EUROfusion

WPSAE-CPR(17) 17425

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Preprint of Paper to be submitted for publication in Proceeding of 13th International Symposium on Fusion Nuclear Technology (ISFNT)

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Development and validation of the blanket First Wall mock-up model in RELAP5-3D

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The Helium Cooled Pebble Bed (HCPB) blanket concept is one of four EU DEMO (Demonstration Power Plant) blanket concepts running for the final design selection. For the development of the equatorial outboard blanket module of the HCPB blanket concept, the qualification and testing of mock-ups are foreseen by means of different experiments and are mandatory to qualify the thermo-mechanical and thermal-hydraulics robustness of the design. Therefore, a functional test mock-up of the first wall (FWMU) is planned to be integrated in the HELOKA facility (helium loop Karlsruhe) at KIT in order to investigate typical safety relevant transients and to provide a database for design tool validation.

This work is aimed to derive a prototypical experimental set-up simulating a LOFA (Loss Of Flow Accident) in the FWMU plate. To this purpose, a detailed model has been developed by means of the system code RELAP5-3D, validated by comparison with a CFX analyses for both steady-state and transient conditions, and calibrated by adopting the pressure loss characteristics experimentally determined under air conditions. The present model will be integrated into the completed HELOKA loop model to simulate different operational scenarios, but also to optimize the piping layout and instrumentation set-up.

Keywords: DEMO, HCPB, LOFA, RELAP-3D.

1. Introduction

In the frame of the development of the Helium Cooled Pebble Bed (HCPB) blanket concept, one of four EU DEMO (Demonstration Power Plant) blanket concepts running for the final design selection [1], qualification mock-ups testing is planned to be performed with different requirements and objectives. In particular, mock-up experiments have to contribute to the qualification of the thermo-mechanical behavior of the designed blanket module, of the ancillary systems for the operation and of the fabrication techniques and processes, as well as to the validation of numerical simulation tools, cooling control, instrumentation technology and implementation [2].

In this context, a functional test mock-up of the first wall (FWMU) is planned to be integrated in the HELOKA helium loop facility at KIT in order to test different thermal-hydraulics and thermo-mechanical issues (such as the heat removal from the First Wall (FW), the coolant flow control, the mechanical endurance and cycling etc.) and to provide an excellent database for validation of numerical tools used for design and performance analyses.

To this purpose, the present work is aimed at putting in place the experimental set-up for the FW-LOFA experiment adopting an existing FWMU plate made of P92 steel, which was developed in a previous study carried out by KIT concerning different fabrication options for the blanket FW [3].

In order to define the testing parameters as well as to improve the set-up of the experiment, a model for the FWMU adopting the system code RELAP5-3D version 4.3.4 [4], has been developed for thermal-hydraulics analyses under both normal and accidental conditions [5]. The prediction capabilities and limitations of the model has been verified by comparison with the results of CFX simulations previously carried out in [6], in a single channel and two channels representations for both steady-state and transient conditions. The mock-up pressure loss characteristics, experimentally determined under air flow conditions for both vertical and horizontal inlets [7], have been adopted to calibrate and validate the complete 10 channels RELAP5-3D model. The objective is to integrate this FWMU model into the complete helium loop simulating the whole HELOKA facility [8] in order to define the most suitable configuration in terms of testing parameters as well as piping layout (including valves and instrumentation set-up), and to investigate the FWMU behavior under different operating conditions.

2. Experiment description

The experimental investigation of a Loss of Flow Accident (LOFA) is aimed at generating fast transients, similar to the ones occurring during such an event. Since, for the moment, no full DEMO relevant FW mock-up exists, an available manufacturing FW unit will be used (Fig. 1). Since the mock-up has U-shaped cooling channels as opposite to straight channels for the DEMO FW, the relevancy of such geometry to the problem under investigation has been looked at using detailed CFD computations, as described in [6].

Following this study, it has been decided that using the mock-up in a cross-flow cooling scheme would

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provide a configuration close enough to the DEMO FW operation. However, the CFD simulation assumed that both channels have identical thermal-hydraulic conditions (pressure losses and flow) and are completely independent one from each other. In the planned experiment, however, such ideal conditions are not available mainly due to the fact that a single cooling loop is adopted, eventually leading to different inlet pressure levels and pressure losses over the channels. More important, when a LOFA is triggered for some of the channels by, for instance, closing a valve, it could result in an increased flow in the remaining channels if no compensatory measures are taken.

To address this matter, a cooling scheme as shown in Fig. 1 has been proposed: from the inlet manifold two separate lines are providing helium to the cooling channels; the line selected to simulate the LOFA event is equipped with a valve V-1 that can partially reduce or completely stop the flow in the corresponding channels, the flow being measured by the Flowmeter 1; to keep constant the flow rate in the remaining active channels, a bypass valve V-2 controlled by the Flowmeter 2 has been introduced, allowing the excess of helium to return to the outlet manifold.

To define the suitable parameters and dimensioning the corresponding control elements, essential for ensuring a stable operation of the loop during both stationary and LOFA conditions, the FWMU RELAP5-3D model developed in this work will be integrated in into an existing RELAP model of the HELOKA loop.

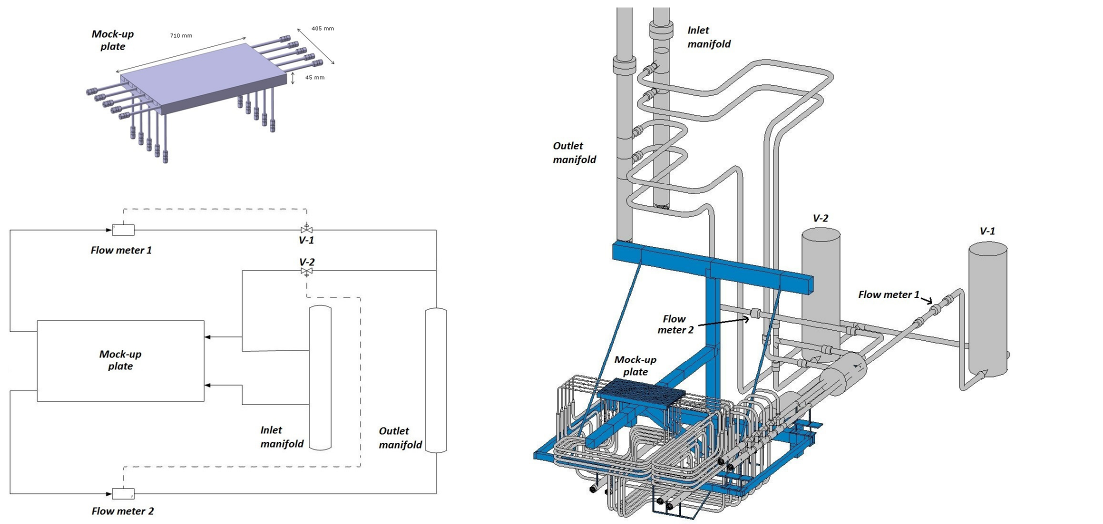

Fig. 1. FWMU, piping layout and experimental set-up.

3. FWMU modelling with RELAP5-3D

The FWMU plate consists in 10 independent cooling channels. Each channel has a total length of 1812 mm, and a round-edged cross-section, having a size of 15x15 mm^2 (Fig. 2). The wall between two neighboring channels has a width of 5 mm. As discussed in the previous section, the flow paths in the cooling channels are designed in such a way that counter-flow pattern is established between two neighboring channels. Therefore, channels 1-5 will have a vertical inlet whereas channels 6-10 a horizontal inlet.

The RELAP model developed for the FWMU simulates the 10 independent channels which are linked each other by different heat structures (HSs). The coupling between two neighboring channels is represented in Fig. 3 where channel 1 and 6 are shown. The inlet and outlet of each channel can be either vertical (green) or horizontal (black) according to the flow path, and they are modelled by means of time dependent volumes (tmp) defining the pressure and temperature. The inlet mass flow rate is set using time dependent junctions (tj). The inlet and outlet pipes (P101, P105) are connected with the round-edged cross-section cooling channels (red objects in Fig. 3) by means of branch objects (B102, B104). The cooling channels (e.g., P103) are divided into 21 hydraulic volumes. The volumes connected with the vertical pipes (e.g., volume 1 of P103) are shifted by few millimeters with respect to the outlet volume to take into account the configuration of the channels represented in Fig. 2.

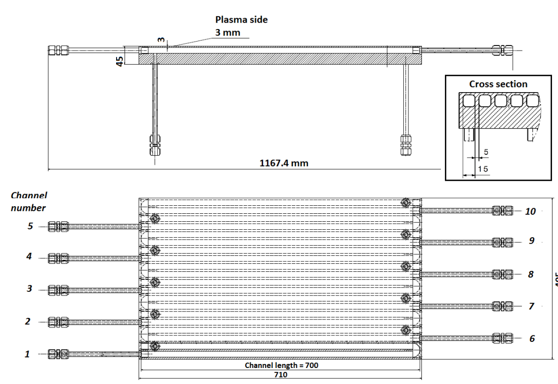

Fig. 2. Horizontal and vertical view of the FWMU plate.

As far as the modelling of the heat structure is concerned, a specific approach similar to that employed in Ref. [6], is needed due to the particular geometry configuration, since each cooling channel is surrounded by the Mock-up plate. Considering channel 1, two heat structures HS1 and HS2 are defined for the upper (plasma side) and lower sides, respectively (Fig. 4).

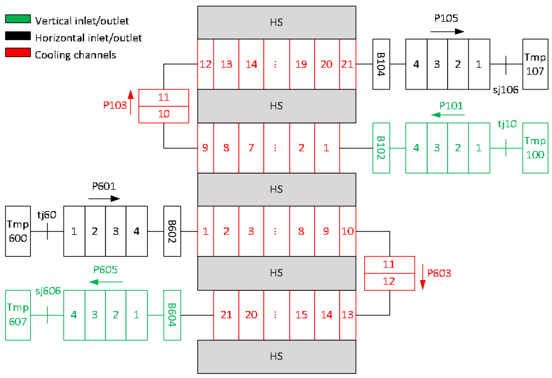

Fig. 3. RELAP nodalization for the FWMU.

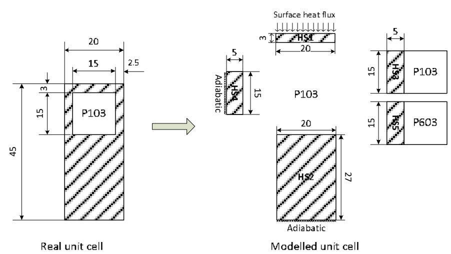

Fig. 4. HS modelling.

Two additional structures are defined to model the heat exchanged between the neighboring channels located at the left (HS4) and right (HS5) sides of channel 1, and heat structure (HS3) is implemented to model the heat transfer between the 2 sides of the channel 1. The same representation of the HS in Fig. 4 is implemented for the other channels taking into account that adjacent components are sharing the same heat structure. As far as the boundary conditions are concerned, the heat flux is imposed on HS1 due to the plasma heating, whereas adiabatic conditions are given to HS4 of channel 1 (P103) and HS5 of channel 10, as well as to HS2 being the outer structures of the mock-up. Adiabatic conditions are chosen for the outer walls since the plate will be working under vacuum conditions. The material properties for the Mock-up plate refer to A3.S18E Eurofer steel measured data [9].

4. Assessment of the numerical model

In this section, the capabilities and the adequacy of the developed RELAP model for the FWMU are verified by comparison with CFX analysis [4] concerning a single-channel and two-channel simulations in both steady-state and transient conditions. The objectives are also to improve some of the model parameters affecting pressure loss calculations and to identify eventual limitations and discrepancies.

4.1 One-channel analysis

In the single channel case, helium flows through the horizontal inlet into the cooling channel (as channel 6 in figure 3) having a pressure of 8 MPa, a temperature of 300 °C and a mass flow rate of 50 g/s. The total heat flux applied to the Mock-up is 300 kW/m^2 resulting in a total power of 8.5 kW. Symmetric boundary conditions are applied on the left and right side of the heat structure and adiabatic conditions on the bottom side. The pressure loss characteristics of the RELAP model (energy loss coefficients at branches and at channel U-turn) have been preliminarily determined to match the pressure profile calculated by the CFX analysis. The main results are compared in Table 1 in terms of outlet temperature, velocity and pressure losses, whereas the detailed comparison is shown in Fig. 5 for stationary conditions.

Table 1. Comparison between RELAP and CFX main results.

	CFX Analysis		RELAP
	Coarse mesh	Fine mesh	
Outlet temp. (°C)	332.3	332.3	329.2
Outlet vel. (m/s)	165.8	166.6	163.6
Pressure loss (bar)	1.91	2.03	1.84
Max FWMU temp# (°C)	454.2	457.5	467.7

at the middle of the channel

The developed RELAP model is able to reproduce the CFX solution with a reasonably good agreement in terms of overall quantities, but also in terms of local pressure variations being within the coarse and fine mesh results provided by CFX code. The small discrepancies found in the temperature profile are due to 3D hydrodynamics effects at channel bend and at the connection with the outlet tubes, which cannot be taken into account by the simplified RELAP solution.

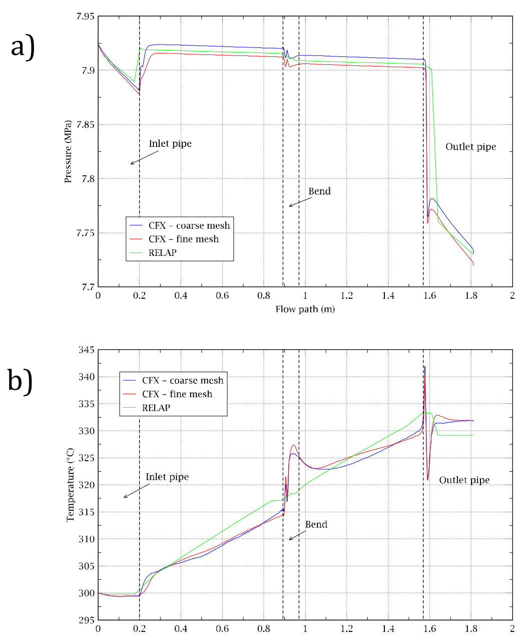

Fig. 5. Comparison between CFX and RELAP calculated pressure losses (a) and helium temperature (b) along the channel flow path.

As far as the temperatures of the heat structure are concerned, the calculated RELAP maximum surface temperature (i.e, directly in contact with the plasma) is in a reasonably good agreement with the CFX solution as shown in Table 1. The discrepancy is due to limitations in the RELAP modelling, and related to the fact that heat conduction between different heat objects cannot be accounted for by the code. Nevertheless, for the purpose of the present work, this approximation is satisfactory as RELAP will provide conservative predictions of the maximum FWMU temperature.

4.2 Two-channel analysis

In this paragraph, FWMU model is tested against the two-channel CFX simulation results reported in Ref. [6] in order to address the heat flow redistribution between adjacent channels in transient conditions (LOFA test). The loss of flow accident is assumed to occur in the channel n°1 of the CFX model which corresponds to all the even channels of the RELAP model (channel 6 to 10 of Fig. 2) for symmetry reasons. The mass flow rate decreases exponentially in these channels according to Fig. 6 whereas it remains constant in the adjacent channels (channel 2 in the picture). The sudden decrease of helium flow immediately leads to the worsening of the heat transfer coefficient, and therefore of the heat flux (Fig. 6). As a consequence, the temperature of the FWMU increases as shown in Fig. 7.

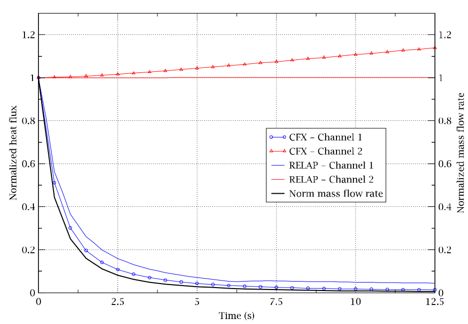

Fig. 6. Normalized channel heat flux and imposed mass flow rate during LOFA.

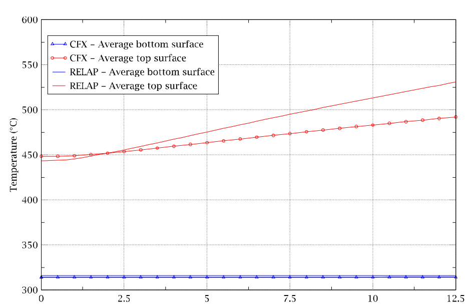

Fig. 7. Average surface temperature on top and on bottom of the FWMU plate during LOFA

The results of the transient are consistent with the findings of the one-channel case in stationary conditions. The differences in the calculated heat flux and temperatures between RELAP and the CFX analysis are due to the heat transfer by conduction between the structural objects that is neglected by RELAP. This is more evident during fast transient because the heat redistribution across the channels plays an important role as shown by the increase of channel 2 heat flux predicted by CFX results. Therefore, RELAP tends to overestimate the Mock-up surface temperature and this behavior should be taken under consideration for the planned experiment design and analysis. In spite of the mentioned limitations, the developed model provides a satisfactory representation of the FWMU plate when compared with more sophisticated fluid-dynamic simulations, which is suitable for the purposes of the present work.

5. Model calibration

The FWMU pressure loss characteristics of developed RELAP model have been calibrated based on experimental data provided by the characterization analysis formerly performed in [7]. The experiments were conducted using a compressed air loop, where the HCPB FW helium parameters (80 bar, 300 °C, 90 g/s) were scaled down using the same Reynolds number to air parameters (i.e., 6 bar, 25 °C, 50 g/s). The pressure drop across the channels was measured using a differential pressure sensor, connected thanks to two flexible tubes with the horizontal and vertical connection pipes of a certain channel as inlet and outlet measuring locations. The mass flow rate was measured by a Coriolis mass flow meter located downstream of the FWMU. For every channel, the measurements were performed in two flow schemes: (i) vertical inlet and (ii) horizontal inlet. Since the analysis and the conclusions are similar for both cases, only the results concerning the vertical inlet case will be presented in this section, for the sake of brevity.

As far as the numerical model is concerned, the measured mass flow rate is given as boundary condition at the inlet whereas the pressure is imposed at the outlet. A fictitious transient simulation has been settled where each value of the mass flow rate and outlet pressure is held for approximately 1 s [5]. To reduce the number of variables involved in the calibration, some of the RELAP model parameters need to be settled, based on the previous RELAP/CFX analysis. In particular, the pipe roughness, the energy loss coefficients at the horizontal connection pipes and at the channel U-turn are assumed to be the same for every channel. In this way, the calibration is performed by varying only the loss coefficient related to 90° turn that connects the channel with its vertical connection pipe, which actually provides the highest contribution to the total channel pressure loss (see Fig. 5a).

The comparison between predicted and measured pressure losses is reported in Fig. 8. One can see that the measured pressure drop values are different from one channel to another and the differences increase with increasing the mass flow. The pressure drop values for channels 6 – 10 are comparable, whereas the differences in the pressure drop with increasing the mass flow are larger for channels 1 – 5.

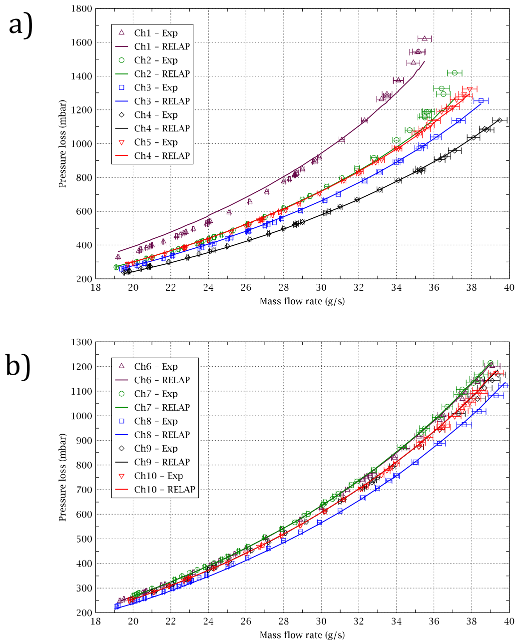

Fig. 8. Comparison between measured and calculated pressure losses for channel 1-5 (a) and 6-10 (b) in case of vertical inlet.

The comparison with RELAP results shows an excellent agreement with the experimental data for all the channels. Small discrepancies can be found for channel 1 and 2 at high mass flow rate values, where also the experimental data deviation is larger. This behavior is also more clearly reported in Fig. 9 where the calculated vs. measured pressure losses are plotted for each channel. This overview shows that RELAP is able to predict measured values within ±10% discrepancy.

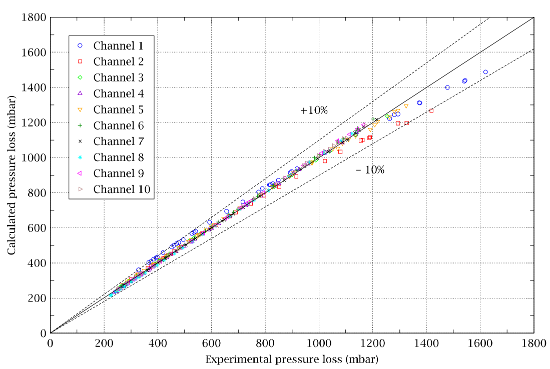

Fig. 9. Calculated vs. measured pressure losses in case of vertical inlet.

6. Conclusions

In the present work, a detailed RELAP5-3D model for the FWMU consisting of the 10 independent cooling channels has been developed and verified based on both CFX results and experimental data. The preliminary code-to-code comparison showed a good agreement in terms of helium temperature, and pressure losses, but also highlighted some model weaknesses related to the heat conduction between different heat structures. For the purpose of the present work, such discrepancies are acceptable since the calibration is performed to define the parameters needed for pressure loss calculations. Experimental data collected under air environment have been adopted for such a purpose. The comparison between calculated and measured pressure drops is excellent, and allowed to establish the pressure loss characteristics for each of the 10 independent channel, needed for the future simulations and analyses of experiments in the HELOKA facility under helium flow. This FWMU model will be integrated into an existing helium loop model of the HELOKA facility.

Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053.

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