{\partial x} = \frac{q}{V} \tag{3}$$

where all variables are summarized in Table 1.

In this study, we are not interested in modeling fast dynamics of the momentum. The partial differential equation (2) is thus simplified by setting $\frac{\partial \dot{M}}{\partial t} = 0$ in order to obtain the following equation corresponding to the equation of momentum in steady-state:

$$\dot{M} = \sqrt{-\left(\frac{\partial P}{\partial x} - \frac{\rho g z}{100}\right) \cdot \frac{2D\rho}{fr}} \tag{4}$$

As supercritical helium flows are generally turbulent flows with high Reynold numbers ($Re > 10^4$), the friction factor fr is computed using the empirical Haaland equation [10]:

$$fr = \frac{1}{\left[1.8 \cdot \log_{10}\left(\left(\frac{\epsilon}{3.7D}\right)^{0.11} + \frac{6.9}{Re}\right)\right]^2} \tag{5}$$

4.2. Numerical implementation

Differential algebraic equations can be directly written in EcosimPro using the quote symbol ($'$) to define a time derivative. However, partial differential equations cannot be directly written and thus a spatial discretization scheme has to be applied along the x axis to compute $\partial \dot{M}/\partial x$, $\partial P/\partial x$ and $\partial h/\partial x$. Each partial derivative is approximated by a first-order backward finite difference. The three following equations are thus obtained after discretization of the flow in N nodes:

$$\rho_i' + \frac{\Delta \dot{M}_i}{\Delta x} = 0 \tag{6}$$

$$\dot{M}_i = \sqrt{-\left(\frac{\Delta P_{i+1}}{\Delta x} - \frac{\rho_i g z_i}{100}\right) \cdot \frac{2D\rho_i}{fr_i}} \tag{7}$$

$$\rho_i \cdot h'_i + \dot{M}_i \cdot \frac{\Delta h_i}{\Delta x} = \frac{q_i}{V_i} \tag{8}$$

where the subscript i represents the number of the node between 1 and N and the Δ operator is defined as $\Delta X_i = X_i - X_{i-1}$. Note that M_i is the output momentum of the node i and the equation (7) is executed for i equal 1 to $N-1$ whereas equations (6) and (8) are executed for i equal 1 to N.

Hence, these three equations allow the density ρ_i, the enthalpy h_i and the momentum M_i in each node to be computed. Boundary conditions are selected to ensure the consistency of the model. The boundaries are the inlet enthalpy h_0, the inlet momentum M_0 and the outlet momentum M_N. Then, the numerical values of boundary conditions will be given by other components linked to the beam screen cooling tube (namely the inlet/outlet valves) and all thermodynamic properties (k_i, P_i, Pr_i, T_i, μ_i) in each node are computed from the density ρ_i and the specific enthalpy h_i using thermodynamic tables of the cryogenic library obtained from HEPAK.

The heat transfer coefficient hc between the fluid and the pipe is then deduced from the Nusselt number:

$$hc_i = Nu_i \cdot \frac{k_i}{D} \tag{9}$$

where Nu is obtained from the Colburn formulation:

$$Nu_i = 0.023 \cdot Pr_i^{1/3} \cdot Re^{0.8} \tag{10}$$

It is assumed here that a cold mass Mc is in contact along the pipe. The heat conduction in the pipe and in the cold mass is neglected in our 1D model where the cold mass and the cooling pipe are considered homogeneous (same material) and isothermal in each discretization node. Finally, an energy balance between the pipe and the fluid allows the pipe temperature Tw to be computed:

$$(Mw_i + Mc_i) \cdot Cpw_i \cdot Tw'_i = -hc_i \cdot Sw_i \cdot (Tw_i - T_i) + Q_{lin} \cdot \Delta x \tag{11}$$

where the heat capacity of the pipe Cpw is obtained as function of the temperature in the cryogenic library according to the material chosen and Q_{lin}

is another boundary condition of the model representing the linear heat load applied to the beam screen.

The heat input q_i applied to a node is then deduced from:

$$q_i = hc_i \cdot Sw_i \cdot (Tw_i - T_i) \tag{12}$$

Note that this numerical implementation using a backward finite difference does not allow the computation of reverse flow.

4.3. Modeling of LHC beam screen

This section explained how the model presented before is included in a larger model to have a complete model of the LHC beam screen cooling circuits embedding its temperature regulation.

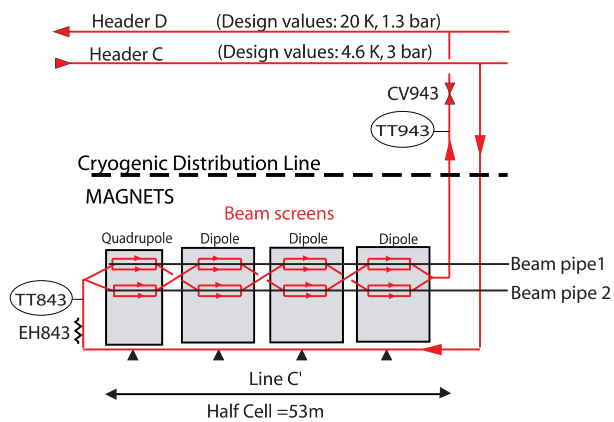

Figure 3: LHC beam screen cooling scheme

Figure 3 represents the cooling scheme of the beam screen. First, magnet supports are cooled through the line C' and then, the flow is split in four cooling tubes of 53 m long and 3.7 mm diameter each (two cooling tubes per beam pipe). To have an homogeneous extraction of the heat along the line, cooling tubes are mixed two by two at the end of each magnet.

The model developed in subsection 4.2 is integrated in an EcosimPro schematic where four equivalent parallel cooling tubes are considered where a cold mass of 27 kg representing the beam screen is attached to each cooling tube.

The ecosimpro schematics includes also the outlet valve *CV943* regulating the outlet temperature *TT943* and the inlet heater *EH843* regulating

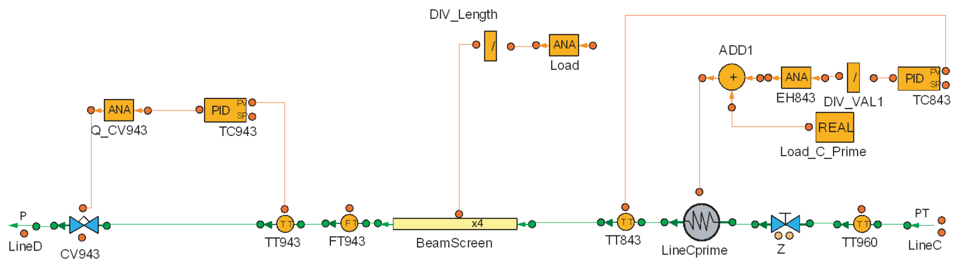

Figure 4: LHC beam screen cooling schematic in EcosimPro

the inlet temperature *TT843*. Both regulations makes use of PI controllers (Proportional-Integral) where regulation parameters used in simulations are the same as the parameters used on the real process. An additional constant heat load is applied at the beginning to model the load induced by the magnet supports in the line C'. A valve is also included between the beam screen and the Header C to introduce an hydraulic impedance, see Figure 4. The boundary conditions of the model are the pressure and temperature of the Header C (3 bar and 5.6 K), the pressure of the header D (1.2 bar), the heat load of the Line C' (12 W) and the heat load applied to the Beam screen will be variable according to the simulations.

4.4. Result of simulations

The pressure drop along the beam screen cooling tubes has been checked in steady-state with experimental data obtained in an experimental setup described in [11]. The Figure 5 shows the different pressure drops obtained in simulation for different heat loads applied on one cooling tube and shows a good agreement between simulated pressure drops and observed ones.

To validate the model during transients, it was decided to compare simulations with some experimental tests performed in 2002 on the *LHC String 2*, an experimental setup reproducing exactly a complete LHC cryogenic cell of 106 m [12].

The first test to validate the model is an open loop test where the control valve *CV943* is forced with a positive and a negative steps of 4 %. Figure 6 shows the result of the simulation compared to the experimental data taken on LHC String 2. The dynamics are well approximated by the model and the steady-state values are similar. This comparison validate the model in term of dynamic response of the beam screen temperature against control valve movements.

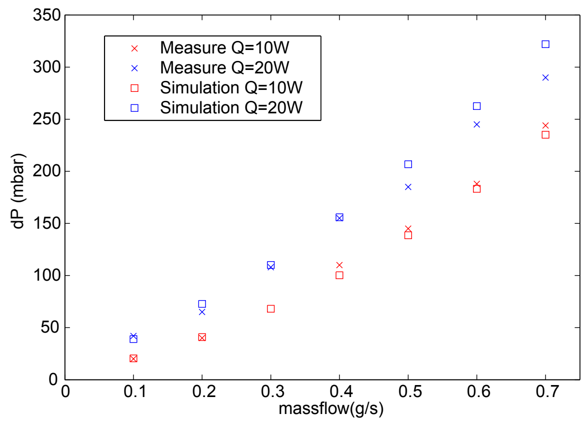

Figure 5: Experimental and simulated pressure drop in steady-state for different heat loads.

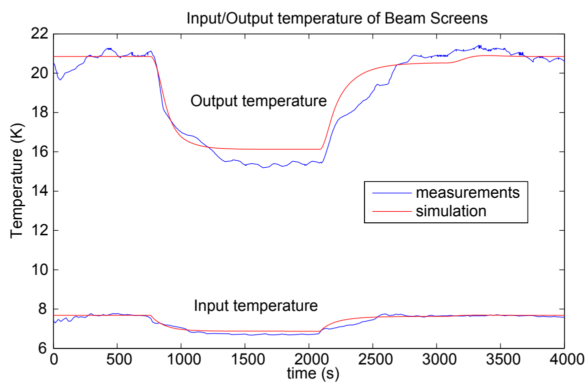

Figure 6: Open loop simulation compared to experiment performed on the LHC String 2

The second test consists in applying different heat loads on the beam screen between 40 W and 120 W per beam pipe and on the electric heater $EH843$ located at the inlet of the beam screen to control the inlet temperature. The Figure 7 shows results of simulations compared with experimental data. The simulations show a good agreement between the model and the measurements during the transients. The difference observed on the valve opening mainly comes from a lack of knowledge of the valve characteristic and it has no impact on the global model behavior.

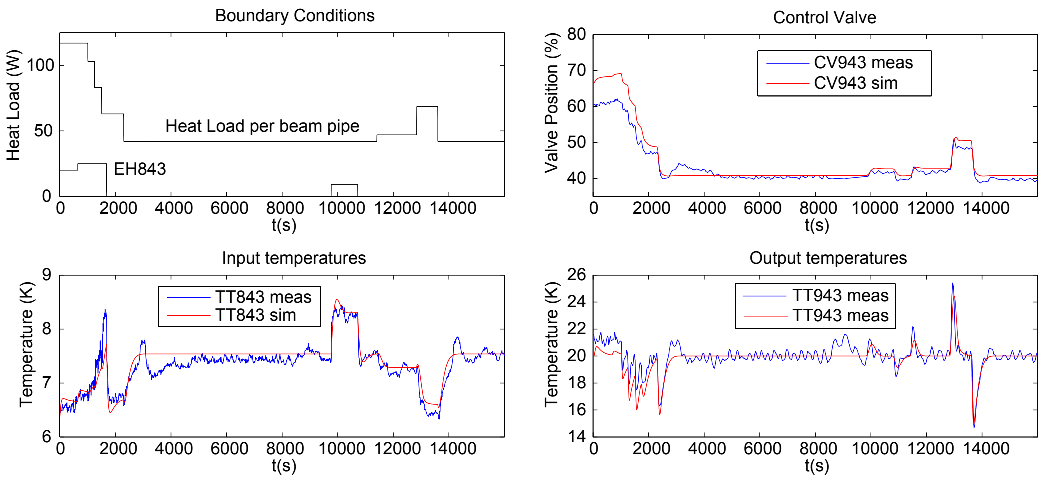

Figure 7: Close loop simulation compared to experiment performed on the LHC String 2

4.5. Thermally induced flow oscillations

Thermally induced flow oscillations can appear in supercritical helium flows if the temperature gradient is too important due to the large density variations along the flow. A study on these oscillations has been made and an experimental prototype was built in 2000 to reproduce such oscillations [11].

Hence, the model developed in this paper has been adapted to fit this experimental setup with only one cooling tube similar to the LHC beam screen cooling pipes and without cold mass attached to the cooling pipe ($Mc = 0$). Simulations were then compared to the experimental results.

The model is able to reproduce the oscillations when the mass flow is sufficiently low regarding the heat load applied on the cooling tube as shown in the Figure 8 where a simulation is compared to experimental data for a heat load of 10 W and an inlet temperature of 5 K. Series of simulations were performed for different heat load values establishing the mass flow and the oscillation period at the transition between the stable and the unstable regime, Figure 9 shows these results compared with the experimental results obtained in [11].

The transition between the two regimes is performed at lower mass flow in simulation and the difference increases when the heat load value is more important. About oscillation periods, they are well approximated for high heat load values but oscillations are faster in simulation for low heat loads.

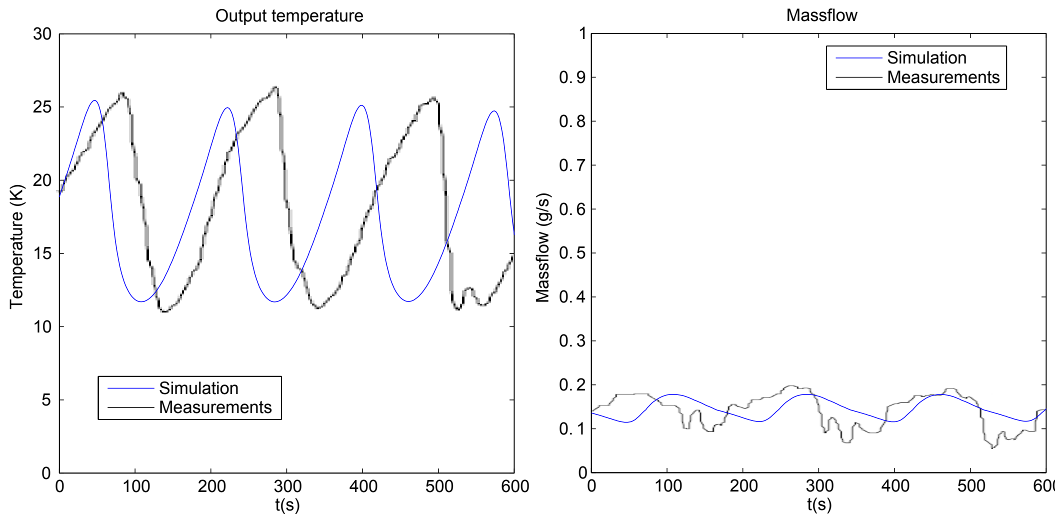

Figure 8: Thermally induced flow oscillations reproduced in simulations and compared with experimental data for a heat load of 10 W and an inlet temperature of 5 K

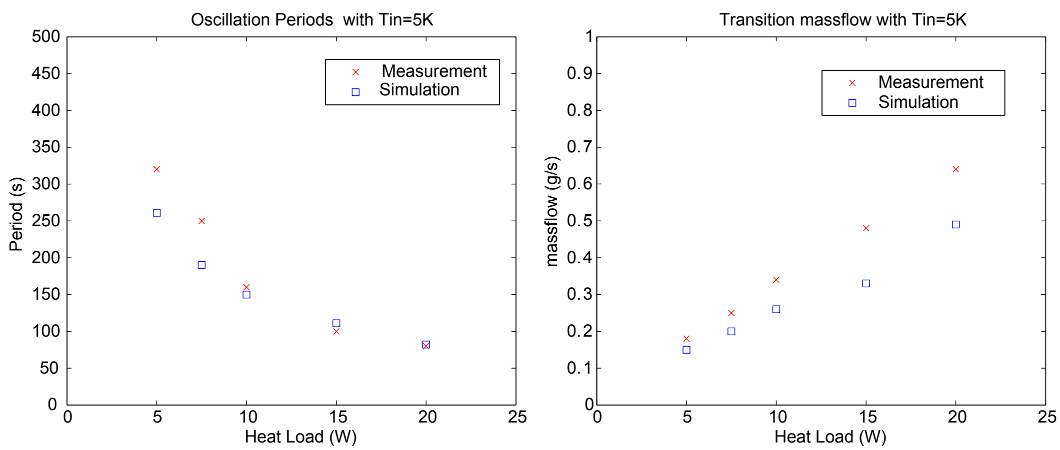

Figure 9: Oscillation periods and mass flows at the transition regime for an inlet temperature of 5 K

5. Conclusion

EcosimPro is a flexible modeling and simulation tool able to simulate 0D or 1D systems from Differential Algebraic Equations. The cryogenic library can be easily modified to include new features and new specific components such as the model of the LHC beam screen cooling circuits developed in this paper.

The model of the LHC beam screen cooling circuits show good results during the regulation of the outlet temperature and the different dynamics due to the heat load variations are well reproduced in simulation (in term of amplitude and time).

The eventual thermally induced flow oscillations observed experimentally have also been reproduced with this model but the simulations show slight differences on the transition between the stable and the unstable regime.

In this paper, simulations were confronted to experimental data coming from different test benches of the LHC beam screen and it will be needed to perform precise comparisons with the real LHC beam screen.

Moreover, it can be interesting to improve this model to have a better reproduction of thermally induced flow oscillations and to optimize the regulation of the beam screen outlet temperature to ensure the good operation of the LHC in the next years due to the increase of the LHC energy and luminosity where regulation problems can appear due to the important heat loads on beam screen.

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Table 1: Main variables of the supercritical helium line

Symbol	**Description**	**Unit**
Cpw	Heat capacity of the pipe	$J.kg^{-1}.K^{-1}$
D	Diameter of the pipe	m
fr	Darcy-Weisbach friction factor	$-$
h	Specific enthalpy	$J.kg^{-1}$
hc	Heat transfer coefficient	$W.m^{-2}.K^{-1}$
k	Thermal conductivity	$W.m^{-1}.K^{-1}$
L	Length of the pipe	m
$\dot{m}$	Mass flow	$kg.s^{-1}$
$\dot{M}$	Momentum	$kg.m^{-2}.s^{-1}$
Mw	Mass of the pipe	kg
Mc	Cold Mass	kg
N	Number of discretization nodes	$-$
Nu	Nusselt number	$-$
P	Pressure	Pa
Pr	Prandtl number	$-$
q	External heat inputs	W
Q_{lin}	linear heat input	$W.m^{-1}$
Re	Reynolds number	$-$
S	Hydraulic cross section of the pipe	m^2
Sw	total internal surface of the pipe	m^2
T	Fluid temperature	K
Tw	Pipe and cold mass temperature	K
V	Internal volume of the pipe	m^3
z	Slope of the pipe. Positive if go up	$\%$
Δx	spatial discretization step	m
ϵ	Roughness of the pipe	m
μ	Viscosity	$Pa.s$
ρ	Density	$kg.m^{-3}$
g	Gravity acceleration	$m.s^{-2}$