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Thermal-hydraulic study of the EU-DEMO Helium Cooled Pebble Bed Breeding Blanket Primary Heat Transport System

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Abstract. The European DEMO reactor will work under normal operating conditions in accordance with a pulsed duty cycle. However unplanned and planned transients of plasma overpower may occur compromising the integrity of its plasma-facing components structures. Consequently, adopting appropriate tools is essential to accurately and consistently model the thermal-hydraulic response of the involved cooling systems under both normal operating conditions and accidental events. Given this background, the University of Palermo, in collaboration with EUROfusion, started a research work to study the thermal-hydraulic behaviour of the Primary Heat Transport System (PHTS) of the Helium Cooled Pebble Bed Breeding Blanket (HCPB BB) of the DEMO device under steady-state and transient conditions. The activity has been performed adopting a computational approach, employing the thermal-hydraulic system code TRACE version 5.0 patch 6. The key point of the work has been the code-to-code benchmark with the outcomes previously obtained with the RELAP5-3D code, to estimate the impact of the physical models, numerical resolution schemes and modelling techniques adopted on the predictive capabilities of the system codes considered. The models and the analysis results are presented and critically discussed herein.

1. Introduction

By the middle of this century, in agreement with the European roadmap, nuclear fusion is going to be part of the energy mix for electricity production [1]. To achieve this goal, the EUROfusion consortium is working on the development of a DEMOnstration fusion reactor (DEMO) following the ITER path in exploring fusion energy. Unlike ITER reactor, DEMO is conceived to provide electricity to the grid. Since the energy conversion and cooling systems of the tokamak ([2], [3]) have a fundamental role to the realization and the licensing of the plant, a detailed assessment of their features is needed.

Based on the tokamak design, the EU-DEMO operates according to a pulsed operating cycle. These operating conditions induce thermal and mechanical cycling and could potentially compromise the qualified lifetime of the relevant equipment. Furthermore, planned and unplanned overpower transients of the plasma could put the integrity of the plasma-facing components structures at risk [4]. Thus, it is crucial to have adequate computational tools which can accurately and consistently model the thermal-hydraulic features of the cooling systems of these kinds of machines, during both major operational and accidental transients.

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Thermal-hydraulic system codes, like RELAP5-3D [5], developed by Idaho National Laboratories, and TRACE [6], developed by the U.S. Nuclear Regulatory Commission, are extensively used to characterize the thermal-hydraulics of operational and innovative nuclear fission power plants, and their use in this field is widely validated by the experience of nuclear power plants that operated in the second half of the 20th century and those that are currently in operation and by validation campaigns with experimental data on innovative reactors.

At present, the study of the predictive capabilities and, therefore, the verification of the potential use of thermal-hydraulic system codes in the field of fusion reactors is severely limited by the scarce availability of experimental data. A powerful tool currently available to the research community involved in Research and Development (R&D) on fusion technologies to assess the impact on the predictive capacities of a system code of the physical models, numerical resolution schemes and modelling techniques adopted is indeed the code-to-code benchmark.

Within this framework, University of Palermo started a thermal-hydraulic research programme to assess the Primary Heat Transport System (PHTS) in a DEMO device equipped with the Helium Cooled Pebble Bed (HCPB) Breeding Blanket (BB) ([7], [8]). The activities have been carried out in collaboration with EUROfusion. A computational methodology has been adopted to conduct the thermal-hydraulic analyses, and the thermal-hydraulic system code TRACE (version 5.0 patch 6) has been used to simulate both steady-state and transient conditions. First efforts have been focused on creating a TRACE nodalization which could realistically predict the response of the system with an acceptable computational time. Afterwards, the core point of the activity has been the code-to-code benchmark with results previously obtained with the RELAP5-3D code [9] to estimate the impact of the physical models, numerical resolution schemes, and modelling techniques adopted on the predictive capabilities of the system codes considered and to obtain a preliminary validation of their use in the field of fusion reactors. The models, assumptions and analysis results are herein presented and critically argued.

2. The design of the HCPB BB PHTS

The latest baseline design of the HCPB BB for the DEMO machine has 16 identical sectors. Each sector is composed of 5 BB segments, namely Left Inboard Blanket (LIB), Right Inboard Blanket (RIB), Left Outboard Blanket (LOB), Central Outboard Blanket (COB) and Right Outboard Blanket (ROB) [7]. In Figure 1, a general scheme of one of the 16 sectors is shown.

A EUROFER97 exterior box consisting of a First Wall (FW), bottom and top caps, sidewalls, and the backplate containing the Breeding Zone (BZ) makes up a typical HCPB BB section. An Advanced Ceramic Breeder (ACB) is present in the BZ and positioned in the fuel-breeder pins configuration. Its main function is the tritium production. The ACB is positioned within the inner and outer cladding of a pin, which is made up of two concentric tubes. The pins serve as structural components to prevent pressurisation in the event of a potential LOCA scenario. They are placed within pressure tubes that link the FW to the BZ backplate. The Be12Ti is positioned outside the pressure pipe holding the pins in the shape of hexagonal prismatic blocks and functions as a neutron multiplier [10]. Pressurized helium at 8 MPa and an inlet temperature of 300 °C cools the FW and BZ zones. First flowing from the FW inlet manifold to its cooling channels, helium is then delivered to the pins via the BZ inlet manifold. Inside the BZ inlet manifold it is chilled in a counterflow system to equalise the temperature distribution. It finally reaches the BZ pins at approximately 520 °C into the outlet plenum and sent to the BZ outlet manifold [7].

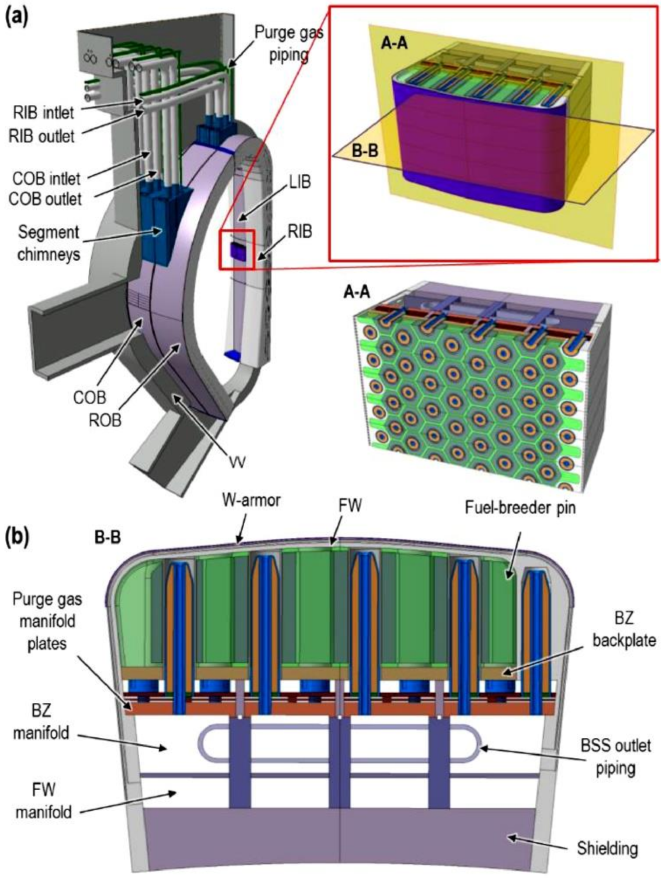

Figure 1. Typical HCPB BB Segment [1].

The thermal power removal is the main goal of the HCPB BB primary circuit. From the components inside the vessel, it is transferred via the Intermediate Heat eXchangers (IHXs) to an Intermediate Heat Transport System (IHTS). At an 8 MPa inlet pressure and operating temperatures of 300÷520 °C, it is intended to extract around 2029 MW of thermal power using helium [7]. Table 1 shows the principal data of the HCPB BB primary circuit.

Table 1. Primary circuit main parameters.

Parameter	Value
Coolant [-]	Helium
Inboard Blanket segments [-]	32
Outboard Blanket segments [-]	48
Inboard Blanket power [MW]	575.4
Outboard Blanket power [MW]	1453.7
I/O Blanket inlet pressure [MPa]	8.0
I/O Blanket inlet temperature [°C]	300.0
I/O Blanket outlet temperature [°C]	520.0
I/O Blanket pressure drop [kPa]	79.9

The HCPB BB PHTS is divided in eight distinct cooling loops in its current configuration [2]. Each loop feeds two blanket sectors and consists of In-vessel BB cooling circuits, an IHX, two circulators, and the piping that connects these sections. Figure 2 illustrates the HCPB BB PHTS [2].

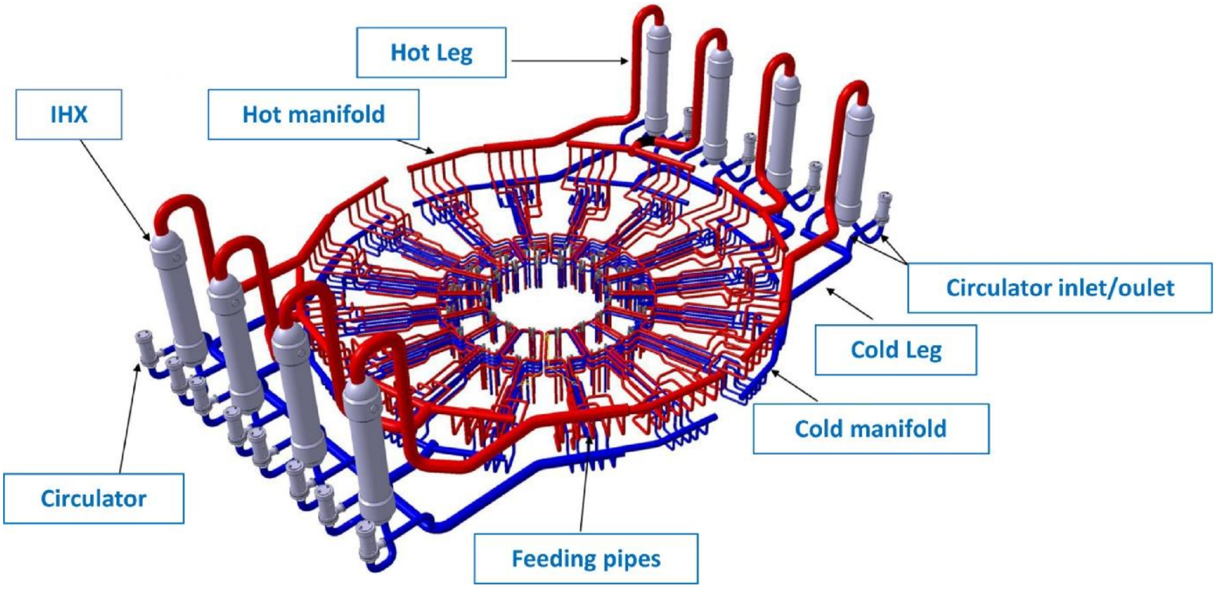

Figure 2. Three-dimensional layout of the HCPB BB PHTS [2].

In the tokamak cooling rooms, which are situated on the upper level of the Tokamak Building, the eight IHXs are placed on two opposing sides (see Figure 2). Every IHX is installed in a row and distributed equally at the same location [2]. The IHX thermally couples the HCPB BB PHTS to the IHTS. The main design option for the IHX consists of a shell and tube type [9], with the helium circulating on the tube side (primary side) and the HITEC® molten salt [11] flowing in the shell side (secondary side). In Table 2 the key thermal-hydraulic features of the latest IHX design are presented.

Table 2. IHX main thermal-hydraulic parameters.

Parameter	Helium	Molten salt
Inlet pressure [MPa]	7.89	0.8
Inlet temperature [°C]	520.0	270.0
Outlet temperature [°C]	290.9	465.0
Mass Flow Rate [kg/s]	222.2	867.9
Pressure Drop [kPa]	60.7	462.7

The IHXs lower head is not far from the helium circulators. Each circulator has two short pipes that connects it upstream to the IHX and downstream to the cold leg [2].

3. Model setup

As the HCPB BB PHTS is composed by eight independent circuits, attention has been focused on modelling only one loop of the HCPB BB PHTS in analogy to what has been done in [9] and simulating its thermal-hydraulic response under the transient conditions expected during the duty cycle.

The main goal has been to create an accurate finite-volume model representing all of the significant thermal-hydraulic properties that distinguish both components inside and outside the vessel, in compliance with the TRACE system code criteria. The finite volume model has been developed starting from the RELAP5-3D model described in [9] in order to obtain valuable indications from the benchmark between the two system codes. More in detail, the model is made of four different sub-models.

The cooling circuit architecture is approximated in quasi-2D by the geometrical sub-model. The flow domain nodalization has been done while maintaining the volume of every component, enabling an accurate modelling of the total amount of coolant. In addition, sub-volumes have been appropriately positioned and modelled to replicate their respective heights and positions. Therefore, concerning the geometrical factors involved in their evaluation, both gravitational effects and distributed pressure drops have been accurately represented. Additionally, the model nodalization has been created to accurately forecast the selected loop overall thermal-hydraulic behaviour while requiring allowable calculation time. Figure 3 shows the nodalization of the single loop of the HCPB BB PHTS.

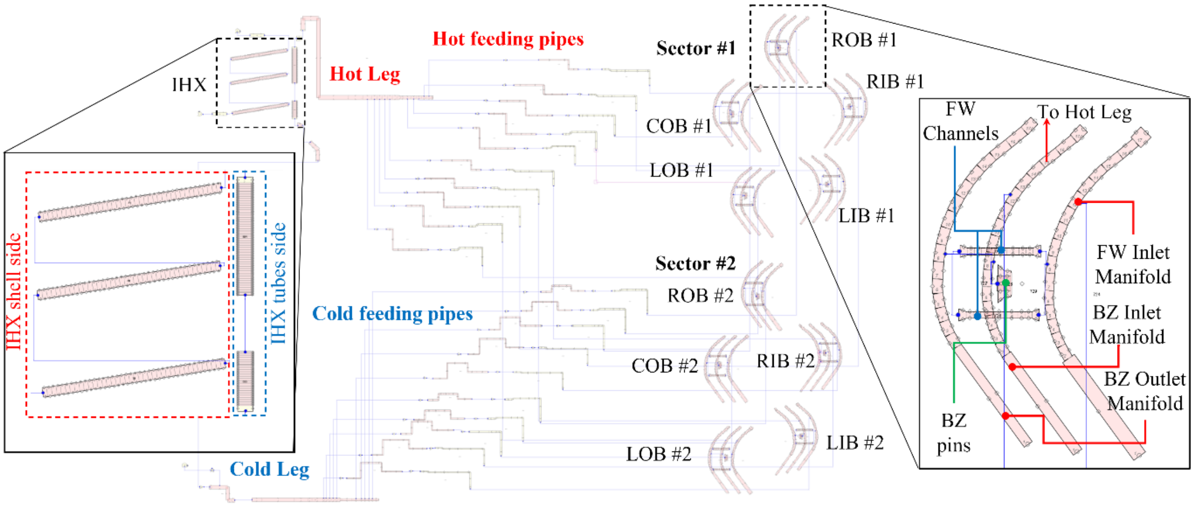

Figure 3. Nodalization of the HCPB BB PHTS cooling loop.

The constitutive sub-model explains how the thermophysical features of the adopted fluids depend on temperature and pressure and how the thermophysical properties of the structural materials present in the model depend on temperature. In this respect, as far as the helium is concerned, the properties dependence on pressure and temperature is based on TRACE libraries while, regarding the HITEC® molten salt, its thermophysical properties have been introduced within the TRACE code [11] as an external material library. Furthermore, several materials have been considered to accurately simulate the thermal response of structural elements inside and outside the vessel. Regarding the BB structural materials, their thermophysical properties, e.g. EUROFER and Tungsten ([12] and [13]), have been inserted in the TRACE code as tabular temperature functions. As far as the IHX is concerned, only the tube bundle structures, which are made of Alloy-800H [14], have been simulated.

The goal of the hydraulic sub-model is to replicate the fluid flow through the systems. The model described in [9] has been considered as a reference to assess the hydraulic performance of the helium in the PHTS side and the HITEC® on the shell-side of the IHX while obtaining valuable indications from the benchmark between the two system codes.

The aim of the thermal sub-model is to replicate the heat transport processes via the cooling systems as accurately as possible. All the structural components have been modelled in order to accurately simulate their heat capacity. The heat transfer phenomena have been replicated by using appropriate heat transfer models. Specifically, the widely used Gnielinski correlation, which is incorporated into the TRACE code, has been employed in conjunction with the Bell-Delaware procedure, a method that has been also used in [9], to replicate the heat transfer characteristics of the IHX. The TRACE model incorporates both the nuclear heating, and the FW heat fluxes in its thermal loads, which vary according to the DEMO duty cycle [9].

4. Thermal-hydraulic analyses

The benchmark between the RELAP5-3D analysis [9] and the purposely set-up TRACE model has been conducted considering the nominal DEMO duty cycle, as reported in [9].

It is important to note that the TRACE field equations have been developed with the idea that viscous shear stresses are negligible, at least in the first approximation, and therefore explicit turbulence modelling is not coupled to the conservation equations [6]. Although this assumption can generally be considered acceptable, it can lead to significant errors when the working fluid is a gas and one is dealing with complex circuits such as those envisaged for the DEMO device.

Aiming at assessing the effect of this assumption associated with the formulation of the field equations adopted in TRACE and at the same time overcoming its drawbacks, two models have been developed: a base model, called Model I, and an alternative model, called Model II, in which a fictitious thermal power source has been added to the helium domains.

In particular, in order to evaluate this additional power source, the helium coolant domain of the BB PHTS circuit has been divided into r regions. In each of these regions, the following heat balance may be applied:

$$\sum_{i=1}^{n} G_i h_i - \sum_{j=1}^{p} G_j h_j + \sum_{k=1}^{m} Q_k = W_r \qquad (1)$$

where W_r is the additional power for the r-th region, G_i and h_i are respectively the mass flow rate and the fluid enthalpy of the i-th inlet section and G_j and h_j are respectively the mass flow rate and the fluid enthalpy of the j-th outlet section while Q_k is the heat transferred from the k-th heat structure of the r-th region to the helium coolant. Then, the additional energy source calculated for the r-th region is evenly distributed over the r-th region.

Furthermore, as far as the helium mass flow rate is concerned, it has been varied at a rate of 12.5 percent per minute throughout the ramp-up and ramp-down phases, from its largest value during the pulse period (see Table 2) to its minimum of 83.34 kg/s for the duration of the dwell time (Figure 4). The mass flow rate of the secondary side is calculated by the code by a control system adopting a proportional integral control. The aim is to keep the inlet temperature of the BB system at 300°C (see Figure 5).

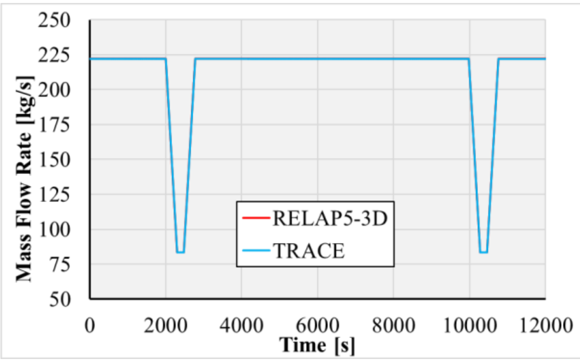

Figure 4. Primary side mass flow rates.

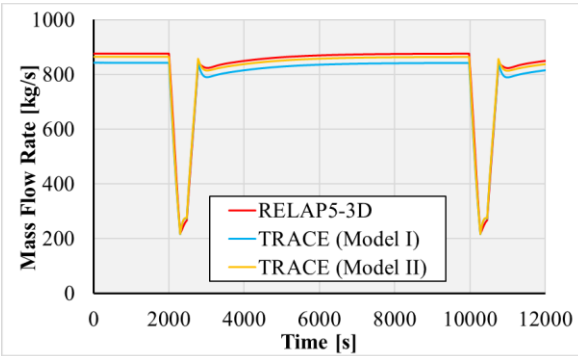

Figure 5. Secondary side mass flow rates.

The time evolution of the inlet pressure and inlet temperature of the cold leg and the inlet temperature of the hot leg are reported in figures from Figure 6 to Figure 8, respectively, while Figure 9 gives the temperature trends along the axis of the intermediate heat exchanger during the pulse period. Furthermore, Table 3 shows the main results for the pulse period compared with the design data.

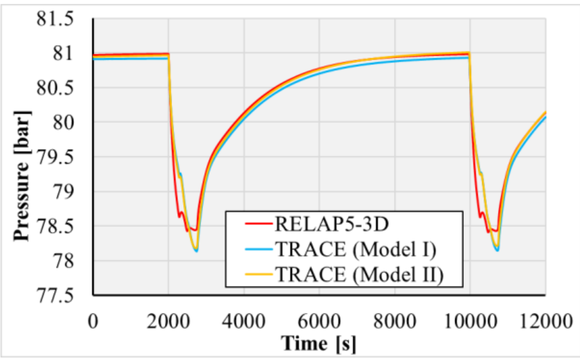

Figure 6. Cold leg inlet pressure.

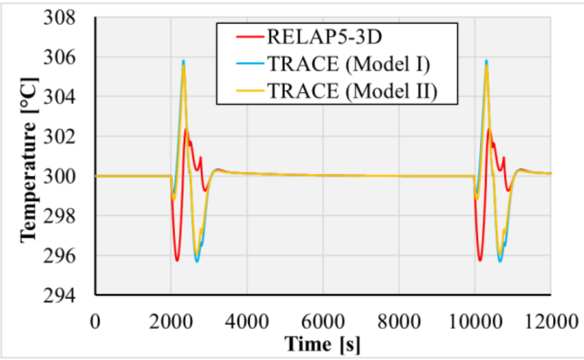

Figure 7. Cold leg inlet temperature.

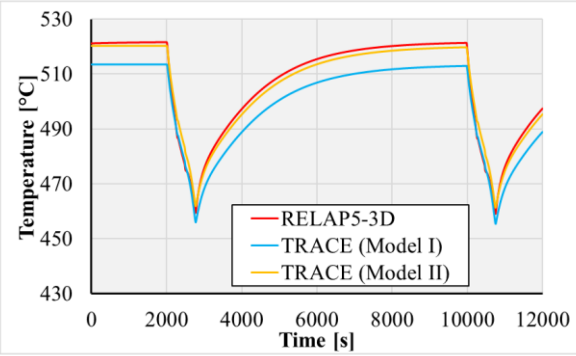

Figure 8. Hot leg inlet temperature.

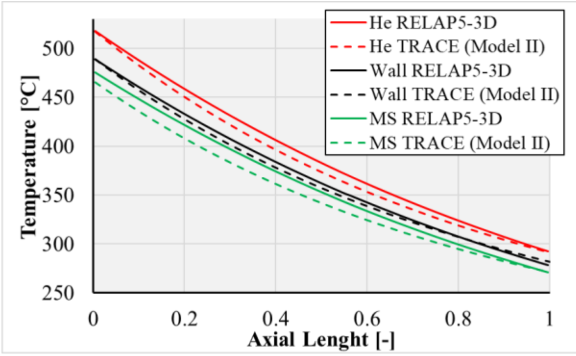

Figure 9. IHX temperature profiles.

Table 3. Comparison of main numerical results.

Parameter	Design	RELAP5-3D	TRACE (Model I)	TRACE (Model II)	$\varepsilon_{RELAP5\text{-}3D}$ [%]	$\varepsilon_{Model\ I}$ [%]	$\varepsilon_{Model\ II}$ [%]
G_{Helium} [kg/s]	222.2	222.2	222.2	222.2	0.00%	0.00%	0.00%
$G_{Molten\ Salt}$ [kg/s]	867.9	876.09	842.68	864.60	0.94%	-2.91%	-0.38%
$p_{Cold\ Leg}$ [bar]	78.29	80.98	80.91	80.96	3.44%	3.35%	3.41%
$T_{Cold\ Leg}$ [°C]	300.00	300.00	300.00	300.00	0.00%	0.00%	0.00%
$T_{Hot\ Leg}$ [°C]	520.00	521.43	513.45	520.25	0.27%	-1.26%	0.05%

From the analysis of the results, it can be inferred that the time trends of the main quantities examined are very close to those previously estimated by the RELAP5-3D calculation [9] with the exception of the temperature trend at the hot leg inlet for the Model I results. This last point is related to what has been mentioned above regarding the formulation of the field equations adopted in TRACE which translates in practice into a numerical heat sink distributed along the circuit. The introduction of a fictitious thermal power source in Model II significantly improves the quality of numerical results. This is further confirmed by the comparison with design values that refer to hypothetical steady-state conditions analogous to those occurring at the end of the pulse phase (see Table 3) and the temperature trend along the axis of the intermediate heat exchanger at the end of the pulse period (see Figure 9).

It is worth emphasising that the two codes examined have slightly different temperature and pressure trends at the inlet of the cold leg during the dwell period. This point could be connected with the slightly different definition of proportional-integral control between the two codes. Nonetheless, it can be seen from the results that this does not significantly affect the timing of the transient.

5. Conclusions

In accordance with the EUROfusion Consortium initiative, the University of Palermo initiated an investigation of the thermal-hydraulic response of the HCPB BB PHTS ([7], [8]) of the EU-DEMO reactor during steady-state and transient conditions. A computational approach has been adopted to perform the activity and the TRACE thermal-hydraulic system code has been adopted. The core point of the activity has been the code-to-code benchmark with the results previously obtained with the RELAP5-3D code [9] to estimate the impact of the physical models, numerical resolution schemes, and modelling techniques adopted on the predictive capabilities of the system codes considered and to obtain a preliminary validation of their use in the field of fusion reactors. In this context, to assess the effect of a potential weakness identified in the TRACE system code with respect to RELAP5-3D and associated with the particular formulation of the field equations adopted in TRACE, and at the same time overcome its drawbacks, two models have been developed: a base model, called Model I, and an alternative model, called Model II, in which a fictitious thermal power source has been added to the helium domains.

The results have highlighted that the time trends of the main quantities examined are very close to those previously estimated by the RELAP5-3D calculation [9] with the exception of the temperature trend at the hot leg inlet for the Model I results. In practice, the particular formulation of the field equations adopted in TRACE results in the presence of a numerical heat sink distributed along the circuit, which becomes evident when the working fluid is a gas and one is dealing with complex circuits such as those envisaged for the DEMO device. The introduction of a fictitious thermal power source in Model II significantly improves the quality of numerical results. This is further confirmed by the comparison with design values that refer to hypothetical steady-state conditions analogous to those occurring at the end of the pulse phase.

Acknowledgements
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