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 scenarios. This work presents the development of a code for this kind of analyses, called the GEneral Tokamak THErmal-hydraulic Model (GETTHEM), together with the first results obtained with it.

Introduction

The EU DEMO tokamak will be the first reactor to produce electrical energy from fusion; it is currently in its pre-conceptual design stage, and it will include for the first time the Primary Heat Transfer System (PHTS), removing the heat produced in the reactor. The main source of heat for the PHTS will be the Breeding Blanket (BB), which is the first component facing the plasma and the component where the tritium will be produced; the BB is hence the component that faces the largest total heat load, coming from the plasma and from the nuclear reactions happening inside the Breeding Zone (BZ). Its cooling is then fundamental, also from the safety point of view, as the BB is “the most nuclear component” in a fusion reactor.

For the EU DEMO design and analyses activity, a tool for system-level thermal-hydraulic modelling of the PHTS is under development since 2015 at PoliTo, supported by the EUROfusion PMU. The aim of this code, named “GEneral Tokamak THErmal-hydraulic Model” (GETTHEM), is to allow fast parametric analyses of the PHTS, in support of the designers. 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. 1) [1], the Water-Cooled Lithium-Lead (WCLL, see Fig. 2) [2], the Helium-Cooled Lithium-Lead (HCLL) [3] and the Dual-Cooled Lithium-Lead (DCLL) [4]; at the present stage, GETTHEM contains models for HCPB [5] [6] [7] and WCLL [8] [9].

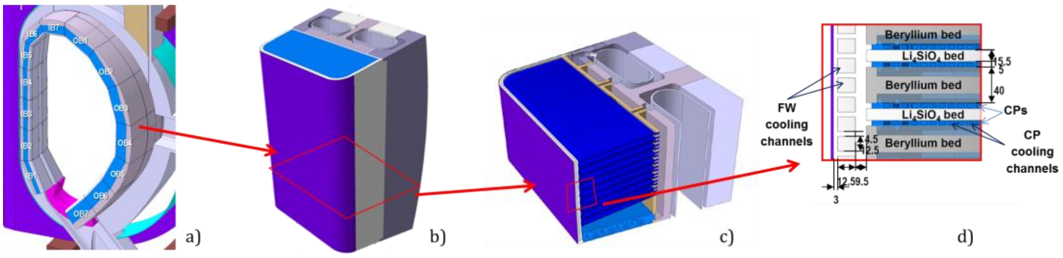


Fig. 1: The HCPB BB (adapted from [1]): a) a BB sector; b) the equatorial outboard BM OB4; c) a radial-poloidal cross section of the OB4; d) detailed radial-poloidal cross section of the OB4.

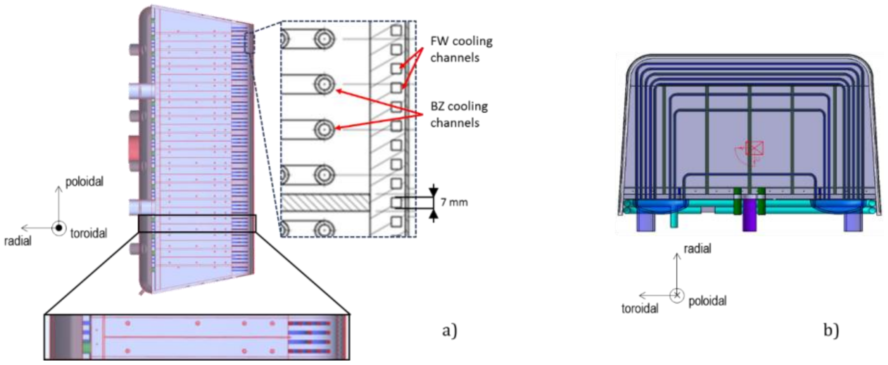


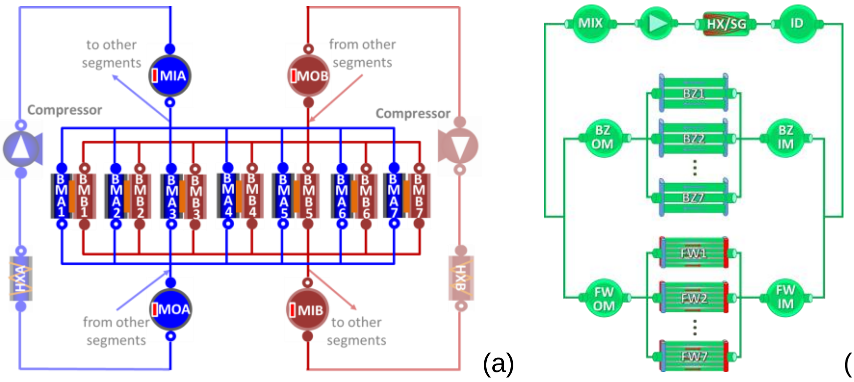
Fig. 2: The WCLL BB (adapted from [2]): OB4 radial-poloidal (a) and toroidal-radial (b) cross sections.

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 components can be 1D along flow direction or 0D; in each model, the mass and energy conservation equations 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. 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.

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

A scheme of the models available in GETTHEM for nominal operating conditions is reported in Fig. 3. The focus is here on the differences which may be found among the different cooling channels in a BB segment; each BM has ~1700 cooling channels [1], and, to model all of them separately, the computation of the thermo-physical properties of the coolant was simplified, modelling the helium as an ideal gas in its working conditions (8 MPa, 300 – 500 °C) and by linearizing the properties of water in the temperature range (15.5 MPa, 285 – 325 °C), introducing an input error below 3.5 %. Also, the thermo-physical properties of the solid materials are assumed to be independent on temperature, introducing an input error below 8 %, and the heat transfer coefficient between solid and fluid is assumed constant. These simplifications affecting the code output by less than 3 %, make the code very lightweight, thus allowing fast transient simulation of an entire blanket segment with all its cooling channels, enabling parametric analyses.

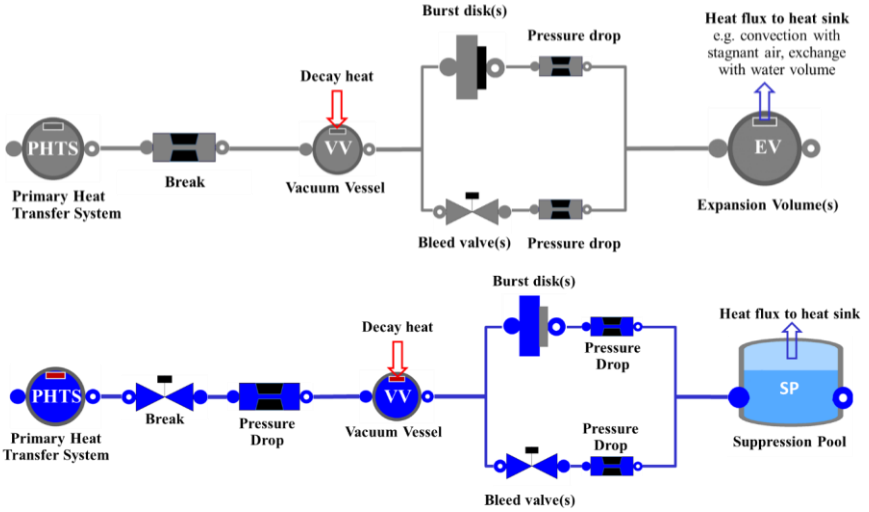


(a) (b)

Fig. 3: Scheme of the different nominal operation models available in GETTHEM: a) HCPB; b) WCLL.

Conversely, 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 ~10 mPa), the coolant rapidly goes out of its working window and, being released at very low pressures, it flashes. Moreover, in view of the huge pressure differences the fluid is subject to, choked flow will necessarily occur. So, for these transients, the coolant is modelled in its details but the geometry of the PHTS has been simplified, by lumping it in a 0D volume.

A scheme of the different in-VV LOCA models available in GETTHEM is reported in Fig. 4.



(a)

(b)

Fig. 4: Scheme of the different in-vessel LOCA models available in GETTHEM: a) HCPB; b) WCLL.

Results

Nominal operation

GETTHEM was applied to analyse the cooling performances of a HCPB BB segment under nominal heat loads [5]; it was found that, in view of their different dimensions, see Fig. 5, the BM caps cooling channels had a much smaller hydraulic resistance than the Cooling Plates (CPs) channels, used to cool the BZ, so that most of the coolant flowed through the caps bypassing the CPs. 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 (consequently reducing also the pumping power, which is a non-negligible fraction of the output power) while maintaining the coolant within the design temperature range; this result is summarized in Fig. 6, 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.

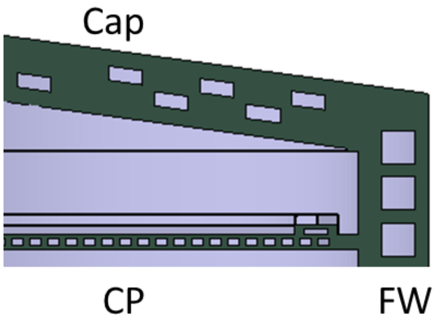


Fig. 5: Cross section of a HCPB BM, showing the different sizes of the Cap, CP and FW cooling channels.

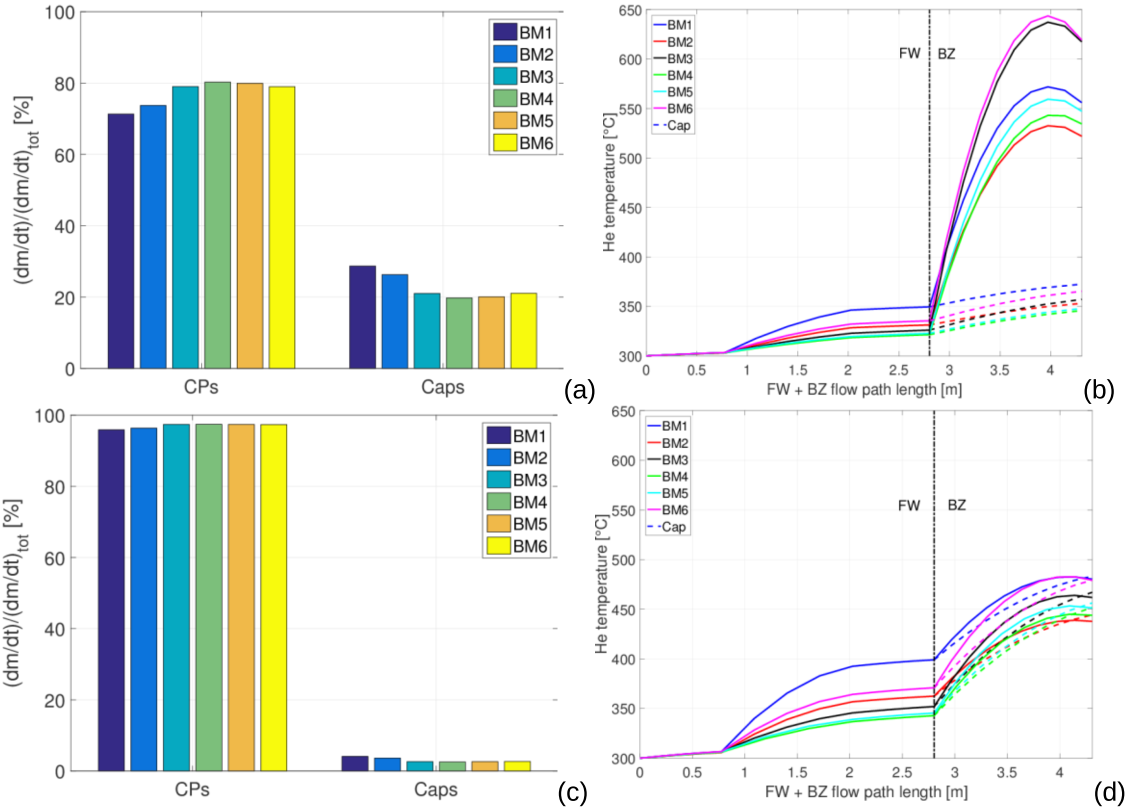


Fig. 6: Temperature distribution in the HCPB OB cooling system (2014 design): a) mass flow rate distribution before optimization; b) temperature distribution before optimization; c) mass flow rate distribution after optimization; d) temperature distribution after optimization.

In-vessel LOCA

The second module of the code was developed 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 the PHTS, the VV and the Expansion Volume (EV) 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 was assessed through a benchmark against the CONSEN code [11] for the case of helium coolant [7] and a validation against the ICE experimental campaign for the case of water coolant [9], showing in both cases excellent outcomes.

The code was applied to analyse an in-vessel LOCA in the EU DEMO caused by the melting of 10 m² of FW under overconservative assumptions. As visible in Fig. 7, in both cases the pressure in the VV overcomes the limit of 2 bar. 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.

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 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.

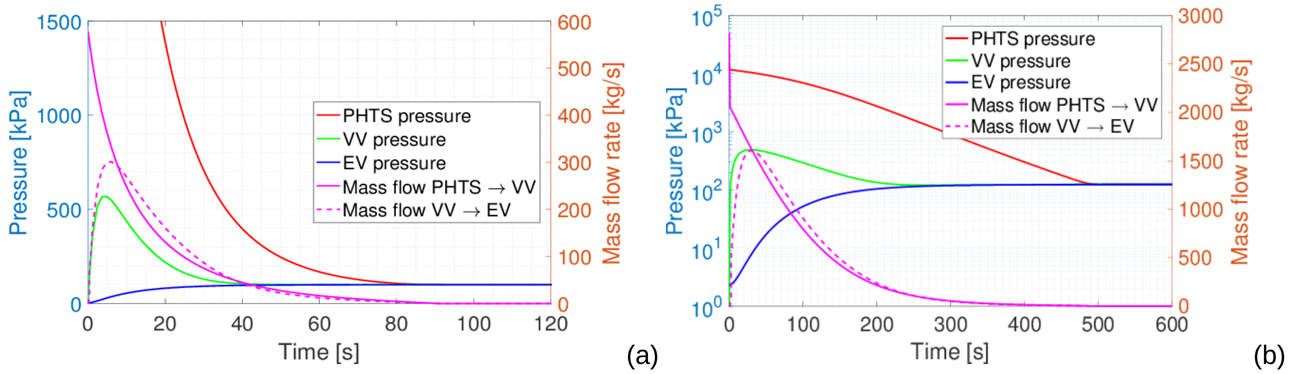


Fig. 7: Evolution of pressures (left axes) and mass flow rates (right axes) in the relevant volumes during an in-vessel LOCA: (a) HCPB; (b) WCLL.

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. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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