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Development of a Model for the Thermal-Hydraulic characterization of the He-FUS3 Loop

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He-FUS3 is a helium facility designed and realized by ENEA in order to test the thermal-mechanical properties of prototypical breeding blanket module assemblies of a DEMO reactor. The actual facility has been upgraded with a high performance Turbo Circulator and a water Heat Exchanger integrating the pre-existent Air Cooler. In addition, a new Test Section located in the loop hot zone has been settled down with the objective of investigating safety relevant transient conditions of "In-TBM" LOCA scenarios. A RELAP5-3D© model has been developed to perform a set of preliminary simulations on the new He-FUS3 layout. Both cold and hot stationary conditions have been analyzed evaluating the Turbo Circulator performances for a wide range of helium flow rate. Outcomes have shown that RELAP5-3D© is an effective tool in reproducing the most significant phenomena of He-FUS3 system, providing relevant insight supporting future experimental campaigns. The post-test analysis phase will be, of course, fundamental for the qualification of a consistent numerical model.

Keywords: RELAP5-3D, He-FUS3, HCPB, HCLL

1. Introduction

The 1st Specific Grant (SG) of the Framework Partnership Agreement (FPA) 372, co-financed by the ITER European Domestic Agency "Fusion for Energy", deals with experimental activities in support of the Conceptual Design of HCLL and HCPB Test Blanket Systems. In particular, Task 2 is focused on thermal-hydraulic tests with high pressure helium for validation and benchmarking of suitable dedicated tools. Within this frame a newly numerical model of the actual He-FUS3 facility layout has been generated using RELAP5-3D© aimed at simulating the system's operating conditions. Results of steady state preliminary numerical simulations of He-FUS3 operative conditions are presented with a particular emphasis on the compressor's performances. The analysis focuses on the loop's steady state thermal-hydraulic behavior for a wide range of compressor rotational velocities in both cold and hot conditions. Moreover, the cold By-pass effect on the loop characteristics has been investigated.

2. Facility description

The He-FUS3 facility [1, 2], planned for the thermal-mechanical and thermal-hydraulic testing of prototypical breeding blanket module assemblies for the DEMO reactor, was chosen for the selected European Helium Cooled Pebble Bed (HCPB) Blanket design to be tested on ITER reactor. The system, located at the ENEA Brasimone Laboratories (Italy), is characterized by an eight-shaped closed loop arrangement to separate two zones at different temperatures: the cold one including the Turbo Circulator [3] and the hot one hosting the experimental Test Section. The facility upgraded in 2009 [4] consists of the following main components:

– three modules electrical heaters, E219-1/2/3;
– a high efficiency He-He Economizer, E214;
– a counter flow Air Cooler, E240;
– a shell/tube water Heat-Exchanger (HX), E215;
– a Turbo Circulator (TC), compressor K300;
– a tank, V205, for "CVCS area" LOCA tests;
– a Test Section (TS) for "In-TBM" LOCA tests.

The Economizer reduces both the need for external power to get the required temperature at the TS inlet and the cooler size to reduce the compressor inlet temperature to its maximum continuative operating temperature. The piping overall length is about 80 m, with an integral volume of 4.5 m^3 including 3 m^3 of the storage tank and a weight of about 15 ton. The diameters of the main pipes are 4" (sch.80) for the cold zone and 5" (sch.80) for the hot zone. The "In-TBM" LOCA TS line branches out from a "*C*" shaped pipe, 3" (sch.80), located in hot zone uppermost part. The piping material is stainless steel AISI 316. The loop component are insulated to reduce contact temperature below 50°C.

3. RELAP5-3D© Model of He-FUS3

The actual He-FUS3 experimental configuration has been modelled with RELAP5-3D© [5] in order to simulate the system thermal-hydraulics in both normal operation and accidental scenarios [6]. Figure 1 illustrates the nodalization characterized by the eight-shape loop flow-path of the two working temperatures regions together with the cold and hot By-pass branches (dotted lines). The model reproduces the main components relevant for the experimental tests in normal flowing conditions, object of the present numerical analysis. Moreover, the hot line TS for "In-TBM" LOCA tests and the cold line, connected to the storage tank V205, for "CVCS area" LOCA tests, can be identified in the nodalization. The high-performance TC, that makes the helium circulate inside the loop (up to a maximum flow rate of 1.4 kg/s and a rotational velocity

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of 40000 min^{-1} at 80 bar), has been simulated using RELAP5-3D© *compressor* component implementing in

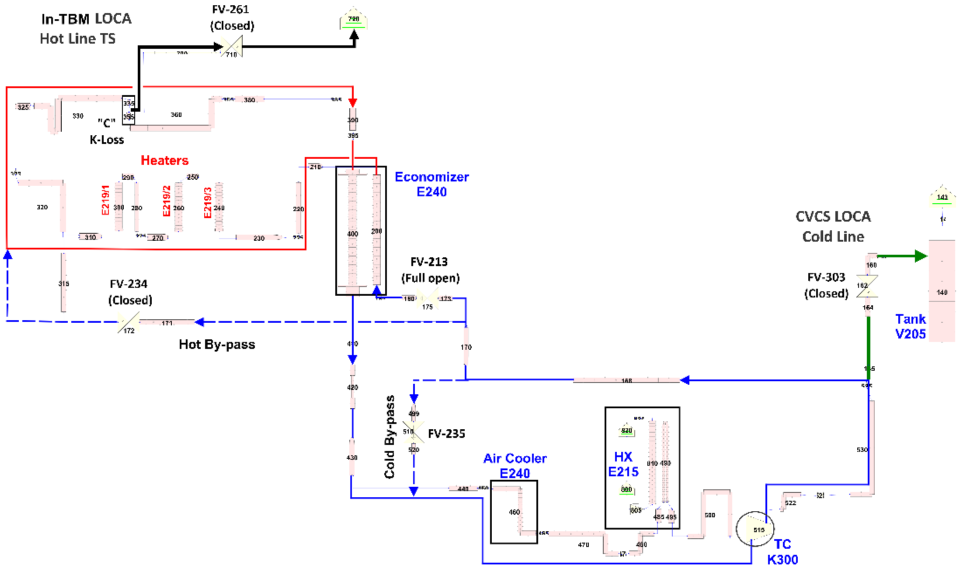

Fig. 1. RELAP5-3D model for the upgraded He-FUS3 facility.

the model the TC theoretical performance map. The performance map is an xy representation with a mass flow rate parameter *v* (expressed as a fraction of the rated corrected mass flow rate, namely 1.08 kg/s), as the abscissa and a head-related parameter PR (pressure ratio), as the ordinate. Lines of constant rotational velocity and lines of constant efficiency are represented parametrically on the TC performance map. To validate the component at nominal conditions (inlet temperature and pressure of 50°C and 88 bar), a stand-alone simulation procedure [7] has been carried out showing very good agreement with the theoretical data. Depending on the opening of valves FV-213 and FV-235, the total cold helium flow from the TC is divided over the main flow-path (going towards the TS) and the cold By-pass. The hot By-pass is assumed to be closed. The cold helium following the main flow-path goes through the Economizer (shell side) increasing its temperature by exchanging power with the hot helium (tube side) countercurrent flow. The pre-heated helium temperature further increases passing through the heating line, removing a global power up to 210 kW generated by the three Heaters, achieving thus its maximum temperature. The flow then goes towards a *C*-shaped pipe of the TS (located in the uppermost zone of the facility) to the Economizer, flowing back towards a 5" return line. The TS consists of a *C*-shaped 3" pipe from which branches out a ¾" line normally isolated from the main loop by means of valve FV-261 that allows the helium discharge in atmosphere during the hot "In-TBM" LOCA experimental tests. The hot helium flows downward through the Economizer tubes releasing heat to the cold shell side helium. The pre-cooled helium exits in a 4" piping hosting a Flow Transducer FT-228 (FT) in a 2" fitting. At the FT exit, the main flow mixes with the cold By-pass flow before going towards the Air Cooler. The Air Cooler model contains a detailed primary side (helium) model while, the secondary side (air) with its regulation system has been modelled in a simplified way consisting of a heat structure facing a heat sink; heat transfer coefficient and sink temperature are tuned so that helium outlet temperature matches a predefined set point. From the Air Cooler, helium flows through the primary side HX tubes to be further cooled by the secondary side water. As for the TC, a stand-alone validation process for this component has been performed to qualify the HX model in its nominal working conditions. Once cooled to its minimum loop temperature, helium goes through a 4" line to the TC inlet (suction line). The whole system is thermally coupled with the external environment. Thermal dispersion is simulated taking into account rock wool insulating the stainless steel AISI 316 loop components. The main valves relevant for the simulations have been modelled providing a suitable Flow Coefficient (*Cv*). Referring to flow control valves, FV-213 and FV-235, they have been modelled using RELAP5-3D© motor valve components.

4. Preliminary He-FUS3 Simulations

The various upgrading and improvements performed on He-FUS3 facility in order to achieve the best layout in perspective of the forthcoming experimental campaign request a validation process of the associated numerical model. As a starting point of this process, the simulations here described have the goal of investigating the thermal-hydraulic behavior of the facility using RELAP5-3D© system code with helium as the primary working fluid. A particular emphasis is dedicated to the analysis of the Turbo Circulator's performances.

4.1 Test Matrix and Boundary Conditions

The performed numerical tests can be subdivided in two cold simulations (CS-1 and CS-2) and one hot simulation (HS-1). In table 1 the main simulation parameters are defined. For all simulations, the reference loop configuration is characterized by the storage Tank V205 and TS "In-TBM" LOCA line isolated from the loop, valves FV-303 and FV-261 being closed. In addition the hot By-pass is not activated (valve FV-234 closed). Furthermore a concentrated hydraulic friction loss coefficient $K_{C,LOSS}$, placed in the hot line (in the TS *C*-shaped pipe junction) has been introduced. This artificial resistance is representative of the presence in the loop of additional valves, fittings, reduced pipe diameter, obstruction or other generic components. Cold simulations are characterized by helium circulating, without the activation of the Heaters, in two different loop layouts. More specifically, simulation CS-1 refers to the He-FUS3 loop with the cold By-pass closed (valve FV-235 closed) while simulation CS-2 differs from CS-1 in that the valve FV-235 is opened to 35% of its maximum cross section area, in such a way that a fraction of the total circulating helium flows through the cold By-pass. In these conditions the loop performances and in particular the TC response are analyzed and compared. Hot simulation HS-1 is characterized by the same loop layout as CS-2 but, after reaching a cold steady state, the three Heaters are activated (t_h = 7000 s) supplying the maximum power experimentally available of 210 kW. To limit the variables to be analyzed it is assumed, for cold and hot simulations, that the helium cooling is performed only by the Air Cooler, the water HX being deactivated. The Air Cooler acts as a cold sink with a predefined set point limiting thereby the TC inlet temperature to a fixed value. The cold sink temperature has been fixed to 65°C for cold simulations and to 46°C for hot simulation. The activation trip is set to "on" when the Air Cooler outlet temperature exceeds a set point value. For all sets of simulations, the loop's initial conditions are 25°C and 50 bar with an external environmental temperature of 13°C. The mass of the circulating helium is approximately 13 kg.

Tab. 1 Performed simulations.

Simulation name	Loop conditions	FV-235 opening	Cold sink temperature
CS-1	Cold	0 %	65°C
CS-2	Cold	35 %	65°C
HS-1	Hot	35 %	46°C

In this preliminary analysis, the dedicated TC water cooling system [3] has not been modelled; therefore the entire, rather significant, heating resulting from the TC operation acts as an active power source in the system energy balance. Furthermore, it is worth pointing out that the TC is characterized by its rotational velocity from the beginning of the simulations (the start-up phase is not simulated). Six rotational velocities, from N_0 to N_5, corresponding to 20%, 40%, 60%, 80%, 100% and 107% of the TC rated rotational velocity, N_R = 38418 min^{-1}, have been considered in order to cover the TC whole operational range.

4.2 Cold Simulations

The two cold simulations aim at investigating, for the whole range of selected TC velocities, the following loop features:

– Steady-state thermal-hydraulic performances with cold By-pass closed (CS-1);

– Effect of the cold By-pass opening (CS-2).

The obtained results for the two performed simulations are summarized in figure 2 illustrating the loop hydraulic characteristic curves on the TC theoretical performance map. Each curve consists of six points (one for each rotational velocity) defined by the relative corrected mass flow rate, *v*, and pressure ratio PR, p_2/p_1. The simulation time required to achieve a stationary condition is 5000 s. Curve CS-1 is characterized by an higher slope compared to curve CS-2, implying that the partial valve opening results in a reduction of the loop head losses caused by the deviation of a fraction of the total flow (about 10%) towards the cold By-pass. That is, the total helium flow rate exhibits higher values with equal TC rotational velocities, *N*. At the rated TC velocity, N_R, the head and the total helium flow are 7.9 bar and 1.05 kg/s for CS-1 and 7.7 bar and 1.21 kg/s for CS-2. The two characteristic curves are found within the operating limits of the theoretical TC map in the right zone of efficiency η = 0.67−0.68. Thus, the compressors operates adequately within the high efficiency region even at the highest imposed rotational velocity N_5 = 41107 min^{-1} (beyond the compressor nominal speed of 40000 min^{-1}).

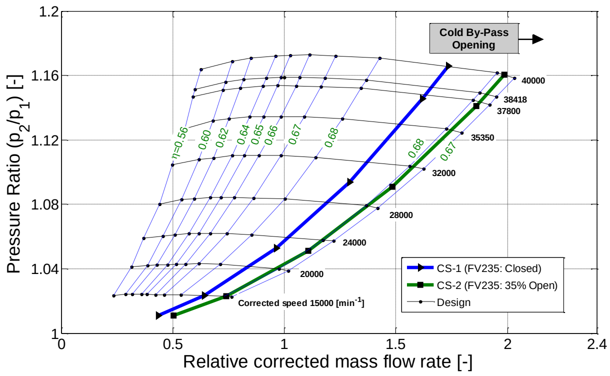

Fig. 2. Loop hydraulic curves for CS-1 and CS-2.

4.3 Hot Simulation

In hot simulation HS-1, after a cold transient (much like the previous cold simulations) an external power source of 210 kW is introduced at time t_h = 7000 s simulating the electrical Heaters activation. In HS-1, the TC inlet temperature T_1 (equal to the Air Cooler outlet temperature), does not exceed the value of 50°C (as the cold sink temperature is fixed to 46°C) resulting in a general improvement of the TC performances. The HS-1 simulation outcomes, which generate the loop hydraulic characteristic curve, are reported in figure 3.

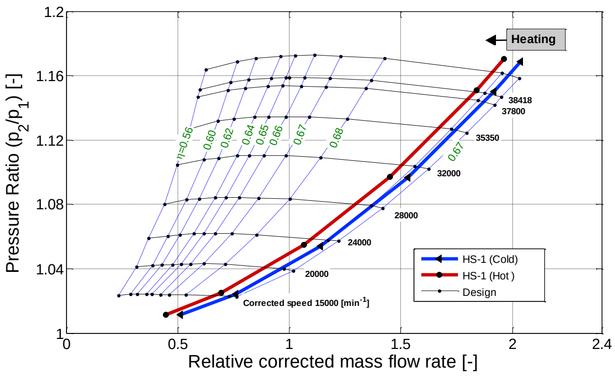

Fig. 3. Loop hydraulic curves for HS-1.

Two distinct curves are shown. The first curve (HS-1, Cold) represents the results in cold stationary conditions (similarly to CS-2) when the TC operates, its heating power is removed by the Air Cooler but the Heaters have not yet been activated (just before 7000 s). Whereas the second curve (HS-1, Hot) is related to the Heaters activation phase when the system has reached hot steady state conditions (15000 s) and the Air Cooler removes both power generated by the TC and the Heaters. The effect of heating on the system can be observed in the left shift of the curve switching from cold to hot conditions. In a hot steady state the value of the flow rate ranges from 0.4 kg/s for N_0 to 1.4 kg/s for N_5. The fraction of the total mass flow rate going towards the Heaters is estimated at 90% of the total. The maximum helium flow temperature at the Heaters outlet, related to this flow fraction, ranges from 450°C for N_0 to 166°C for N_5. The maximum loop pressure p_2, at the TC discharge line, approximately ranges from 79 bar for N_0 to 68 bar for N_5; this quantity depends on both the loop temperature distribution and the TC head. The corresponding pressure losses, (TC head) ranges from 0.9 bar for N_0 to 10 bar for N_5. The TC power ranges from 9 kW for N_0 to 227 kW for N_5. Referring to TC velocity N_2 (60% of N_R), figure 4 plots the temperature trends associated with the major facility components during the simulation, indicating the activation time of the Air Cooler (t_c) and of the Heaters (t_h).

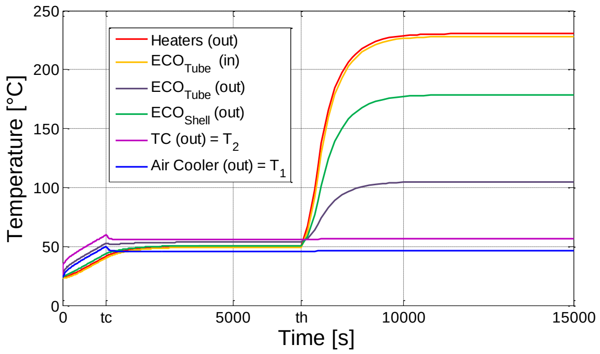

Fig. 4. Temperature trend for HS-1 (N_2).

Temperature and pressure profiles along the He-FUS3 loop main flow-path are illustrated in figure 5, comparing cold and hot steady state conditions. The cold state temperature profile ranges approximately between the compressor inlet and outlet temperature T_1 and T_2; the inlet temperature T_1 being imposed by the cooling system (Air Cooler). In hot steady state conditions helium from the TC flows towards the shell side of Economizer increasing its temperature by 123°C, up to about 180°C. In the Heater zone (70 kW for each module) the helium temperature further increases, up to a maximum of 230°C. After crossing the hot line hosting the TS (the temperature decreases slightly due to thermal dispersion), the helium flows towards the tube side of the Economizer decreasing its temperature to a value of 105°C (with about the same temperature jump of the shell side). At this point the main helium flow mixes with the cold By-pass helium (at 56°C) to a mixture temperature of about 96°C, before going through the Air Cooler where the temperature is lowered to about 46°C. The flow-path is completed in the TC where the temperature rises by 10°C to an outlet temperature T_2 of about 56°C. The analysis of the pressure profile along the main flow-path has highlighted that a major contribution to total pressure losses is due to the flow transducer FT and the Air Cooler tube bundle.

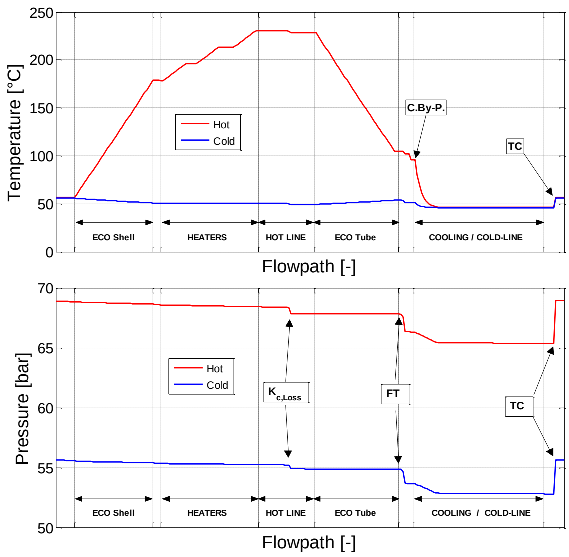

Fig. 5. Steady state T and p profile for HS-1 (N_2).

Conclusions

RELAP5-3D© preliminary results on He-FUS3 appear fully consistent providing an extensive overview of the system behavior in hot and cold steady state conditions. Outcomes for a wide range of TC operation will be used in support of future experimental campaigns. Moreover the adopted code is a very promising tool in reproducing the thermal-hydraulic phenomena involved in a helium circulating system for future development activities. Nevertheless a consistent numerical model will require a validation process against experimental data.

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