Multi-scale thermal-hydraulic modelling for the Primary Heat Transfer System of a tokamak

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Abstract

During the pre-conceptual design stage, which the EU DEMO fusion reactor is currently facing, fast-running models can be very helpful by providing hints to support the designers, analysing several alternative scenarios. This paper presents the development of a code for this kind of analyses, called the GEneral Tokamak THErmal-hydraulic Model (GETTHEM). The code is developed to allow fast transient simulations of the tokamak primary cooling system, both under nominal conditions and off-normal transients; it has been benchmarked and validated in different scenarios which are presented here. So far, it has been successfully applied to the optimization of the coolant flow for two Breeding Blanket concepts, and it has also been used to analyse the effects of an accidental scenario on the primary confinement barrier.

Introduction

The DEMO tokamak will be the first fusion reactor to produce net electrical energy from fusion reactions; the European version (see Fig. 1) is currently in its pre-conceptual design stage within the EUROfusion Consortium, and it will include for the first time the systems needed to produce electricity, such as the Primary Heat Transfer System (PHTS, removing the heat produced by fusion from the reactor) and the Power Conversion System (PCS, including the secondary loop used to produce electricity with a Rankine cycle). The main source of heat for the PHTS will be the Breeding Blanket (BB), which is the first component that faces the plasma and the component where the tritium needed to sustain the reactions will be produced; the BB is consequently the component that faces the largest total thermal load, both coming from the plasma and from the nuclear reactions happening inside the Breeding Zone (BZ). Its adequate cooling is then fundamental, also from the safety point of view, as the BB is “the most nuclear component” in a fusion reactor.

The EU DEMO tokamak is toroidally segmented in sectors (18 sectors are foreseen according to the 2015 design [1]), with each sector containing three outboard (OB) and two inboard (IB) BB segments; each segment, in turn, contains several Blanket Modules (BMs).

In the framework of the EU DEMO design and analyses activity, a new tool for fast, system-level thermal-hydraulic modelling of the PHTS of tokamak fusion reactors is under development since 2015 at Politecnico di Torino, with the support of the EUROfusion Programme Management Unit. The main objective of this code, named “GEneral Tokamak THErmal-hydraulic Model” (GETTHEM), is to allow fast transient simulations of the tokamak cooling system, to enable parametric analyses in support of the EU DEMO designers during the pre-conceptual design stage. The code should then be: flexible, computationally light, modular.

The GETTHEM development focused so far on the modelling of the BB cooling loops; within the EU DEMO, four BB concepts are being explored: the Helium-Cooled Pebble Bed (HCPB, see Fig. 2) [2], the Water-Cooled Lithium-Lead (WCLL, see Fig. 3) [3], the Helium-Cooled Lithium-Lead (HCLL) [4] and the Dual-Cooled Lithium-Lead (DCLL) [5]; at the present stage, GETTHEM contains models for HCPB [6] [7] [8] and WCLL [9] [10].

Methods

To achieve the needed modularity, all GETTHEM models have been developed with an object-oriented approach using the Modelica language. Depending on the geometry, the different component models can be 1D along flow direction (e.g. pipes) or 0D (e.g. manifolds, valves); in each model, the mass and energy conservation equations (+ the momentum balance for 1D components) are imposed in each fluid control volume, according to the Finite Volumes (FV) approach; optionally, also the solid structures can be modelled, again with a 1D FV or 0D approach, solving the energy conservation equation in each control volume (+ heat conduction in 1D components). GETTHEM include detailed models for the cooling system of the BZ and of the First Wall (FW), which are in general both cooled by the BB cooling circuit.

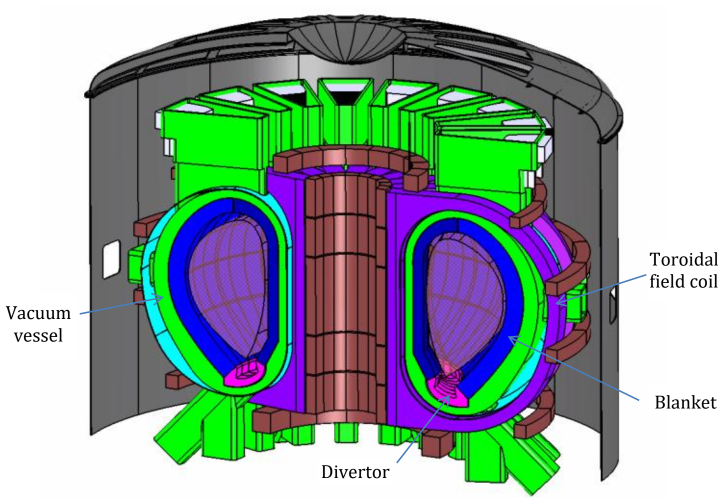

Fig. 1: Sketch of the EU DEMO1 reactor, showing the main components (reproduced from [1]). The BB is the blue-coloured component, facing the plasma.

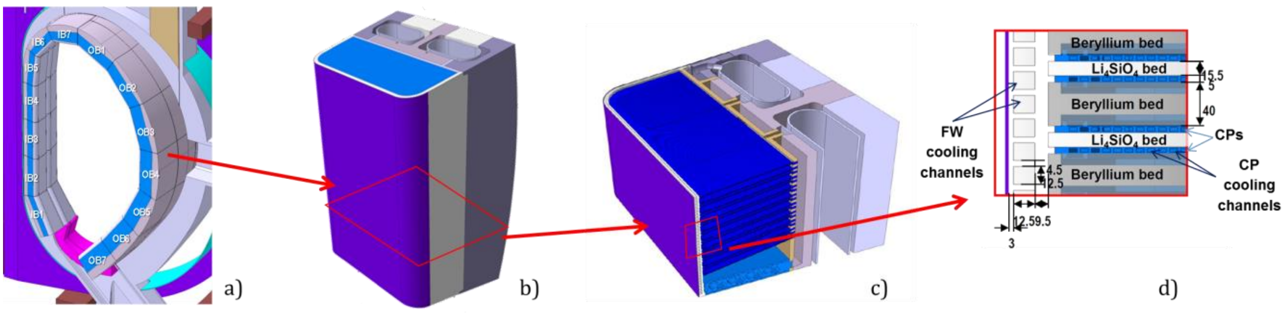

Fig. 2: The HCPB BB (adapted from [2]): a) a BB sector, showing all the BMs; b) the equatorial OB BM OB4; c) a radial-poloidal cross section of the OB4; d) detailed radial-poloidal cross section of the OB4.

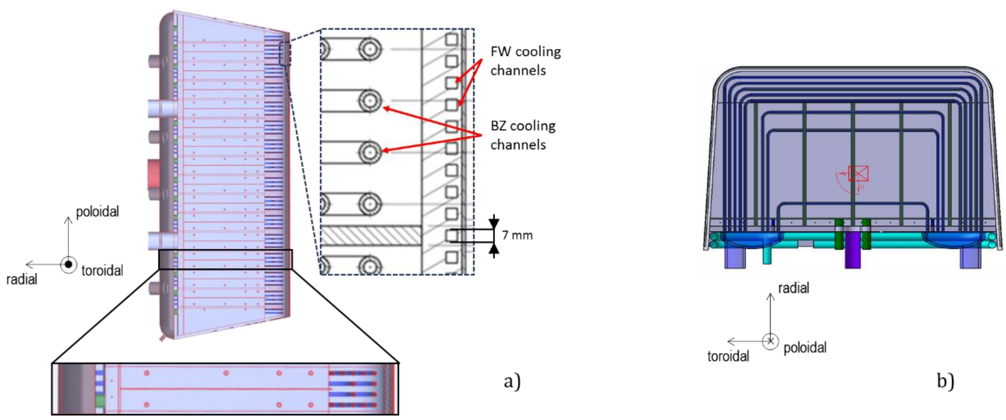

Fig. 3: The WCLL BB (adapted from [3]): a) a radial-poloidal cross section of the OB4, showing the details of the FW and BZ cooling channels; b) a toroidal-radial cross section of the OB4, showing the BZ cooling channels.

Two different modules of the code have been developed, including different simplifying assumptions, to model nominal operating conditions and accidental transients.

A scheme of the HCPB and WCLL models available in GETTHEM for nominal operating conditions is reported in Fig. 4. For these conditions, the focus is on the differences (due e.g. to different geometries or heat loads) which may be found among the different cooling channels in a BB segment; considering for instance the HCPB in its latest design, each BM has ~1700 cooling channels, and, in order to model all of them separately, the computation of the thermo-physical properties of the coolant has been simplified, by modelling the helium as an ideal gas (which is reasonable, considering the range of pressure and temperature of interest, i.e. 8 MPa and 300 – 500 °C) and by linearizing the relevant properties of water in the temperature range (15.5 MPa, 285 – 325 °C), introducing a relative error on the input below 3.5 %. In addition, the thermo-physical properties of the solid materials are assumed to be independent on temperature (i.e., their value is fixed at the average temperature), introducing an input error below 8 % on average, and also the heat transfer coefficient between solid and fluid is assumed constant and equal to the value computed with correlations suggested by the BB designers [2] [3]. All of these simplifications, however, have been shown to affect the code output by less than 3 %; at the price of this relatively small error, the code is considerably simplified, and thus allows fast transient simulation of an entire blanket segment with all its cooling channels, enabling parametric analyses which could not be easily achieved by existing tools at this level of detail.

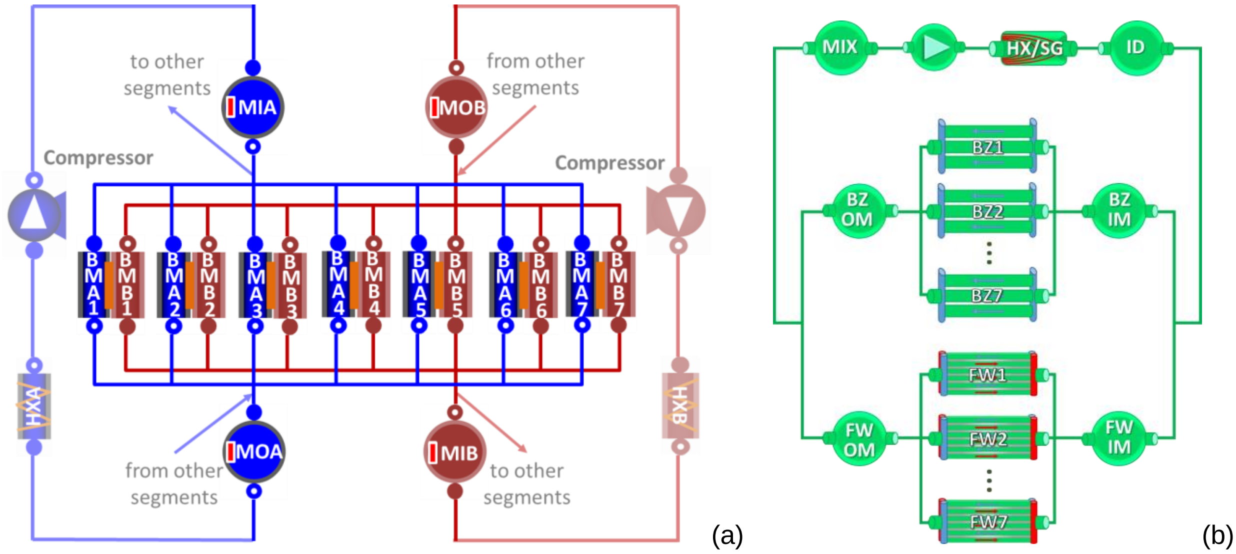

Fig. 4: Scheme of the different nominal operation models available in GETTHEM: a) HCPB (the circuit is divided in two loops, A and B; M: manifold; HX: heat exchanger; I: inlet; O: outlet); b) WCLL (SG: steam generator; ID: inlet distributor; IM: inlet manifold; OM: outlet manifold; MIX: mixer).

On the other hand, in case of accidents such as an in-vessel Loss-Of-Coolant Accident (LOCA), when the coolant is released to the Vacuum Vessel (VV, normally operating at ~0.1 µPa – ~0.1 mPa), the coolant rapidly goes out of the normal working windows and, being released in an environment at very low pressures, it changes phase by flashing and re-condensing (it may even desublimate). Moreover, in view of the huge pressure differences the fluid is subject to, choked flow will necessarily occur. So, for this kind of transients, the coolant is modelled in its details but the geometry of the cooling loop has been simplified, by lumping the entire PHTS in a 0D volume.
A scheme of the different in-VV LOCA models available in GETTHEM is reported in Fig. 5.

Results

Nominal operation

GETTHEM was applied to analyse the cooling performances of a BB segment for the HCPB BB concept, under the nominal heat loads foreseen during plasma operation; as main outcome [6], it was found that, in view of the different dimensions, see Fig. 6, the BM caps cooling channels had a much smaller hydraulic resistance with respect to the Cooling Plates (CPs) cooling channels, used to cool the BZ, so that with the baseline design most of the coolant flowed through the caps bypassing the CPs, which reached much higher temperatures than the design one. GETTHEM was then used to optimize the distribution of the mass flow rate within the BMs by introducing and dimensioning suitable localized pressure drops at the inlet of the caps, strongly improving the overall cooling performance, which in turn allowed halving the mass flow rate requirements while maintaining the coolant within the design temperature range; this result is summarized in Fig. 7, where the share of mass flow rate between CPs and caps before and after the optimization is shown, together with the temperature distribution along the coolant flow path.
As a side effect, the reduction of the needed mass flow rate gives a reduction of the compression power needed in the PHTS: this point is especially important if considering that, for a helium-cooled BB concept, the electric power needed to circulate the coolant can be as high as 20 % of the overall plant electric output, affecting thus in a non-negligible way the global plant efficiency.

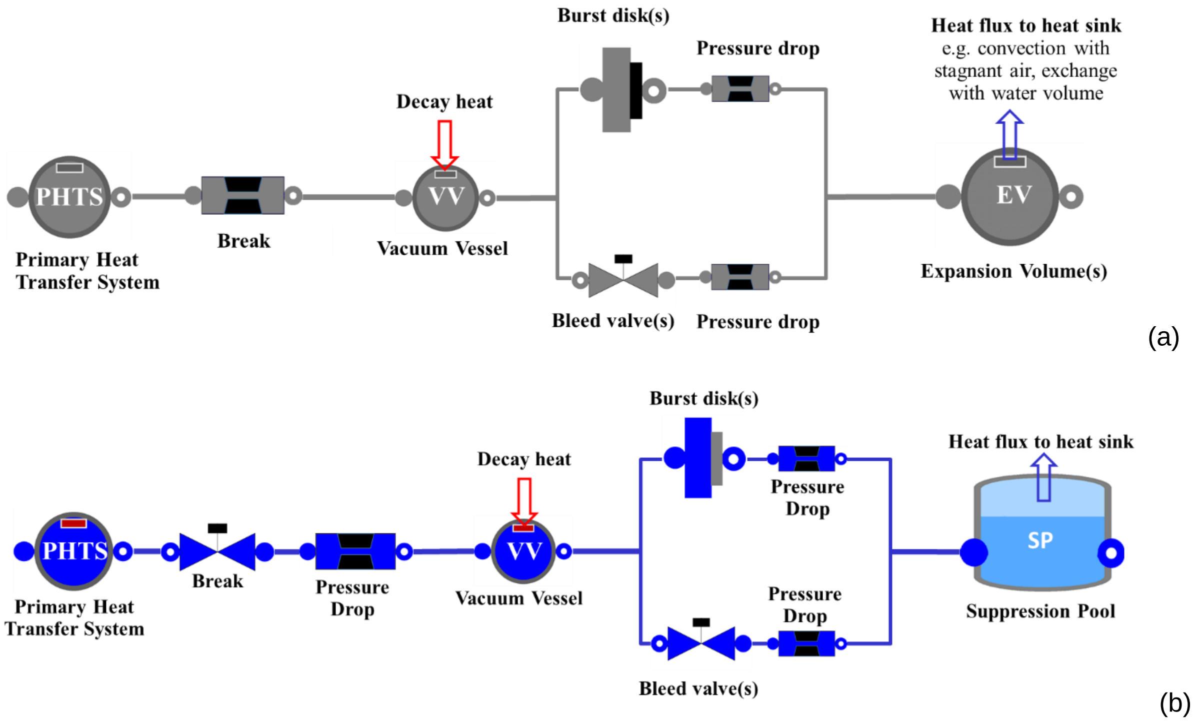

Fig. 5: Scheme of the different in-vessel LOCA models available in GETTHEM: a) HCPB; b) WCLL.

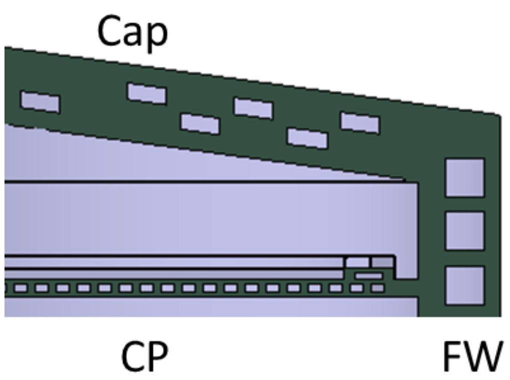

Fig. 6: Cross section of a HCPB BM, showing the different sizes of the Cap, CP and FW cooling channels.

More recently, GETTHEM was applied for a similar analysis on the WCLL BB [9]: in this case, since the coolant is water, it is especially important to ensure that it always remain below the saturation point, to avoid boiling. The temperature distribution in the BZ of the 2015 WCLL BB was analysed, again under the nominal heat loads, showing that, if the mass flow rate is let free to redistribute among the cooling channels, the coolant outlet temperature can reach values as high as 340 °C, whereas the saturation temperature is ~343 °C, leaving a very small margin between the two. On the other hand, by applying localized pressure drop at the inlet of the channels further away from the plasma (which are necessarily also the least loaded), the outlet temperature distribution becomes more uniform, also increasing the overall efficiency of the plant as now the temperature reduction due to the mixing of hot and “cold” water is lower. In this case, the GETTHEM calculations have also been verified against CFD calculations performed by the WCLL designers in a similar scenario, showing a discrepancy always below 5 K in the computation of the temperature increase.
The temperature distribution in the WCLL BZ, for the two cases described above, is reported in Fig. 8.

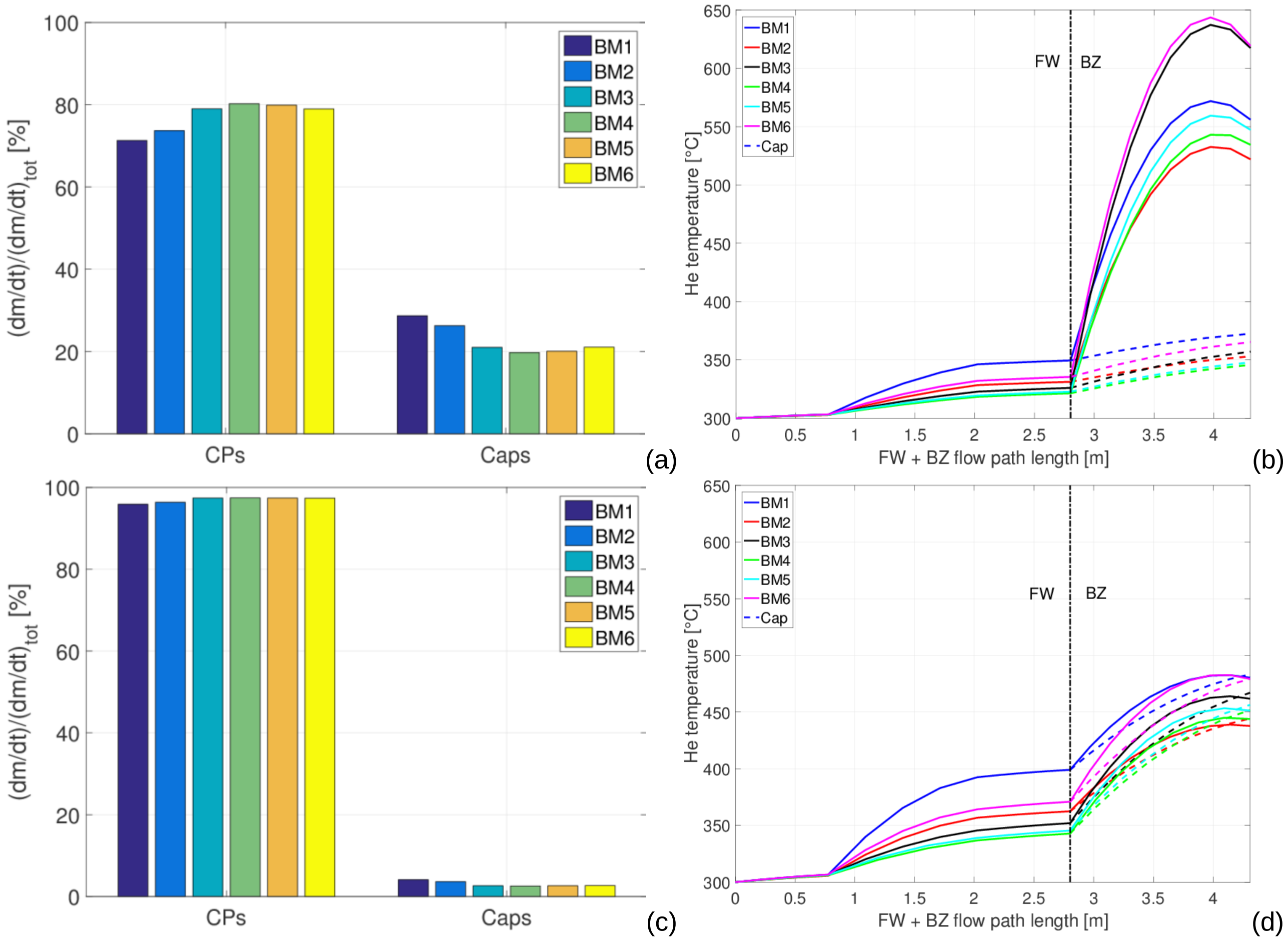

Fig. 7: Temperature distribution in the HCPB OB cooling system (2014 design): a) mass flow rate distribution before optimization; b) temperature distribution before optimization; c) mass flow rate distribution after optimization; d) temperature distribution after optimization.

In-vessel LOCA

As mentioned, another module of the code has been developed, which is used to simulate accidental transients, with the specific aim of simulating in-vessel LOCAs initiated by the break of a portion of FW causing the release of coolant into the VV, which has a pressure limit of 2 bar; the code models (again with 0D or 1D components) the PHTS, the VV and the Expansion Volume (for helium-cooled BBs) or the suppression pool (for water-cooled BBs), together with all the connections between them (FW break, burst disks, relief lines). The validity of the code in this kind of scenario was assessed through a benchmark against the validated CONSEN code [12] for the case of helium coolant [8] and a validation against the ICE experimental campaign for the case of water coolant [10].

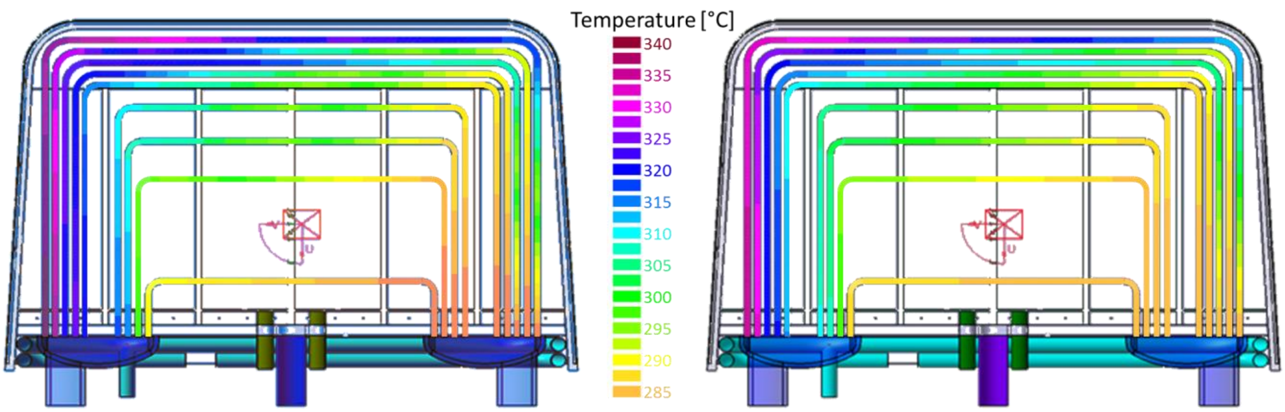

Fig. 8: Distribution in the radial-toroidal plane of the coolant temperature in the WCLL BB, before (left) and after (right) optimization of flow rate.

For the helium case, in particular, the code was initially calibrated (by tuning the parameters of the burst disk model) and then benchmarked with good results against different scenarios found in [13], as reported in Fig. 9: in this scenario the coolant, initially at 8 MPa, is released inside the VV, causing immediately a pressure spike. However, the set-point pressure for the opening of the safety burst disk (150 kPa) is reached after ~0.2 s, rapidly evacuating the coolant and causing a visible reduction of the VV pressure increase, as highlighted in Fig. 9b. In any case, the results, in terms of pressure in the three relevant volumes, benchmarked excellently against the validated CONSEN code.

Concerning the water-cooled BBs, GETTHEM was validated against experimental data collected from the ICE experimental campaign run in Japan between 2000 and 2001, when the in-vessel LOCA was simulated by releasing water at 2 MPa into a tank initially under vacuum ("VV"), connected through burst disks and relief lines to a Suppression Tank (ST). The results for this case are reported in Fig. 10: it is evident how GETTHEM was able to correctly reproduce the evolution of the pressure inside the two modelled volumes, VV and ST, with a slight overestimation of the pressure peak. The most noticeable difference is that, according to the experimental data, the steady-state value of pressure reached in the two volumes is different, which is not physical as the two volumes are perfectly connected; this can be explained considering that the two pressure sensors used necessarily have different scales, as the pressure range they need to measure is sensibly different. In any case, GETTHEM results are in between the two measurements, so it can be safely considered accurate within experimental uncertainty.

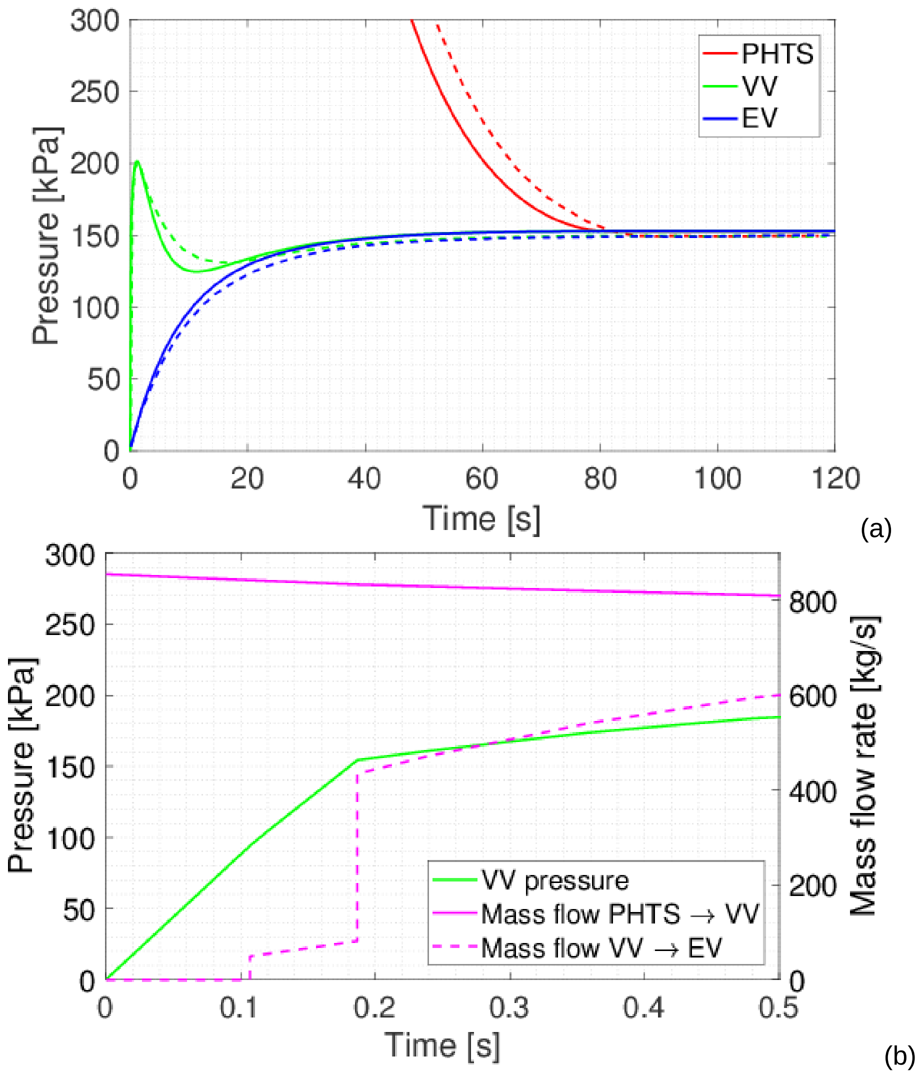

Fig. 9: Results of GETTHEM benchmark for HCPB in-vessel LOCA: (a) benchmark against CONSEN (solid lines: GETTHEM; dashed lines: CONSEN); (b) detail of pressure and mass flow rate evolution in the first half second, as computed by GETTHEM.

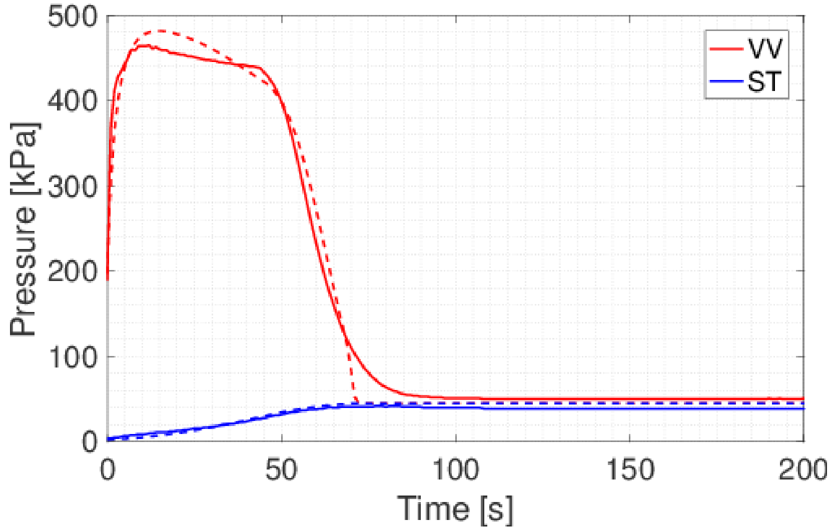

Fig. 10: Results (in terms of pressures in the relevant volumes) of GETTHEM validation for WCLL in-vessel LOCA (solid lines: GETTHEM; dashed lines: experimental results).

The code was applied to analyse an in-vessel LOCA in the EU DEMO caused by the melting of 10 m² of FW in a toroidally continuous strip at the level of the OB4 (which is an overconservative assumption), for both HCPB and WCLL BB concepts. Starting from the geometry of the two BBs, the number of FW channels involved in the break was identified, with the aim of determining the cross section available for the coolant after the break. As a first hypothesis, no heat deposition in the BB and VV structures, due to decay heat, was assumed; moreover, no heat sink at the helium EV was considered. As visible in Fig. 11, in both cases the pressure in the VV overcomes the limit of 2 bar reaching ~6 bar in the helium case and ~5 bar in the water case; however, the limit is overcome for only few seconds (HCPB) or tens of seconds (WCLL). One important difference between the two situations is that the steady-state is reached after ~500 s in the case of water, which is ~5× longer than the helium case (when the steady-state is reached after ~100 s); this is caused by the phase change occurring in water, which, after a fast depressurization of the PHTS in the first ~1 s, reaches the saturation pressure and starts boiling, causing the pressure decrease (and, consequently, the mass flow rate released to the VV) to abruptly slow down (see Fig. 11c). However, the peak pressure is always reached within tens of seconds at most.

Conclusion

The GETTHEM code for the multi-scale thermal-hydraulic modelling of tokamak fusion reactors, developed with the Modelica language, allows fast transient simulation of the PHTS, with helium or water as coolant, enabling parametric analyses, both under nominal conditions and for accidental transients.

The nominal operation of HCPB and WCLL BB has been simulated after that the code was benchmarked against computationally-expensive CFD simulations; the code has been then applied to optimize the flow distribution inside the two BB options.

Accidental scenarios have been also modelled, and the code in this case was benchmarked against other system codes, and also successfully validated against experimental data. The tool was then successfully applied to the analysis of a design-basis accident for the EU DEMO, considering both coolant options, giving a first hint on the maximum pressure value reached in the VV after a large-break LOCA.

In perspective, the code is being extended to include models for the ex-vessel components of the PHTS, with the aim of rapidly analysing the effect of different heat load scenarios or cooling options on the overall efficiency of the power plant. In parallel, a benchmark of the code capabilities to compute the hot-spot temperature distribution in the solid structures of the BB is ongoing. Finally, concerning off-normal operation, the code is being applied to parametrically analyse different break sizes for the EU DEMO in-vessel LOCA, to evaluate the maximum tolerable FW break size with the current parameters, and to help dimensioning the relief lines.

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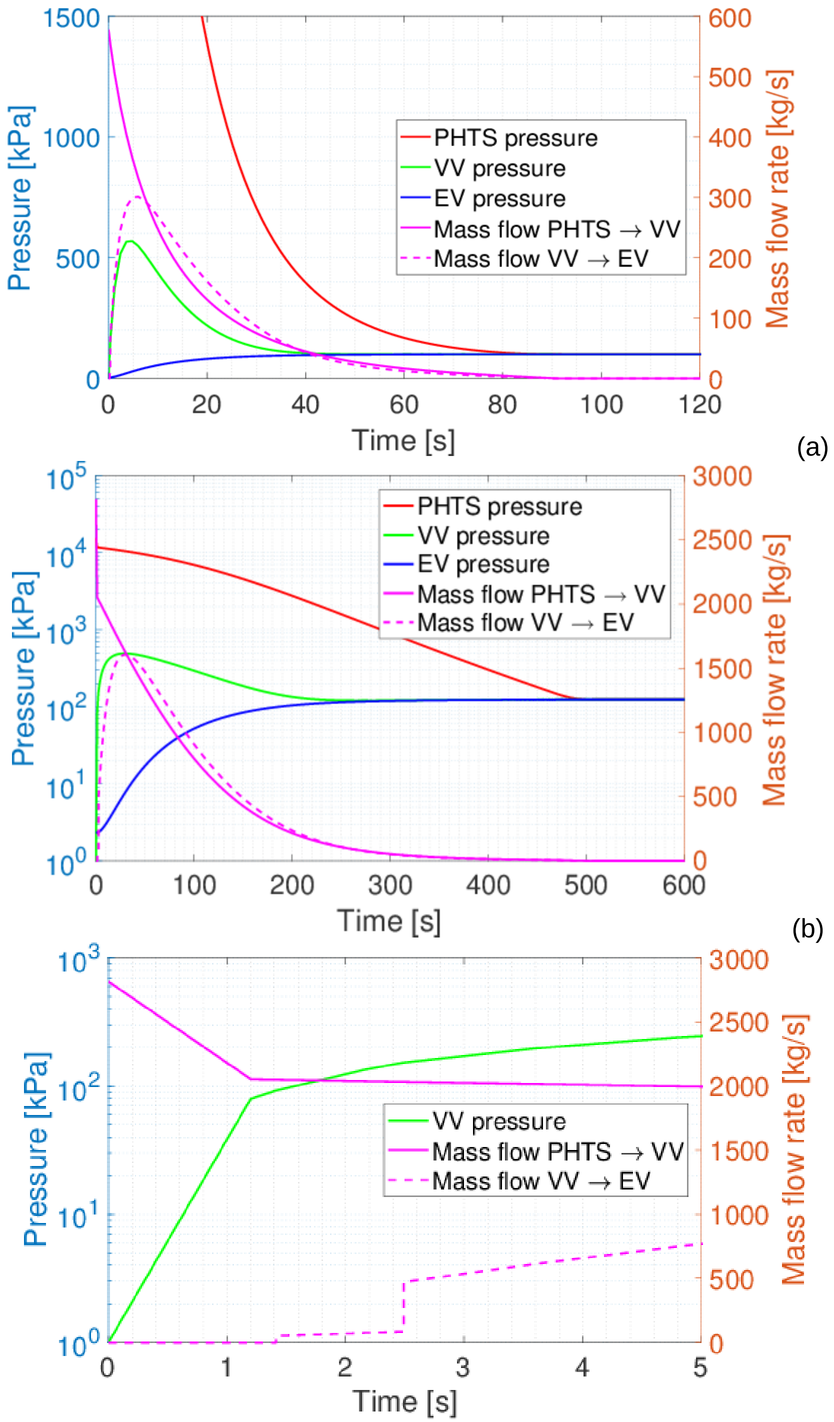

Fig. 11: Evolution of pressures (left axes) and mass flow rates (right axes) in the relevant volumes during an in-vessel LOCA: (a) HCPB; (b) WCLL; (c) zoom in the first 5 s for WCLL scenario.

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