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Development of a thermal-hydraulic model of the EU-DEMO Water Cooled Lithium Lead Breeding Blanket Primary Heat Transport System

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ABSTRACT

The EUROfusion consortium is developing the project of a DEMOnstration Fusion Reactor (EU-DEMO) which would follow ITER in the pathway towards the quest for the exploitation of fusion energy. EU-DEMO has been conceived to deliver net electric power to the grid. Therefore, proper critical evaluations of the tokamak cooling and power conversion systems are needed because they play a pivotal role in the design and licencing of the overall plant. The EU-DEMO reactor will be based on the tokamak concept and, as such, it is supposed to undergo a pulsed duty cycle under normal conditions, which might challenge the qualified lifetime of the main equipment inducing undue thermal and mechanical cycling. Moreover, the EU-DEMO plasma control strategy postulates the possible occurrence of planned and off-normal plasma overpower transients that might jeopardise the structural integrity of the plasma facing components. It is, therefore, of paramount importance to have appropriate tools to reproduce the thermal-hydraulic behaviour of tokamak cooling systems during major operational and accidental scenarios in a realistic and reliable way. In this context, University of Palermo in cooperation with EUROfusion has developed a finite volume model of the Primary Heat Transport System (PHTS) feeding the EU-DEMO Water Cooled Lithium Lead Breeding Blanket (WCLL BB). The activity has been led following a theoretical–computational approach based on the adoption of the TRACE thermal-hydraulic system code. Particular attention has been paid to capturing all the main geometrical, hydraulic and heat transfer features characterising both in-vessel and ex-vessel components. Preliminary analyses have also been carried out to check the code's predictive potential in fusion relevant applications. Models, assumptions, and outcomes of the analyses are herewith reported and critically discussed.

1. Introduction

The European Research Roadmap for the Realisation of Fusion Energy envisages the production of electricity from nuclear fusion by the middle of this century [1]. To this end, the EUROfusion consortium is developing the DEMOnstration fusion reactor (DEMO) project [2], which is expected to follow ITER on the path to harnessing fusion energy. DEMO is designed to supply net power to the grid. Therefore, appropriate critical assessments of the main characteristics of the tokamak cooling and energy conversion systems [3,4], which play a key role in the design and licencing pathway of the entire facility [5], are required.

The EU-DEMO reactor will be based on the tokamak concept and, as such, is expected to operate under normal conditions following a pulsed operating cycle, which could challenge the qualified lifetime of the main equipment by inducing excessive thermal and mechanical cycling. In addition, the EU-DEMO plasma control strategy anticipates that some planned and unplanned plasma overpower transients may occur [6], which could jeopardise the structural integrity of plasma-facing components. Therefore, it is of paramount importance to have adequate tools to realistically and reliably simulate the thermal-hydraulic behaviour of tokamak cooling systems during the main operational and accidental scenarios.

Within this framework, the University of Palermo, in collaboration with EUROfusion, developed a finite volume model of the Primary Heat Transport System (PHTS) that feeds the EU-DEMO Water Cooled Lithium Lead Breeding Blanket (WCLL BB) [7,8]. The work was carried out following a computational–theoretical approach based on the adoption of the TRACE thermal-hydraulic system code [9]. Particular attention was paid to capturing all the main geometric, hydraulic and heat transfer characteristics that characterise both in-vessel and ex-vessel components. Preliminary analyses were also conducted to verify the predictive potential of the code in fusion applications. The models,

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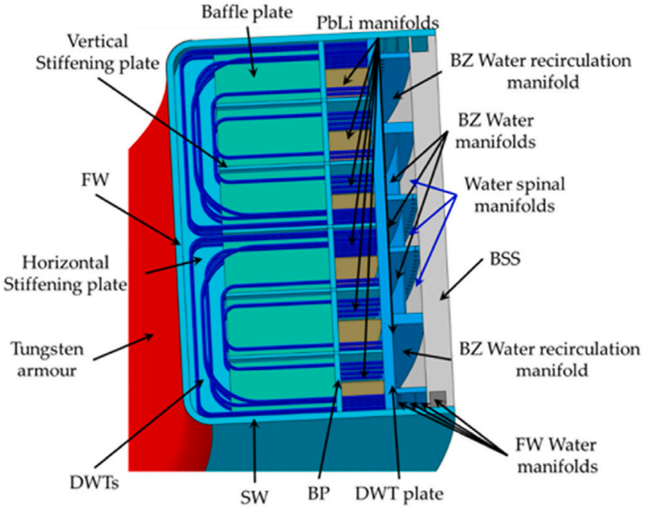

Fig. 1. Overview of a generic WCLL BB segment [10].

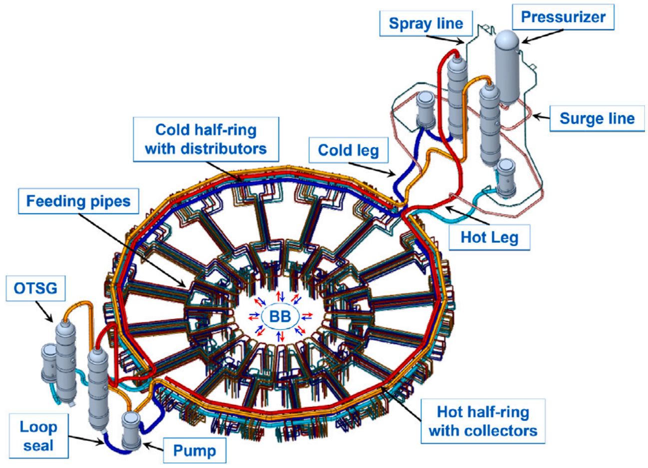

Fig. 2. Overview of the WCLL BB PHTS.

assumptions and results obtained from the analyses are reported and critically discussed here.

2. The design of the WCLL BB PHTS

The BB is a core component of a fusion reactor, as it is intended both to produce tritium, ensuring the plant's self-sustainability, and to channel the fusion energy towards its final conversion into electricity. In this regard, the WCLL BB is one of two candidate technologies [7,8] currently in the process of being selected as a driver blanket for the EU-DEMO conceptual design.

The WCLL BB is based on the use of the eutectic alloy $Pb_{83}Li_{17}$ enriched to 90% in ^6Li as tritium breeder, neutron multiplier and tritium carrier, as well as Eurofer as structural material [7].

Its current design consists of 16 independent sectors. Each sector is further divided into five BB segments, two in the inboard region (left and right segments indicated as LIB and RIB, respectively) and three in the outboard region (left, central and right segments indicated as LOB, COB and ROB, respectively). A generic WCLL BB segment (see Fig. 1) can be seen as being composed of five main regions [10]: (i) the First Wall (FW), a U-shaped plate facing the plasma protected by a 2-mm layer of tungsten; (ii) the Breeding Zone (BZ), i.e. the area where Breeding reactions take place, whose internal structure consists of radial–poloidal and radial–toroidal stiffening plates; (iii) the manifolds, a region where process fluids (i.e. the breeder and the water that cools FW and BZ) are distributed and conveyed; (iv) the Back Supporting Structure (BSS), whose main task is to withstand mechanical loads and ensure the connection of the BB with the Vacuum Vessel (VV); and (v) the caps, which are two plates that close the segment in the poloidal direction.

FW and BZ are actively cooled by water at 15.5 MPa, with an inlet temperature of 295 °C and an outlet temperature of 328 °C, via two independent systems. The FW coolant flows in square counter-current channels while the BZ coolant flows in radial–toroidal Double Wall Tubes (DWT).

The main function of the WCLL BB PHTS is to extract thermal energy from the blanket and transfer it to the Power Conversion System (PCS) via the steam generators, as well as provide a containment boundary to the primary coolant. The WCLL BB PHTS is a water-cooled circuit operating at 15.5 MPa (BB inlet pressure) and 295 ÷ 328 °C. The preliminary sizing of the equipment is based on a reference thermal power of 1884 MW.

The latest design of the WCLL BB PHTS provides a single cooling system feeding FW and BZ cooling circuits in parallel. The system consists of two separate loops, connected by a pressuriser that performs the pressure control function for both. Each cooling loop embraces the entire tokamak, thus allowing the even and odd segments to be fed alternately through different loops. Each cooling loop consists of two sub-sections arranged in series and each of them feeds the BB segments belonging to half a tokamak. A single sub-section consists of a pump, a cold leg, a cold ring header, 32 cold feeding manifolds, 32 hot feeding manifolds, a hot ring header, a hot leg, a steam generator and a cross-over leg.

The inlet/outlet ring headers have a variable diameter to minimise inventory. There are reductions every 2 sectors.

Feeding pipes are routed to each blanket segment from the ring headers through the ports to feed the in-vessel cooling circuits. For each BB sector 8 inlet and 8 outlet feeding pipes are routed from the headers through the bioshield into the port to feed separately the FW and BZ circuits of both IB and OB segments. Specifically, the FW cooling circuits of the IB segments are fed by 2 inlet and 2 outlet feeding manifolds while the BZ cooling circuits are fed by other 2 couples of inlet/outlet feeding manifolds. Similarly, 2 couples of inlet/outlet feeding manifolds feed the FW cooling circuits of the OB segments while other 2 couples feed the BZ cooling circuits. The cooling circuits of the lateral OB segments are fed in parallel by feeding manifolds which split inside the upper port.

The cold feeding pipes are equipped with globe valves that allow the flow rates between the different blanket segments to be balanced, while the hot feeding pipes are equipped with gate valves that, in conjunction with the former, allow the blanket segments to be isolated for maintenance operations.

As far as the steam generator is concerned, the technology that is currently being studied is the Once-Through Steam Generator (OTSG) typically used in Babcock&Wilcox nuclear fission plants.

The two surge lines can be equipped with safety isolation valves to isolate the intact circuit from the faulty one in the event of a loss of coolant (LOCA).

It should also be added that the design considered for the purposes of this paper envisages the use of different diameters for the ex-vacuum section of the feeding pipes among blanket segments of the same type belonging to different sectors. This should facilitate the balancing of flow rates, reducing the use of globe valves and at the same time containing total pressure drops. Fig. 2 shows the latest design of the WCLL BB PHTS while Table 1 reports its main design data.

3. Model setup

Since the WCLL BB PHTS consists of two identical circuits that share only the pressuriser, attention was first focused on the modelling of

Table 1
WCLL BB PHTS design data.

Total thermal power [MW]	1884
Total pumping power [MW]	26
BB inlet/outlet temperature [°C]	295/328
Loop mass flow rate [kg/s]	2438
Total water volume [m^3]	629
Total piping length [m]	9734
Cooling loops [–]	2

the single cooling circuit and the simulation of its thermal-hydraulic behaviour under hypothetical steady-state conditions similar to those expected during the pulse period of the DEMO duty cycle. Based on the requirements of the TRACE system code, emphasis was placed on the development of a realistic finite-volume model that could capture all the main thermal-hydraulic features that characterise both in-vessel and ex-vessel components. Actually, the computational model consists of four main sub-models:

- the geometrical sub-model, reproducing in a quasi-2D approximation the layout of the cooling circuit;
- the constitutive sub-model, provided by the system code to describe the thermo-dynamic behaviour of the water circulating inside the cooling system;
- the hydraulic sub-model, intended to simulate the fluid flow along the cooling system;
- the thermal sub-model articulated in different sub-patterns aimed at realistically reproducing the heat transfer phenomena that take place along the cooling system.

Each one of the TRACE sub-models of the WCLL BB PHTS will be described in detail in this paragraph.

3.1. Geometrical sub-model

A quasi-2D geometric model was created that realistically simulates the flow domain of the cooling circuit studied. Discretisation of the flow domain was carried out in such a way as to preserve the volume of each component, so that the overall amount of coolant could be accurately modelled. Furthermore, the sub-volumes were correctly oriented in space to reproduce their relative positions and heights. Thus, both distributed pressure drops and gravitational effects were accurately modelled, at least with regard to the geometric parameters involved in their evaluation. In addition, the nodalisation of the model was developed to realistically predict the overall thermal-hydraulic behaviour of the selected loop, while requiring reasonable calculation times.

Figs. 3 and 4 show the nodalization of the half-loop cold section and of the half-loop hot section, respectively. The half-loop cold section includes the cold leg with the cold half-ring header and the cold feeding pipes as well as the main coolant pump and the loop seal (see Fig. 4) while half-loop hot section comprehends the hot feeding pipes, the hot leg with the hot half-ring header, and the OTSG. The feeding pipes connects the blanket segments with the ring headers. Each COB and LIB/RIB segment is fed by a dedicated manifold while the lateral outboard blanket segments share a single manifold that splits inside the upper port. In order to allow the proper mass flow rate flowing within each blanket segment, the first section of both cold and hot feeding pipes (i.e. from the ring header up to the vacuum boundary) varies among sectors for the same segment typology and, in addition, each cold feeding pipe is equipped with a globe valve. On the other hand, hot feeding pipes are equipped with gate valves which, in combination with the valves in the cold feeding manifolds, allow isolating the blanket segments during maintenance operations.

Figs. 5 and 6 show the detailed views of the nodalisation of the inboard and outboard blanket segments, respectively. In this regard, it is worth noting that the FW cooling circuit of each blanket segment was modelled using three pipe components representing the inlet manifold, the FW channels and the outlet manifold, while the BZ cooling circuit of each blanket segment was modelled using three pipe components representing the inlet manifold, the front BZ channels, the intermediate manifold, the back BZ channels and the outlet manifold. In addition, the two lateral outboard blanket segments (i.e. the LOB and the ROB segments) are simulated by a single equivalent blanket segment, as they are identical and are fed in parallel by a single feeding manifold, as already mentioned.

As far as the steam generator is concerned, the technology selected for the WCLL BB PHTS is that of the OTSG typically adopted in Babcock&Wilcox nuclear fission plants, as previously mentioned. Its thermal-hydraulic parameters and the design data used as input for the model were previously estimated analytically on the basis of the primary and secondary fluid conditions, and a large part of the characteristic dimensions were derived by scaling up the available data from existing plants and attempting to preserve the heat transfer characteristics of the original OTSGs. Finite-volume modelling of the OTSG was carried out in order to capture the main heat transfer phenomena while ensuring reasonable calculation times. Fig. 7 shows the detail of the TRACE model of one of the OTSGs of the WCLL BB PHTS. In particular, it can be seen that the tube side of the steam generator, where the primary fluid flows from top to bottom, was simulated by a single pipe component. As for the shell side where the secondary fluid flows, it was simulated by three pipe components representative of the feedwater downcomer, the heat transfer section, where boiling and superheating of the secondary fluid takes place, and the steam downcomer, respectively. The PCS model was limited to the secondary side of the OTSGs. The upstream and downstream equipment were simulated by means of a fill and a break component, respectively, to reproduce the feedwater versus load regulation manoeuvres envisaged by the PCS designers.

3.2. Constitutive sub-model

The constitutive models provided by the TRACE system code were adopted to describe the thermodynamic behaviour of water circulating within the cooling system of the WCLL BB PHTS [9]. The model is based on appropriate libraries describing the dependence of thermophysical properties of water on pressure and temperature.

In addition, different materials were considered to realistically model the thermal behaviour of various ex-vessel and in-vessel structural components. As for BB segments, the thermophysical properties of tungsten [11], Eurofer [12], and lead-lithium [13] were implemented in the code as a function of temperature. In this regard, it is worth noting that lead-lithium was conservatively treated as still assuming that it exchanges almost exclusively by conduction. As for the once-through steam generators, only the tube bundle structures were simulated, and the material defined was Inconel 690, whose thermophysical properties were recovered from [14].

3.3. Hydraulic sub-model

The hydraulic model was set up to correctly simulate the single-phase and/or two-phase flow of water within the investigated cooling circuit. The concentrated and distributed hydraulic resistances occurring within the flow domain were modelled by considering their possible functional dependence on the flow velocity field. In particular, the concentrated hydraulic resistances were modelled by the well-known equation $\Delta p = K\rho\frac{v^2}{2}$, which relates the total pressure drop (Δp) to the flow velocity (v) through the concentrated loss factor (K).

With regard to the different blanket segments, since the characteristic curves giving the functional dependence of the pressure drop on the mass flow rate (G) under steady-state conditions were not available for each of them, the pressure drop value available at the nominal

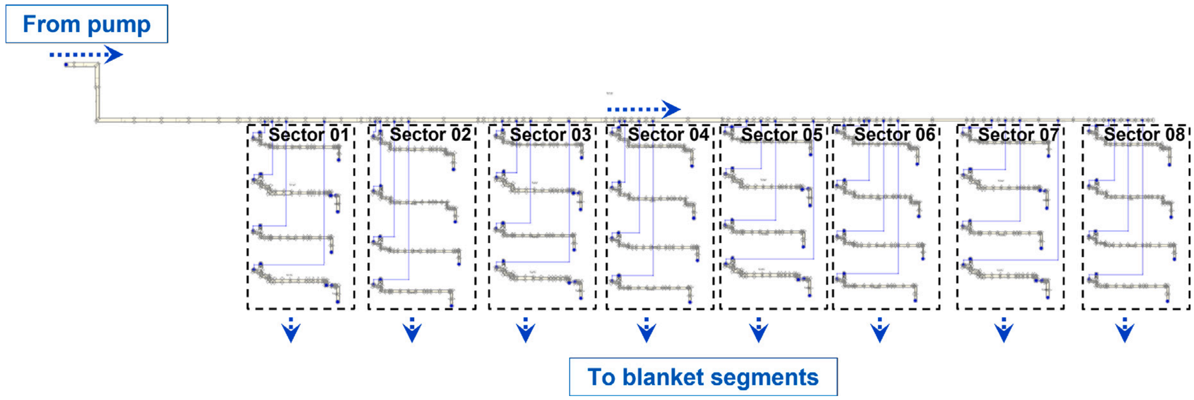

Fig. 3. TRACE model of the half-loop cold section.

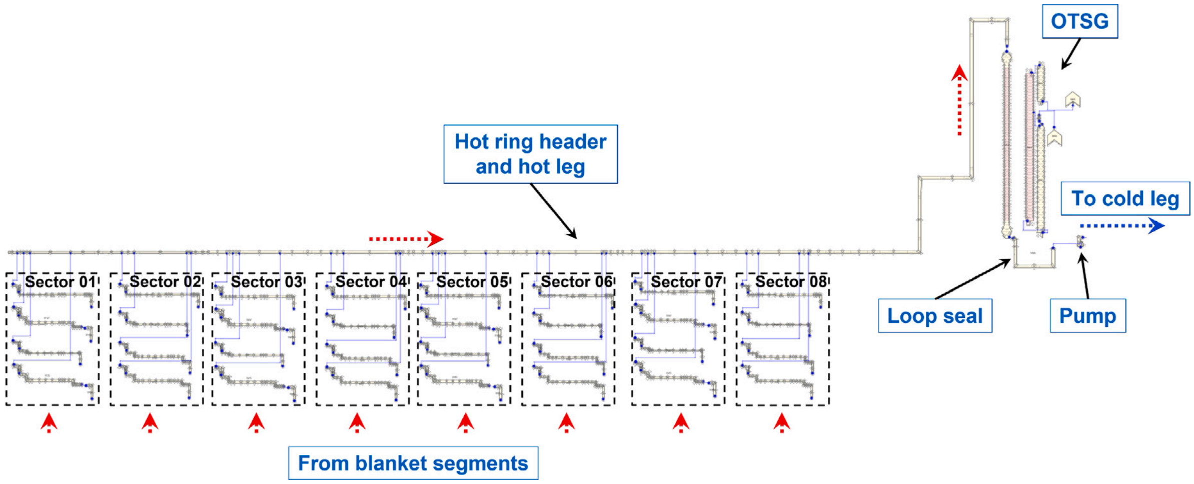

Fig. 4. TRACE model of the half-loop hot section.

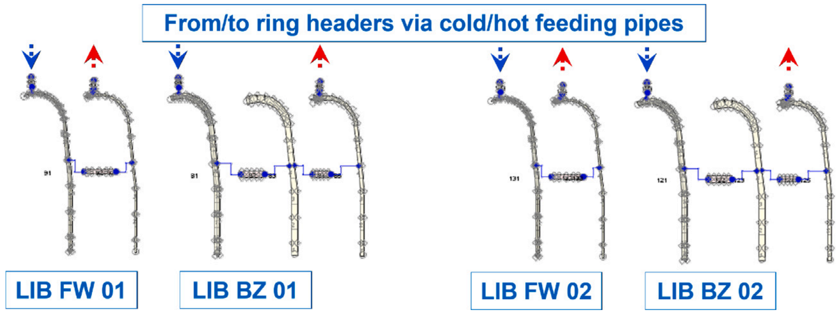

Fig. 5. TRACE model of the inboard blanket segments.

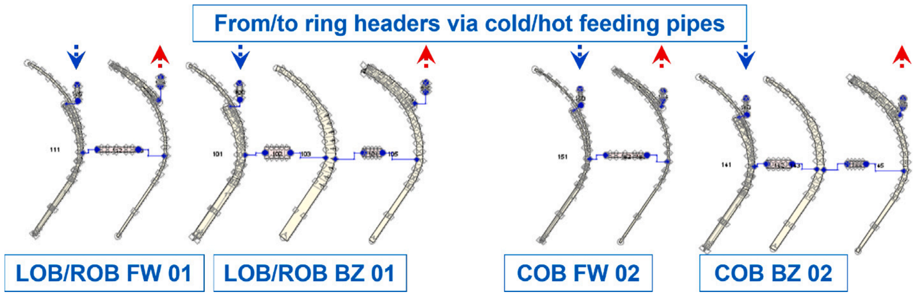

Fig. 6. TRACE model of the outboard blanket segments.

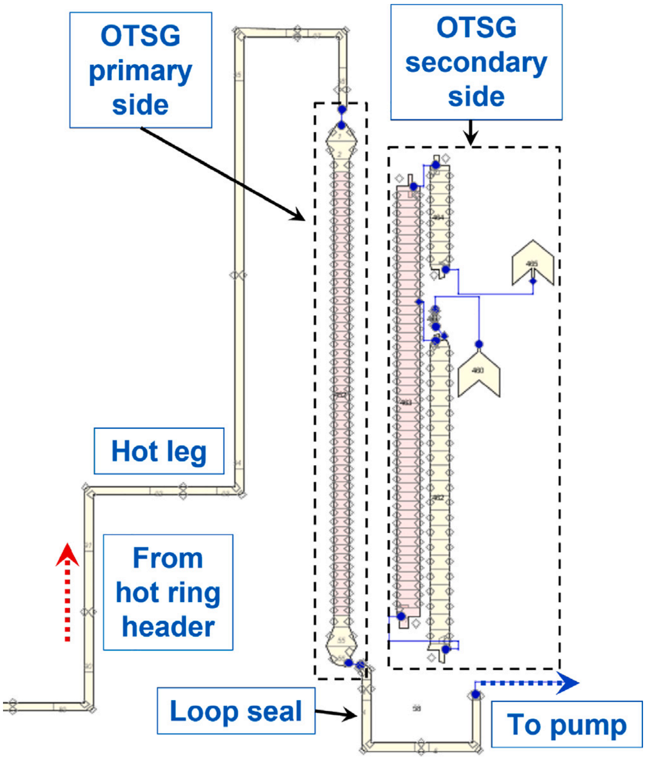

Fig. 7. TRACE model of the OTSG.

mass flow rate for the central outboard segment [15] was taken into consideration and it was assumed that this value would be the same for the other segments at the respective nominal operating conditions. Thereafter, an equivalent hydraulic loss coefficient was calculated for each segment assuming that the pressure drop could be considered proportional to the square of the mass flow rate ($\Delta p \propto G^2$).

On the other hand, for ex-vessel PHTS, the relevant concentrated hydraulic loss coefficients were derived from the well-known Idelchik handbook [16], based on the specific geometrical configurations and flow conditions. In this context, it should be noted that since the concentrated hydraulic resistances depend on the spatial distribution of the flow velocity field, the coolant flow distribution expected under normal operating conditions within the WCLL BB PHTS was assumed. In addition, in order to ensure the required mass flow rate in each segment, the opening degree of the globe valves located on the cold feeding pipes was analytically calculated in advance. This would allow, together with the use of variable diameters for the first section of the feeding manifolds, a proper balancing of the coolant pressure drop. This preliminary analytical assessment was made in accordance with previously adopted procedures [17]. The actual distribution of flow rates among the different blanket segments and the comparison with preliminary design calculations may allow a first assessment of the model's ability to predict the behaviour of the WCLL BB PHTS at least under steady-state conditions.

With regard to the pump component, since a detailed design of the main coolant pump of the WCLL BB PHTS is not yet available, the Westinghouse characteristic curves already implemented in the TRACE code were preliminarily adopted while the main design parameters were estimated in a similar manner as reported in [17].

Finally, the hydraulic wall roughness, in terms of equivalent sand roughness, was assumed to be $\approx 18\ \mu\text{m}$ based on what is typically stated for nuclear fission power plants [18].

3.4. Thermal sub-model

In order to accurately model the heat transfer phenomena occurring within the WCLL BB PHTS, the solid domain discretisation was performed by saving the volumes and heat transfer areas of each structural component, where practicable, and adopting appropriately selected heat transfer models when necessary.

Particular attention was paid to modelling the solid domain of the blanket segments. As mentioned above, it was assumed that lead-lithium exchanges heat almost exclusively by conduction and was simulated as a solid structural component by means of thermal structures. Specifically, the solid structures of each BB segment and the region containing the breeder were simulated by means of three different thermal structure components, two of which are slab-type and one cylindrical. A slab-type thermal structure component relates to the plasma-facing region comprising the tungsten and Eurofer layers, a cylindrical thermal structure component simulates the region between FW and BZ through which the FW and BW channels exchange thermal power and comprises Eurofer parts and lead-lithium regions, while the other slab-type thermal structure component is intended to reproduce the region behind the BZ channels, which is also composed of Eurofer layers and lead-lithium layers.

The plasma-facing thermal structures of each blanket segment were modelled considering a 2 mm thick tungsten layer, while the thickness of the Eurofer layer was assumed to be equal to the distance between the tungsten layer and the plasma-facing channels according to the latest BB design, i.e. 3 mm. The surface area of the thermal structure was calculated simply as the ratio between the volume of the tungsten layer and its thickness from the data given in [19]. With regard to the thermal structure connecting FW and BZ, the equivalent thicknesses of the various solid layers as well as the inner and outer radius of the cylindrical structure were adjusted in order to correctly predict the thermal power exchanged between the refrigeration circuit of the FW and that of the BZ at least under steady-state operating conditions, while at the same time respecting the volume of the solid structures and, thus, their thermal inertia. Finally, the structure behind the channels of the BZ was defined on the basis of equivalent thicknesses and surfaces that would allow the effective volume of the solid structures to be preserved in order to realistically simulate the effect of the thermal inertia of this part of the solid structure on the behaviour of the entire circuit under transient conditions.

With regard to the adopted thermal loads, the power distribution between FW and BZ and, within the former, between surface and volumetric thermal loads envisaged by the most recent DEMO energy map was taken into account. The surface loads on the FW plasma facing surface were then allocated between the different blanket segments on the basis of their surface area, while the volumetric loads were distributed on the basis of their volume. Within each segment then, the volumetric heat power deposited in each region was calculated assuming the distribution reported in [10].

As far as the thermal model of the OTSG is concerned, the heating section of the tube bank is countercurrently connected to the heated section of the fluid flowing through the secondary side of the steam generator via a single cylindrical Inconel 690 thermal structure. In addition, in order to include the effect of localised thermal resistance on the pipe walls, a thin layer of a fake material was introduced into the model to simulate the fouling layer. Specifically, the thermal resistance given by the equivalent fouling layer is $8.8\text{e}{-6}\ \text{m}^2\ \text{K/W}$.

In addition, the contribution of frictional heating of the pump was also considered. The pump model provided by the TRACE system code can take into account the energy deposited in the fluid through irreversible frictional losses in the pump impeller by adding source terms to the liquid and vapour energy equations [9]. It should be noted that for any flow pumped within a closed circuit, in general, the work done on the fluid by the pump will appear as a source of energy in the form of frictional losses, causing an increase in fluid enthalpy.

Table 2
Steady-state conditions.

	Design	Numerical	ϵ [%]
W_{Loop} [MW]	954	940	−1.5%
G_{Loop} [kg/s]	2439	2439	0.0%
Δp_{Loop} [MPa]	1.47	1.62	10.4%
T^{Cold}_{Loop} [°C]	295.0	295.0	0.0%
T^{Hot}_{Loop} [°C]	328.0	327.4	−0.2%
G_{FW} [kg/s]	250	250	0.0%
T^{Cold}_{FW} [°C]	229.1	229.1	0.0%
T^{Hot}_{FW} [°C]	300.5	299.5	−0.3%
p_{Steam} [MPa]	6.38	6.38	0.0%

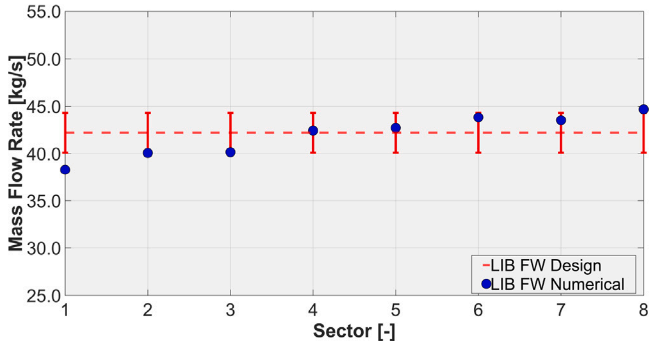

Fig. 8. Mass flow rate distribution among LIB FW cooling circuits.

This aspect is not currently simulated in TRACE. This contribution has been introduced directly into the pump model (described briefly in Section 3.3) via a fluid power component connected to a control system that multiplies the pump friction torque and pump speed by the pump efficiency.

4. Preliminary steady-state analyses

In order to verify the effectiveness of the developed model in predicting the behaviour of the WCLL BB PHTS, and more generally to assess the predictive potential of the code in fusion applications, preliminary analyses were conducted under hypothetical steady-state conditions corresponding to those that would occur during the pulse period of the DEMO operating cycle.

In this regard, the focus was on evaluating the spatial distribution of the coolant mass flow rates between the various blanket segments and the associated pressure drops. Selected results are reported in Table 2 and Figs. 8 to 15.

In particular, Table 2 shows a summary of the main thermal-hydraulic parameters under steady-state conditions, compared with analytical calculations performed following the same approach adopted in [17]. Figs. 8 to 11 show the distribution of the coolant Mass Flow Rate (MFR) among the inboard and the central outboard segments for both FW and BZ cooling circuits, compared to the nominal MFR with 5% error bars. Furthermore, Figs. 12 to 15 report the pressure distributions along the cooling paths for the same segments. In this regard, it should be emphasised that the inlet pressure at the blanket segments varies slightly among the sectors and among the different segment types, and that the value of 15.5 MPa is rather to be regarded as the minimum pressure value required to be ensured at the inlet section of each segment.

From the analysis of the results, it can be stated that the main thermal-hydraulic parameters calculated by the TRACE code are very close to the analytical results (see Table 2) except for the total pressure drop, which is approximately 10% higher than the value calculated

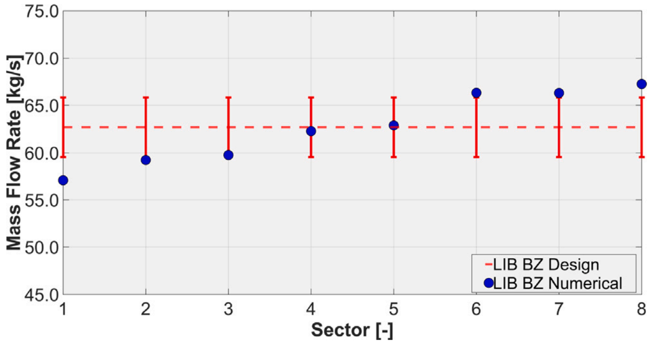

Fig. 9. Mass flow rate distribution among LIB BZ cooling circuits.

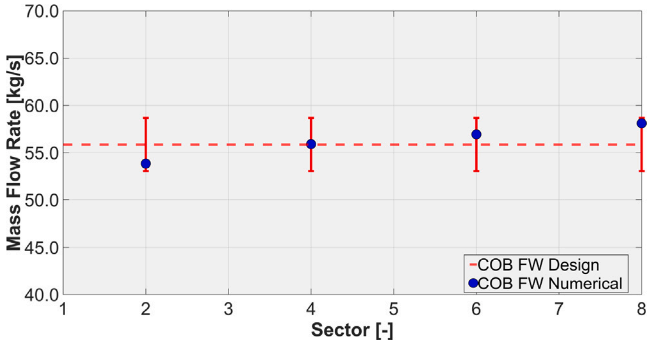

Fig. 10. Mass flow rate distribution among COB FW cooling circuits.

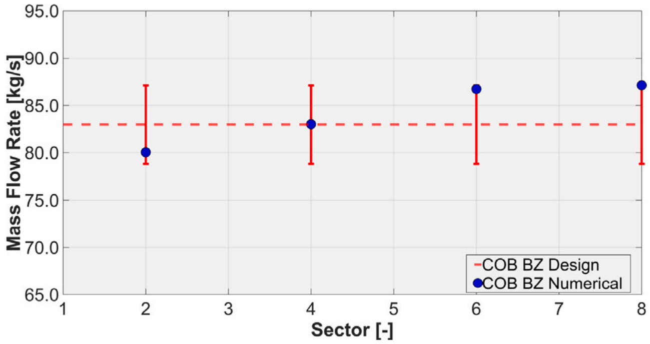

Fig. 11. Mass flow rate distribution among COB BZ cooling circuits.

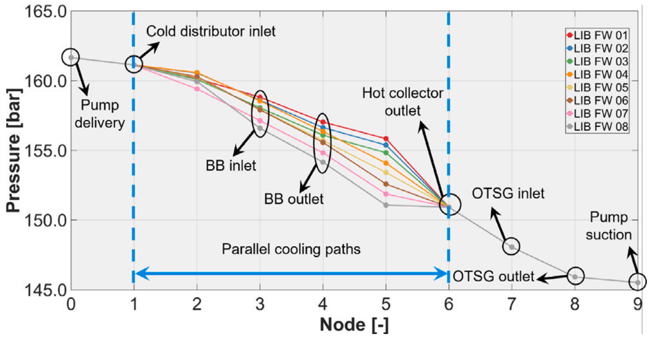

Fig. 12. Pressure distribution within LIB FW cooling circuits.

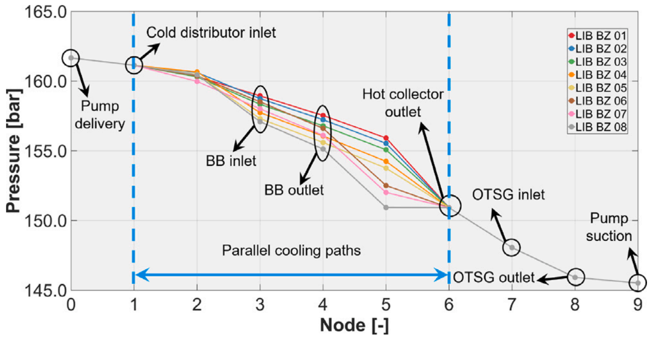

Fig. 13. Pressure distribution within LIB BZ cooling circuits.

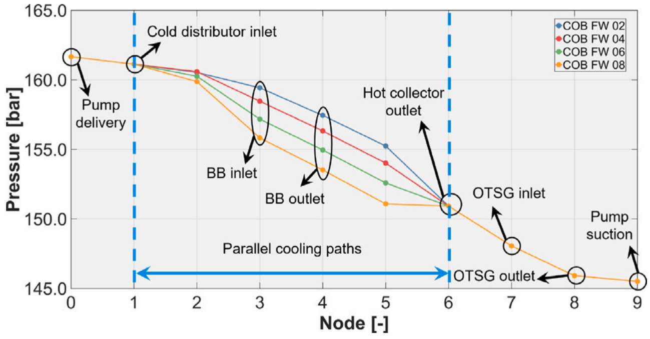

Fig. 14. Pressure distribution within COB FW cooling circuits.

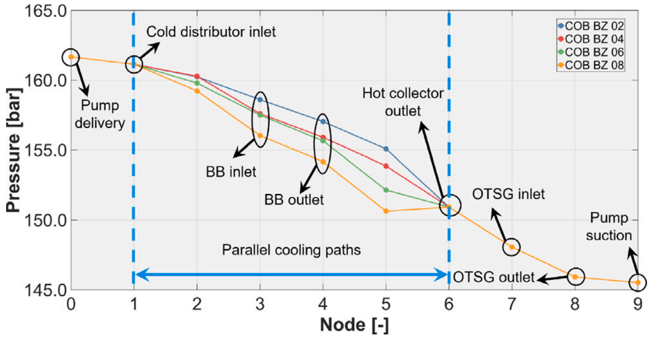

Fig. 15. Pressure distribution within COB BZ cooling circuits.

analytically in the design phase, suggesting that the model could be further optimised.

This is confirmed by the distribution of the mass flow rate between the different blanket segments. In fact, Figs. 8 to 11 show that, although the deviations predicted with respect to the target MFRs are mostly less than 5%, some branches exhibit a MFR that departs more from its nominal value reaching a maximum deviation of ≈9%.

On the other hand, Figs. 12 to 15 support what was observed previously during the design phase, i.e. that the value of the expected overall pressure loss of ≈1.6 MPa is strongly influenced by the pressure loss in the ring headers. For this reason, the geometry of the ring headers is still being optimised precisely in order to reduce the pressure drop and even out the distribution of flow rates between the different blanket segments, thus reducing the need for the use of orifices or other throttling devices.

5. Conclusions and follow-up

As part of the activities promoted by the EUROfusion consortium, the University of Palermo developed a finite volume model of the WCLL BB PHTS. The work has been carried out following a theoretical–computational approach based on the adoption of the TRACE thermal-hydraulic system code.

Particular attention has been paid to capturing all the main geometric, hydraulic and heat transfer characteristics that characterise both in-vessel and ex-vessel components through the development of the various sub-modules of which the model under examination is composed and which are extensively described in the manuscript. Preliminary analyses were also carried out under steady-state operating conditions to verify the correct behaviour of the model and assess the code's predictive potential in fusion reactor applications.

The results showed that, in general, the main thermal-hydraulic parameters calculated by the TRACE code closely match the analytical results, with the exception of the total pressure drop, which is about 10% higher than the value calculated analytically at the design stage. The mass flow distribution between the different blanket segments predicted by the TRACE code shows estimated deviations from the target MFRs mostly below 5%. Nevertheless, the presence of some branches whose MFR deviates more from its target value suggests that there is still room for further improvement of the model. On the other hand, the results confirm what was previously observed during the design phase, i.e. that the value of the predicted overall pressure loss is strongly influenced by the pressure loss in the ring headers. For this reason, the geometry of the ring headers is still being optimised precisely to reduce the pressure loss and ease the balancing of flow rates among the individual blanket segments, thus reducing the need for the use of any throttling devices.

While there is still room for improvement, the scientific work described here has shown that the TRACE model is capable of capturing the main thermal-hydraulic phenomena that characterise the cooling system of the breeding blanket. The model developed will make it possible to evaluate the performance of the WCLL BB PHTS during the main operational and accidental transients, verifying the effectiveness of the design solutions adopted.

By way of conclusion, it is worth emphasising that the design of the BB in a tokamak also depends on other aspects in addition to the thermal-hydraulic one, so studies are underway with the aim of converging towards a design solution that meets all the criteria and requirements imposed by plasma physics and engineering.

CRediT authorship contribution statement

E. Vallone: Conceptualization, Methodology, Investigation, Writing – original draft. **G. Bongiovì:** Conceptualization, Methodology, Investigation, Writing – original draft. **P.A. Di Maio:** Conceptualization, Methodology, Investigation, Writing – original draft. **I. Moscato:** Conceptualization, Methodology, Investigation, Writing – original draft. **A. Quartararo:** Conceptualization, Methodology, Investigation, Writing – original draft. **S. Vacca:** Conceptualization, Methodology, Investigation, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request

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