Preliminary thermal-hydraulic analysis of the EU-DEMO Helium-Cooled Pebble Bed fusion reactor by using the RELAP5-3D system code

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In the frame of the activities promoted and encouraged by the EUROfusion Consortium aimed at developing the EU-DEMO fusion reactor, strong emphasis has been posed to incorporate the needed provisions to improve the overall plant safety and reliability performances as well as to analyse possible mitigation actions.

In this framework, the research activity has been focused on the representative and safety relevant cooling loop of the Helium Cooled Pebble Bed (HCPB) Breeding Blanket (BB) Primary Heat Transfer System (PHTS), purposely selected by the safety team, in order to assess its thermal-hydraulic behaviour during normal operational conditions (ramp up/down and steady state) and to preliminarily investigate the consequences of an ex-vessel LOCA accidental scenario ensuing a double-ended guillotine (DEG) break in the hot leg.

The research activity has been carried out following a theoretical-computational approach based on the finite volume method adopting the RELAP5-3D system code along with the ANSYS CFX computational fluid dynamic code, which were properly integrated to achieve a more detailed and realistic simulation of the EU-DEMO reactor thermal-hydraulics.

Models, assumptions and outcomes of this preliminary study are herein presented and critically discussed.

Keywords: EU-DEMO, HCPB, RELAP5-3D, Thermal-hydraulics, Safety and Environment

1. Introduction

In the framework of the current pre-conceptual design stage of the EU-DEMO reactor [1], to fulfil its potential features in terms of low accident hazard and good operational safety, it has to be considered as pivotal to incorporate the needed provisions to improve the overall plant safety and reliability performances as well as to analyse possible mitigation actions [2], [3]. To this purpose, within the framework of EUROfusion Safety and Environment actions, an intense research campaign has been launched in order to develop a model, at thermal-hydraulic system code level, for the EU-DEMO HCPB BB concept, aimed at characterizing its response both under normal operational conditions and during accidental scenarios.

This paper describes the research activity has been carried out to develop a computational model of the representative and safety relevant cooling loop (i.e. that with the larger helium inventory) for the HCPB BB PHTS, aimed at assessing, first and foremost, its thermal-hydraulic behaviour during the normal operational conditions, considering the ramp-up/down when switching from pulse to dwell and vice versa. In addition, to test the robustness and the capabilities of the model, it has been preliminarily investigate an ex-vessel LOCA scenario in which a DEG break occurs in the hot leg, studying mainly the pressurization of the containment system.

The analyses has been carried out following a theoretical-computational approach based on the finite volume method adopting the RELAP5-3D system code properly integrated with the ANSYS CFX computational fluid dynamic code to realistic simulate the thermal-hydraulic behaviour of the investigated system.

The main results show a good prediction capability of model in simulating the overall thermal-hydraulics and the main phenomena occurring in the system suggesting the possibility to extend the thermal-hydraulic analyses to the some of the scenarios following the Postulated Initiating Events (PIEs) already identified for the EU-DEMO HCPB reactor [4].

2. HCPB BB design reference

The current HCPB reference design is based on the single module segment concept of the tokamak machine which is subdivided in 16 sectors each of which contains a Left, Central and Right Outboard segment (LOB, COB and ROB, respectively) and a Left and Right Inboard segment (LIB and RIB, respectively). These segments are, in their turn, splitted in two main sub-components, namely the First Wall (FW) and the Breeding Zone (BZ). The first one has to withstand the plasma heat radiation and the additional heat loads due to colliding particles and consisting in a 20 mm thick U-shaped plate covered by a 2 mm thick of sacrificial tungsten. In order to enhance the heat transfer capability of such component, the use of turbulence promoters or a properly increased surface roughness has been foreseen [5]. Whilst, the BZ contains an advanced ceramic breeder (KALOS) used to produce tritium and fixed in the so-called fuel-breeder pins arrangement. A pin consists in two concentric tubes forming the inner and outer cladding (with an external diameter of 28 and 64 mm, respectively) within which the breeder pebble bed is located, see Fig. 1. The pins are inserted inside pressure tubes (with an external diameter of 78 mm) that joins the FW with the BZ backplate and which act as structural elements to resist against pressurization in case of some LOCA scenarios. According to this arrangement, the neutron multiplier

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($Be_{12}Ti$) is placed outside the pressure tube containing the pins in form of hexagonal prismatic blocks [6].

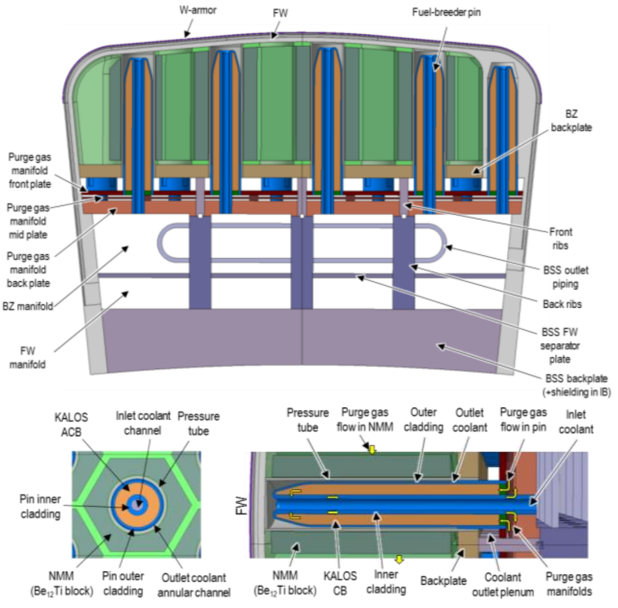

Fig. 1: Reference HCPB BB design for the EU-DEMO [7].

The coolant flow scheme of the HCPB BB is shown in Fig. 2; both the FW and BZ regions are cooled by helium an operating pressure of 8 MPa with an inlet temperature of 573.15 K.

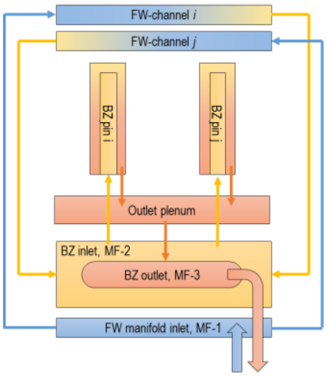

Fig. 2: Schematic flow scheme of the HCPB EU-DEMO [7].

3. HCPB BB-PHTS design reference

The current BB-PHTS architecture relies on the adoption of 8 homogeneous and completely independent cooling loops from both mechanical and functional point of view in order to limit some common mode failures. The general layout of the BB-PHTS is shown in Fig. 3.

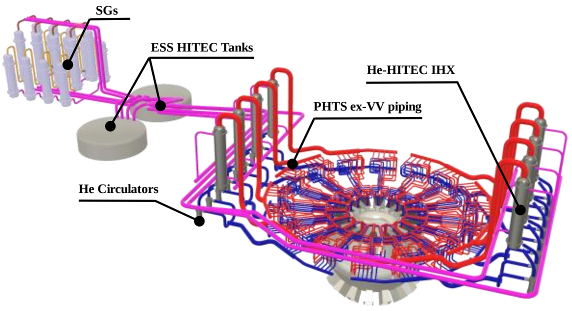

Fig. 3: A 3D view of the HCPB BB PHTS cooling loops.

Each loop, feeding both IB and OB segments of 2 sectors, is equipped with a helium-molten salt Intermediate Heat Exchanger (IHX) and 2 helium circulators [8]. The main data of the HCPB BB PHTS and the IHX are reported in Tab. 1 and Tab. 2, respectively.

Table 1. HCPB BB PHTS main data [9].

Parameter	Value	Unit
Thermal power	2029.1	[MW]
Circulator electrical power	92.3	[MW]
Coolant volume	2031.9	[m^3]
Total piping length	6838.4	[m]
Total pressure drop	2.7	[bar]

Table 2. IHXs main data [9].

Parameter	Value	Unit
Thermal Power	264.10	[MW]
T_{in}/T_{out} helium	793.15/564.05	[K]
T_{in}/T_{out} HITEC	543.15/738.15	[K]
Tubes active length	13.70	[m]
Tube number	9812	[-]
Tube d_{ext}	15.875	[mm]
Tube thickness	1.245	[mm]
Helium pressure drop	60.70	[kPa]
Helium volume	30.20	[m^3]

4. RELAP5-3D computational model

A computational model of the HCPB safety relevant cooling loop has been developed for the RELAP5-3D system code in order to support the design activities assessing the normal operational conditions and to improve its reliability during accidental scenarios.

The model nodalization has been developed to realistically predict the overall thermal-hydraulic behaviour of the selected loop demanding admissible computing time. Indeed, it reproduces accurately the current design of the system reported in [7] and [9] by using 211 thermal-hydraulic components, being 110 PIPEs, 4 MULTIPLE JUNCTIONs, 90 SINGLE JUNCTIONs, 2 SINGLE VOLUMEs, 1 COMPRESSOR, 2 TIME DEPENDENT VOLUMEs, 2 TIME DEPENDENT JUNCTIONs and 93 HEAT STRUCTUREs. In addition, 1031 CONTROL BLOCKs, 167 SIGNAL VARIABLEs and 125 TABLEs complete the model. Fig. 4 shows the nodalization scheme adopted for the cold (a) and hot (b) legs and that adopted to simulate each of the segments (c) related to the analysed loop along with their CAD geometrical model.

In point of fact, the computational model consists of four main sub-models: (i) *the flow domain model*, reproducing in a quasi-2D approximation the lay-out of the cooling circuit; (ii) *the constitutive models*, provided by the system code to describe the thermo-dynamic behaviour of the helium circulating inside the cooling system; (iii) *the hydraulic model*, intended to simulate the fluid flow along the cooling system and the (iv) *thermal model* articulated in different sub-patterns aimed at realistically reproduce the heat transfer phenomena which take place along the cooling system.

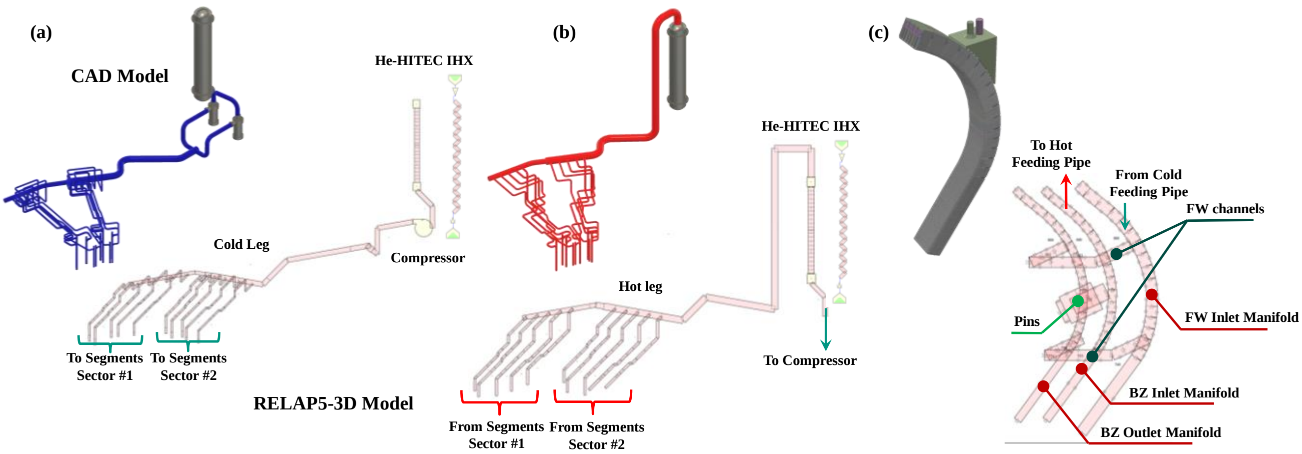

Fig. 4: RELAP5-3D nodalization for cold leg (a), hot leg (b) and each segment (c) of the selected HCPB BB PHTS cooling loop.

4.1. The hydraulic sub-model

In order to better reproduce the hydraulic performance of the analysed system, it has been developed a specific procedure to integrate the RELAP5-3D system code aptitude to synthetically simulate the thermal-hydraulic performances of complex systems with the highly realistic predictive potential guaranteed by ANSYS CFX in the assessment of the fluid-dynamic behaviour of coolant flowing through deeply 3-D circuits.

In particular, with reference to the in-vessel components, a detailed parametric analysis has been performed for the COB segment aiming at assessing the hydraulic characteristic function of such components (namely pins, FW channels and the manifolds), giving the functional dependence of their total pressure drop on the corresponding mass flow rate under steady state conditions, that is $\Delta p = \alpha G^{\beta}$.

The aforementioned hydraulic characterization has been performed by adopting a simplified model of the whole segment based on the porous media approach which allows to reduce the computational domain and consequently the computing time [10], [11], see Fig. 5 and Fig. 6.

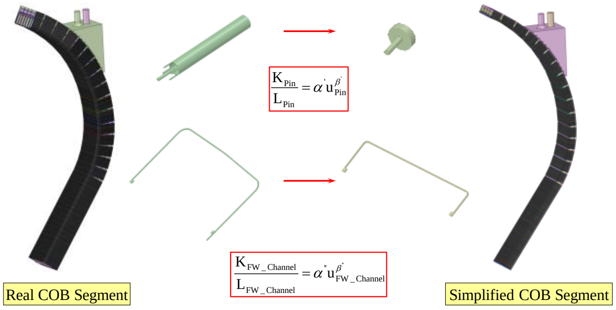

Fig. 5: Model simplification by means of the porous media approach.

Once derived, this function has been adopted to derive the dependence on mass flow rate of the effective concentrated hydraulic loss coefficient ($K = B\cdot Re^{-C}$) giving it in input to the system code in order to let it simulate realistically all the in-vessel components with a lumped parameter approach.

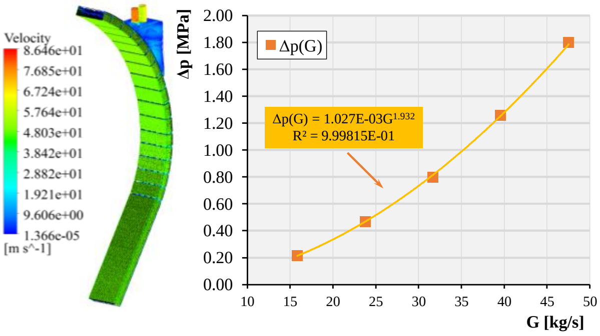

Fig. 6: Hydraulic Characteristic of the COB Segment.

4.2. The thermal sub-model

As concerns the thermal modelling, the heat transfer phenomena have been reproduced implementing the thermo-physical properties of all the structural materials involved [7], [9] and by adopting the properly selected heat transfer models, namely the largely adopted Gnielinski correlation, already implemented in the RELAP5-3D models package and the the Bell-Delaware procedure for evaluating the heat transfer coefficient on the shell side of the IHX, as has been done for its design [8]. For the latter, since it is not directly available into the system code, it has been implemented by using proper CONTROL FUNCTIONs which allow to evaluate the heat flux as boundary conditions for the HEAT STRUCTUREs simulating such component. Concerning the IHX and its model, since the solar molten salt HITEC has been foreseen as working fluid for the Intermediate Heat Transfer System of the HCPB EU-DEMO, a dedicated binary file has been generated to implement its thermo-physical properties into the code fluid libraries [12]. The model reproduces accurately the shell side of the heat exchanger, while the inlet and outlet boundary conditions have been simulated by adopting TIME DEPENDENT VOLUMEs and JUNCTIONs, see Fig. 4. Moreover, the thermal modelling approach here adopted has been assessed by performing a benchmark with the experimental data coming from the experiences conducted on the HETRA facility [12], [13].

4.3. Thermal power and transient loads

The thermal power adopted for simulating the normal operational scenario including the ramp-up /down takes into account both the FW heat flux and the nuclear heating as reported in [14], [15]; the latter is re-scaled to the required tritium breeder ratio [16]. Fig. 7 shows the thermal power profile for the homogenous loops.

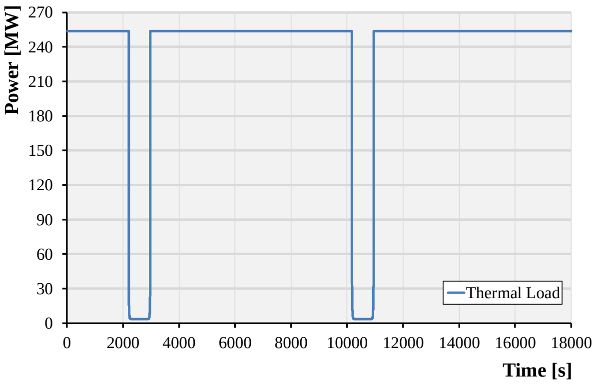

Fig. 7: Thermal power profile.

5. Normal operational conditions results

As concerns the simulation of the normal operational conditions, it has been mainly intended to preliminarily investigate the capability of the model to predict the thermal-hydraulic phenomena occurring into the system studying a possible strategy to control both the helium and HITEC mass flow rate in order to maintain the inlet temperature to the BB equal to 573.15 K as required in [16]. Firstly, in order to qualify the developed nodalization, the pressure drops calculated by the code have been compared to the theoretical ones, see Fig. 8.

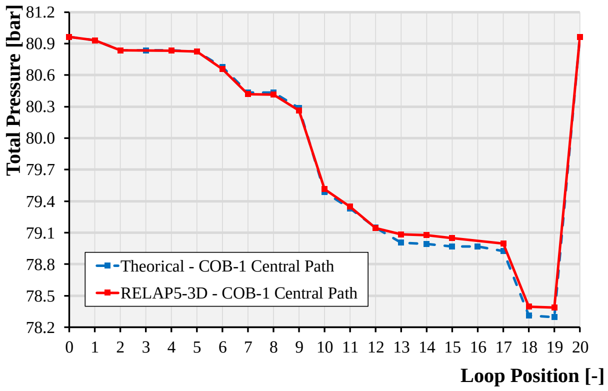

Fig. 8: Pressure drops along the COB-1 central path.

The results show a good accordance between theoretical values and the RELAP5-3D ones; in fact the total pressure drop predicted by the code is 2.58 bar with respect to the 2.67 bar theoretically evaluated (deviation of 3.41%).

A parametric study has been thereafter performed analysing the normal operational conditions. The main objective of this preliminary study has been to assess the dynamic response of the system when it switches from pulse to dwell and vice versa. In particular, 4 cases involving a combination of different mass flow rates on both helium and HITEC sides has been set-up with the aim of understanding the potential maximum variations that relevant quantities such as pressure and temperatures can experience for a given Balance of Plant control. The 4 identified cases are: (I) both the helium and the HITEC mass flow rate are kept constant at the nominal pulse value during the entire period; (II) the helium flow rate is the same that in (I), while the HITEC one follows the same functional shape of the BB thermal power; (III) consists in changing the helium mass flow rate according to the same functional shape of the BB thermal power, while the molten salt mass flow does not change; (IV) both the helium and the HITEC mass flow rates evolve like the power functional shape. Fig. 9 and Fig. 10 depict helium and HITEC mass flow rates, respectively.

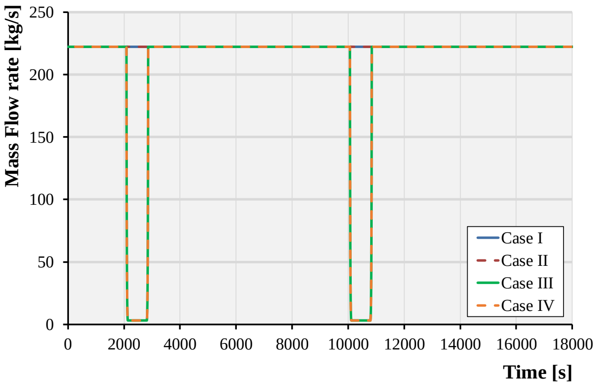

Fig. 9: Helium mass flow rate.

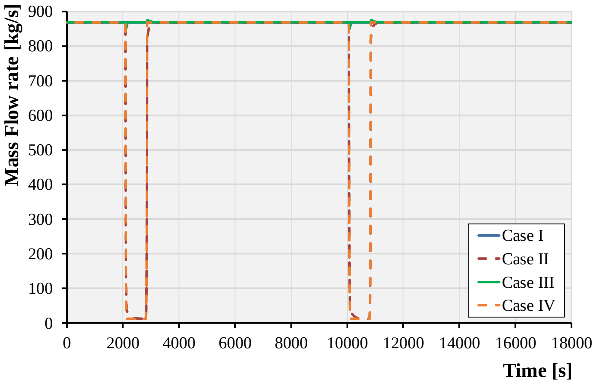

Fig. 10: HITEC mass flow rate

The trend of the temperatures in cold and hot legs is shown in Fig. 11 and Fig. 12, respectively; whilst in Fig. 13 the cold leg pressure is displayed.

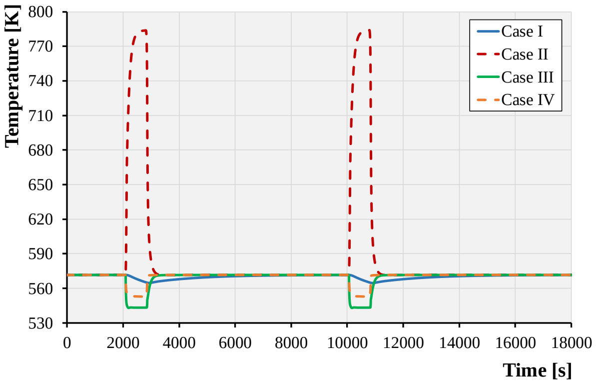

Fig. 11: Cold Leg temperature.

In both case (I) and (II), when the dwell starts, temperatures and/or pressure show high and fast changes. In particular the former presents too large increase of the pressure, while in the latter case the huge thermal-hydraulic variations affect the whole dwell phase as well as the following pulse period. Indeed, the system is able to recover the design values just before the beginning of the next dwell. This is due to the control of PHTS that, keeping the helium mass flow rate at its maximum value, extends the time needed to heat up again the BB structures. Case (III) and (IV) present less marked deviation of the relevant quantities thanks to the helium mass flow rate control which basically follows the BB thermal load profile. However, such regulation seems to be very challenging since it implies a quick and fast variation of the primary mass flow rate.

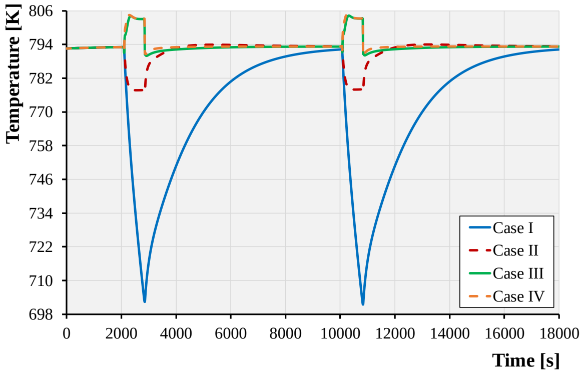

Fig. 12: Hot Leg temperature.

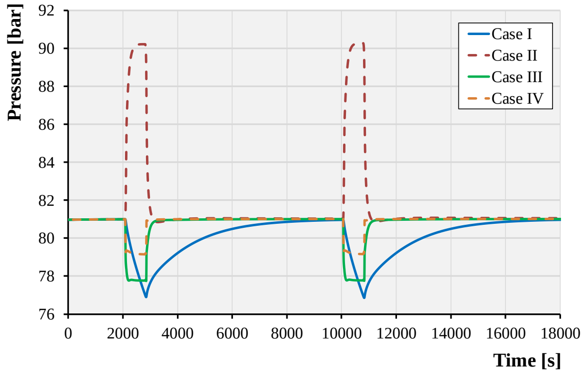

Fig. 13: Cold leg inlet pressure.

Starting from these outcomes, another case has been simulated in which the helium mass flow rate evolves assuming a viable rate of change of 12.5 % per minute, reaching the minimum value of 83.34 kg/s during the dwell, whilst the molten salt mass flow rate is evaluated by the system code with a dedicated proportional-integral controller aimed at maintain the required BB inlet temperature to 573.15 K, see Fig. 14.

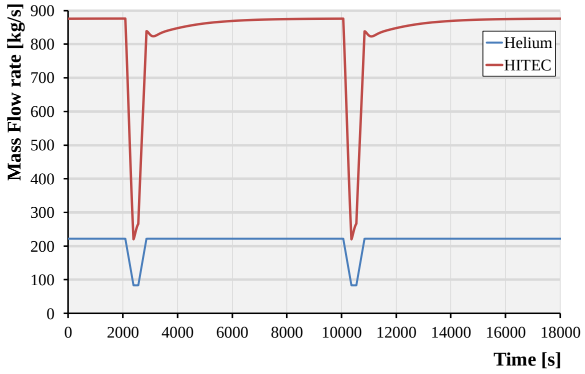

Fig. 14: Helium and HITEC mass flow rate.

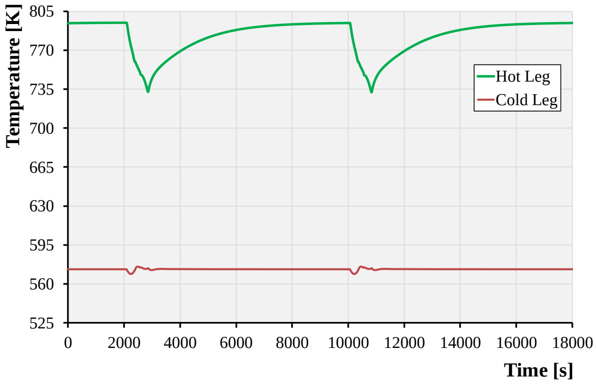

Fig. 15: Hot and cold leg temperature.

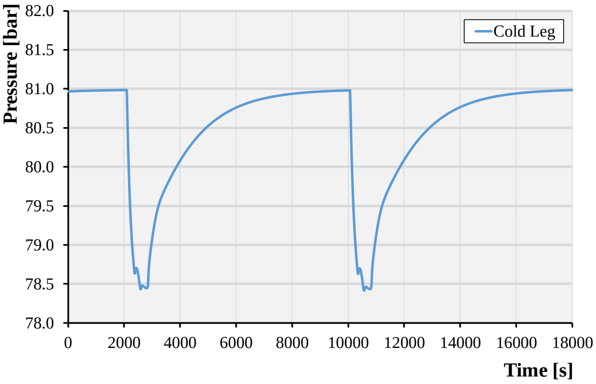

Fig. 16: Cold leg inlet pressure.

The new PHTS system control modelled for this case allows to reduce the main quantities excursion when switching between the two operational phases. Indeed, this can be observed for both the hot and cold temperatures depicted in Fig. 15 and the cold leg inlet pressure which is shown in Fig. 16.

However, further studies will be needed to better understand the feasibility of such PHTS control system mainly in terms of possible regime variation of the circulators and as well as in terms of acceptable thermal stresses for the components involved.

6. DEG-break in hot leg: preliminary results

In order to assess the robustness of the developed computational model, it has been investigated a DEG break occurring in that portion of the hot leg where the cross section is the greatest, namely 1.114 m^2.

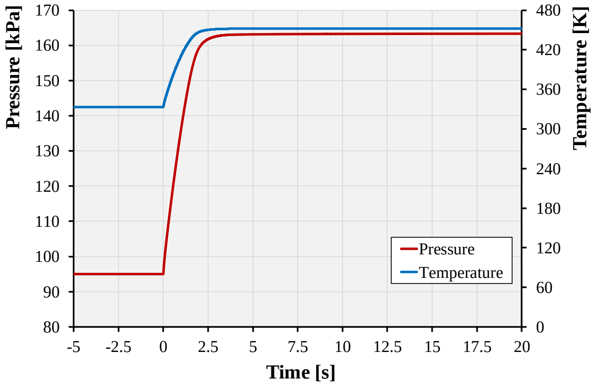

Fig. 17: Pressure and temperature evolution in the EV.

To simulate such an accidental scenario the model has been extended to include the tokamak cooling rooms, that is reported in [17] and from which it has been subtracted the equipment volumes, indeed the volume available is $1.18 \cdot 10^5$ m^3. The rooms have been modelled by using a SINGLE VOLUME component where the air temperature has been set to 333.15 K, while the initial pressure has been considered equal to 95 kPa.

The break has been simulated by using the VALVE component, which opens at time 0 s (starting from the end of the pulse conditions). Due to the large size of the rupture, the transient is extremely fast and after about 2.5 s from the break occurrence, the pressure reaches its maximum of 163 kPa, which is below the prescribed limit of 200 kPa. The equilibrium temperature inside the tokamak cooling rooms is about 450 K, see Fig 17.

It is worth to underline that this study has been focused on the first seconds following the break in order to make a preliminary assessment of the dynamic pressure loads on the civil structures. The long term transient behaviour will be investigated in a future work.

7. Conclusions

The research activity here presented concerns the development of a computational model of the representative and safety relevant cooling loop for the HCPB BB PHTS, which has been devoted to assess its thermal-hydraulic behaviour during the normal operational conditions, considering the ramp-up/down when switching from pulse to dwell and some different strategies to control the PHTS mass flow rates. Moreover, it has been preliminarily investigate an ex-vessel LOCA scenario in which a DEG break occurs in the hot leg, to test the robustness and the prediction capabilities of the model. The results obtained simulating the normal operational scenario are in good agreement with the design data and the model seems suitable to investigate both operational and accidental transients suggesting the possibility to extend the thermal-hydraulic analyses to further the some of the scenarios following the PIEs already identified for the EU-DEMO HCPB reactor.

Acknowledgments

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In this framework, the research activity has been focused on the representative and safety relevant cooling loop of the Helium Cooled Pebble Bed (HCPB) Breeding Blanket (BB) Primary Heat Transfer System (PHTS), purposely selected by the safety team, in order to assess its thermal-hydraulic behaviour during normal operational conditions (ramp up/down and steady state) and to preliminarily investigate the consequences of an ex-vessel LOCA accidental scenario ensuing a Double-Ended Guillotine (DEG) break in the hot leg.

The research activity has been carried out following a theoretical-computational approach based on the finite volume method adopting the RELAP5-3D system code along with the ANSYS CFX computational fluid dynamic code, which were implicitly integrated to achieve a more detailed and realistic simulation of the EU-DEMO reactor thermal-hydraulics.

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1. Introduction

In the framework of the current pre-conceptual design stage of the EU-DEMO reactor [1], to fulfil its potential features in terms of low accident hazard and good operational safety, it has to be considered as pivotal to incorporate the provisions needed to improve the overall plant safety and reliability performances as well as to analyse possible mitigation actions [2], [3]. To this purpose, within the framework of EUROfusion Safety and Environment actions, an intense research campaign has been launched in order to develop a model, at thermal-hydraulic system code level, for the EU-DEMO Helium Cooled Pebble Bed (HCPB) Breeding Blanket (BB) concept, aimed at characterizing its response both under normal operational conditions and during accidental scenarios, [4].

This paper describes the research activity performed to develop a computational model of the representative and safety relevant cooling loop for the HCPB BB Primary Heat Transfer System (PHTS), more specifically the one with the larger helium inventory. The main objective has been to assess, primarily, its thermal-hydraulic behaviour during the normal operational conditions, considering the ramp-up/down when switching from pulse to dwell and vice versa. In addition, an ex-vessel Loss-Of-Coolant Accident (LOCA) scenario has been preliminarily investigate to test the model robustness and its capabilities. For such a scenario, a Double-Ended Guillotine (DEG) break occurring in an Outboard Blanket (OB) segment hot feeding pipe has been postulated. In this manner, it was possible to assess the dynamic pressure loads on the civil structures of the tokamak building checking whether the imposed design limit have been exceeded considering the current expansion volume available in the Tokamak Cooling Room (TCR).

The analyses has been carried out following a theoretical-computational approach based on the finite volume method adopting the RELAP5-3D system code implicitly integrated with the ANSYS CFX computational fluid dynamic code to better simulate the thermal-hydraulic behaviour of the investigated system.

The outcomes herein presented suggest the possibility to extend the thermal-hydraulic analyses to some of the scenarios following the Postulated Initiating Events (PIEs) already identified for the EU-DEMO HCPB reactor. In particular, among them some other ex-vessel and in-vessel LOCAs scenarios have been classified among the most representative events in terms of challenging conditions for plant safety [5].

2. HCPB BB design reference

The current HCPB BB architecture has been developed for the DEMO Baseline 2017 whereby the tokamak machine consists of 16 identical sectors of 22.5° in the toroidal direction (φ) subdivided conforming to the coils number, see Fig. 1. Each sector includes 5 BB segments: a Left and Right Inboard segment (LIB and RIB, respectively) and a Left, Central and Right Outboard segment (LOB, COB and ROB, respectively).The systems composing a typical HCPB BB sector are depicted in Fig. 2. The BB configuration is based on a unique module along the poloidal direction (z), referred to as Single Module Segment (SMS) and on a fuel-breeder pins arrangement. These segments are made up of a poloidally continuous EUROFER97 external box,

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composed of the First Wall (FW), the sidewalls, the bottom and top caps and the backplate and housing the Breeding Zone (BZ). Each segment is connected to the Vacuum Vessel (VV) via the back supporting structure, which acts as a backbone supporting the entire segment.

The FW has to withstand the plasma heat radiation and the additional heat loads due to colliding particles and consisting in a 20 mm thick U-shaped plate covered by a 2 mm thick layer of sacrificial tungsten. In order to enhance the heat transfer capability of such component, the use of turbulence promoters or a properly increased surface roughness has been foreseen [6].

The BZ contains an Advanced Ceramic Breeder (ACB) pebble bed of a solid solution of Li_4SiO_4 and Li_2TiO_3.

This ACB – used to produce tritium and fixed in the so-called fuel-breeder pins arrangement, has been produced at the KArlsruhe Lithium OrthoSilicate (KALOS) facility [7]. This advanced solution has demonstrated to significantly increase the crush load of the breeder pebbles about 1.5 times that of the previous reference material (Li_4SiO_4) with minimal effects on the Tritium Breeding Ratio (TBR): a key figure of merit for the DEMO tritium self-sufficiency [8].

A pin consists of two concentric tubes forming the inner and outer cladding (with an external diameter of 28 and 64 mm, respectively) within which the breeder pebble bed is located, see Fig. 3. The pins are inserted inside pressure tubes (with an external diameter of 78 mm) that connect the FW with the BZ backplate and which act as structural elements to resist against pressurization in case of some LOCA scenarios.

According to this arrangement, the neutron multiplier ($Be_{12}Ti$) is placed outside the pressure tube containing the pins in form of hexagonal prismatic blocks [6].

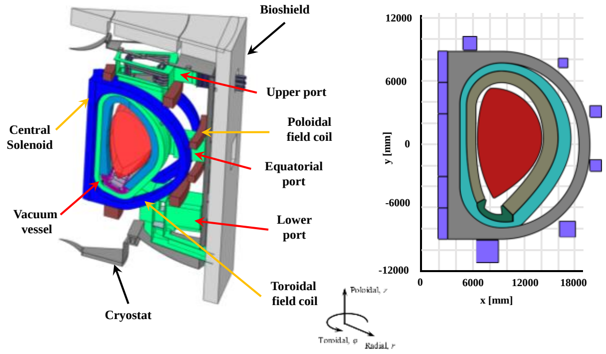

Fig. 1: DEMO Baseline 2017 configuration and section of the reactor core.

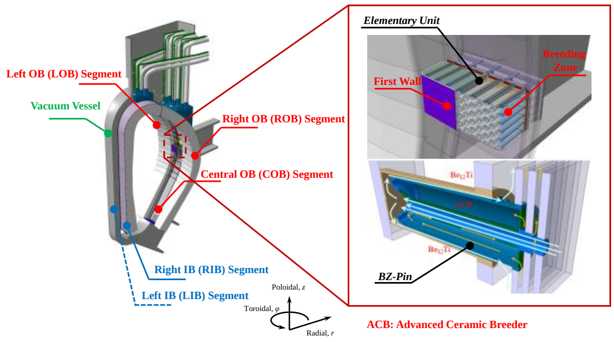

Fig. 2: HCPB DEMO Single Module Segment configuration

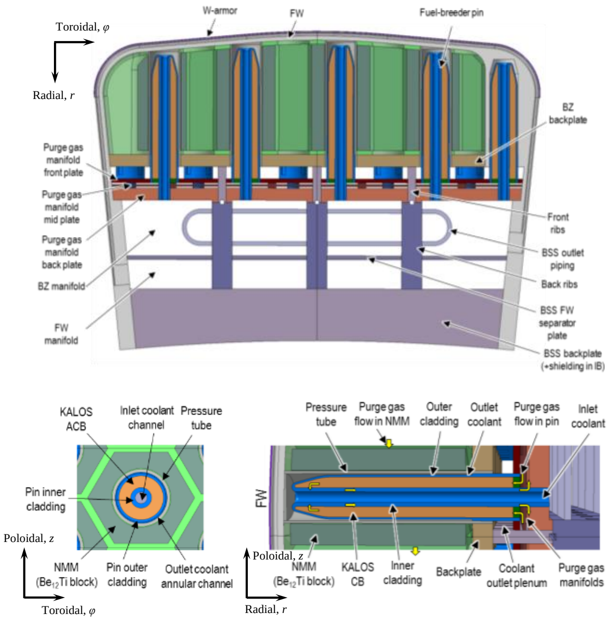

Fig. 3: Reference HCPB BB design for the EU-DEMO [7].

The coolant flow scheme of the HCPB BB is shown in Fig. 4; both the FW and BZ regions are cooled by helium at an operating pressure of 8 MPa with an inlet temperature of 573.15 K. It first flows from the FW inlet manifold (MF-1) to the FW cooling channels, which are cooled in a counter flow arrangement to homogenize the temperature distribution. The coolant is then collected into the BZ inlet manifold (MF-2), where is distributed into the fuel pins. The coolant is then collected from the BZ pins in the outlet plenum and redirected to the BZ outlet (MF-3), which is the outlet piping, at approximately 793.15 K.

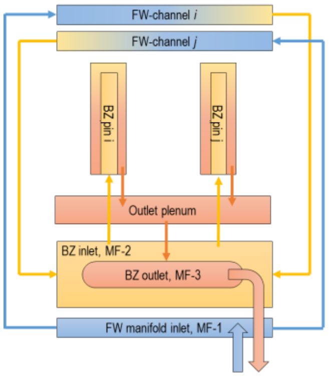

Fig. 4: Schematic flow scheme of the HCPB EU-DEMO [9].

3. HCPB BB-PHTS design reference

The Balance of Plant (BoP) architecture that is currently considered the most promising for the DEMO based on the helium-cooled blanket technology foresees the implementation of an intermediate system with its related energy storage system. Indeed, this ‘indirect-coupling’ solution can be developed relying on better established technologies, whose technology readiness level seems to be above the laboratory test, at least for the majority of its equipment. Moreover, this concept mitigates the potential negative impact of plasma pulsing on the turbine and other equipment. A conceptual scheme of the ‘indirect-coupled’ BoP is depicted in Fig. 5 where can be identified the Intermediate Heat Transfer System (IHTS) equipped with an Energy Storage System (ESS). The ESS is an industrial 2-tanks design commonly used in concentrated solar power plants which uses HITEC molten salt as heat transfer fluid because of its good thermal stability within the range of DEMO operative temperatures and its relatively low freezing point [10]. This gives more margins to withstand normal and off-normal transients. The adoption of an ESS, where part of the thermal energy is accumulated as sensible heat, allows operating the Steam Generators (SGs) at almost continuous load equal to about the 81% of the blanket power. The current BB-PHTS architecture relies on the adoption of 8 identical and completely independent cooling loops from both mechanical and functional point of view in order to limit some common mode failures. The general layout of the BB-PHTS is shown in Fig. 6.

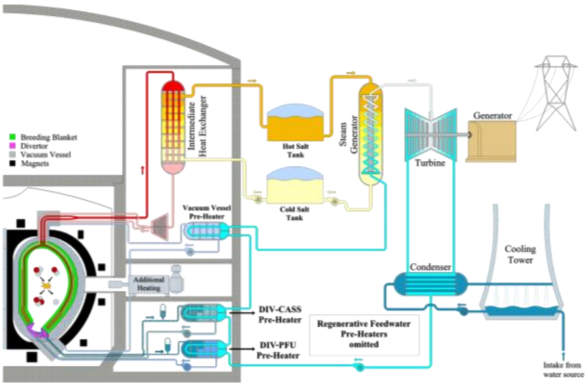

Fig. 5: Simplified conceptual scheme of the indirect-coupling BoP for the HCPB DEMO reactor [11].

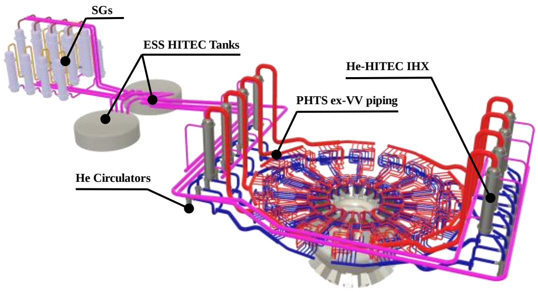

Fig. 6: A 3D view of the HCPB BB PHTS cooling loops.

Each loop, feeding both IB and OB segments of 2 sectors, is equipped with a helium-molten salt Intermediate Heat Exchanger (IHX) and 2 helium circulators [12]. The main data of the HCPB BB PHTS and the IHX are reported in Tab. 1 and Tab. 2, respectively.

Table 1. HCPB BB PHTS main data [13].

Parameter	Value	Unit
BB thermal power	2029.10	[MW]
Circulator electrical power	92.30	[MW]
Coolant volume	2031.90	[m^3]
Total piping length	6838.40	[m]
Circulator isentropic efficiency	0.85	[-]
BB pressure drop	0.79	[bar]
Helium mass flow rate	1777.89	[kg/s]
HITEC mass flow rate	6943.26	[kg/s]
Total pressure drop	2.70	[bar]

Table 2. IHXs main data [9].

Parameter	Value	Unit
Thermal Power	264.017	[MW]
T_{in}/T_{out} helium	793.15/564.05	[K]
T_{in}/T_{out} HITEC	543.15/738.15	[K]
Tubes active length	13.70	[m]
Tube number	9812	[-]
Tube d_{ext}	15.875	[mm]
Tube thickness	1.245	[mm]
Helium pressure drop	60.70	[kPa]
Helium volume	30.20	[m^3]

4. RELAP5-3D computational model

A computational model of the HCPB safety relevant cooling loop has been developed for the RELAP5-3D system code in order to support the design activities assessing the normal operational conditions and to improve its reliability during accidental scenarios.

The model nodalization has been developed to realistically predict the overall thermal-hydraulic behaviour of the selected loop demanding admissible computing time. Indeed, it reproduces accurately the current design of the system reported in [9] and [13] by using 1318 hydraulic volumes deployed between 211 thermal-hydraulic components, being 110 pipes, 4 multiple junctions, 90 single junctions, 2 single volumes, 1 compressor, 2 time dependent volumes, 2 time dependent junctions and 93 heat structures with 1581 axial subdivisions and a minimum of 5 radial nodes. In addition, 1031 control blocks, 167 signal variables and 125 tables complete the model. Fig. 7 shows the nodalization scheme adopted along with the main components CAD geometrical model.

The computational model consists of four main sub-models:

1. the *flow domain model*, reproducing in a lumped parameter approach the lay-out of the cooling circuit;
2. the *constitutive models*, provided by the system code to describe the thermo-dynamic behaviour of the helium circulating inside the cooling system;
3. the *hydraulic model*, intended to simulate the fluid flow along the cooling system;
4. the *thermal model* articulated in different sub-patterns aimed at realistically reproduce the heat transfer phenomena which take place along the cooling system.

4.1. The hydraulic sub-model

In order to better reproduce the hydraulic performance of the analysed system, a specific modelling approach has been developed to integrate the RELAP5-3D system code [14] ability to model the thermal-hydraulic performances of complex systems with the highly predictive capabilities of ANSYS CFX [15] in the assessment of the fluid-dynamic behaviour of coolant flowing through complex and new conceived components. In particular, with reference to the in-vessel

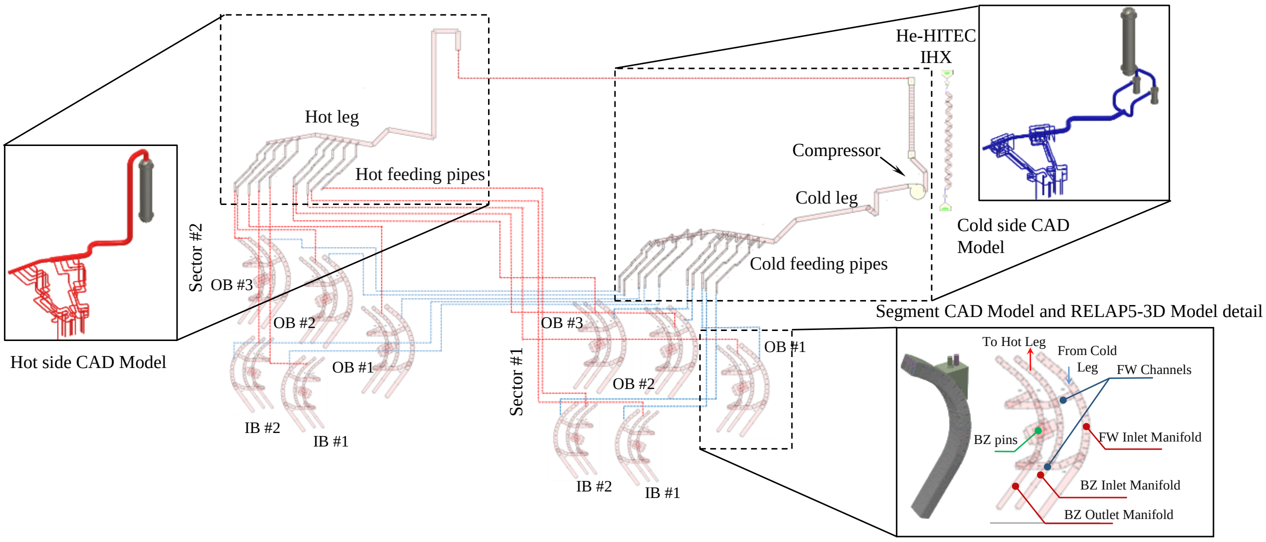

Fig. 7: RELAP5-3D nodalization for the selected HCPB BB PHTS cooling loop with 3D CAD details of the main components

components, a detailed parametric analysis has been performed for the COB segment aiming at assessing the hydraulic characteristic function of such components (namely pins, FW channels and the manifolds), giving the functional dependence of their total pressure drop on the corresponding mass flow rate under steady state conditions, that is $\Delta p = \alpha G^{\beta}$ as depicted in Fig. 8.

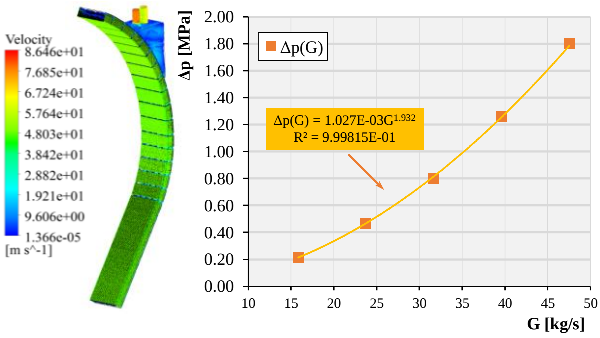

Fig. 8: Hydraulic Characteristic of the COB Segment.

The hydraulic characterization for the COB segment has been performed by adopting a simplified model of the whole segment based on the porous media approach which allows to reduce the computational domain and consequently the computing time [16], [17]. Indeed, the simplified model reproducing the real complex one is obtained by replacing its sub-components with others likewise behaving, as shown in Fig. 9 , thanks precisely to the characteristic functions obtained through detailed ANSYS CFX analyses and acting like transfer functions.

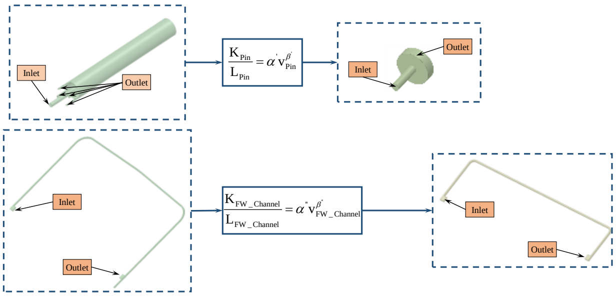

Fig. 9: Sub-components (FW channels and BZ pin) simplification by means of the porous media approach [17].

More details about the procedure and the computational models adopted to obtain the hydraulic characteristic functions of both the sub-components and the simplified COB segment, see Fig. 10, can be found in [17].

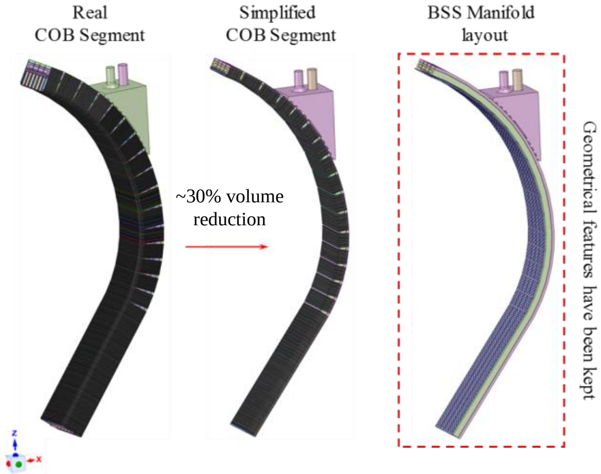

Fig. 10: COB Segment simplification by means of the porous media approach [17].

Once derived, this function has been adopted to derive the dependence on mass flow rate of the effective concentrated hydraulic loss coefficients ($K = B \cdot Re^{-C}$) giving it in input to RELAP5-3D in order to let it simulate accurately all the in-vessel components with a lumped parameter approach.

4.2. The thermal sub-model

As concerns the thermal modelling, all the foreseen structural and functional materials have been modelled in order to precisely reproduce the component heat capacity. The heat transfer phenomena have been reproduced implementing the thermo-physical properties of all the materials involved [9], [13] and by adopting the properly selected heat transfer models. In particular, they are the widely adopted Gnielinski correlation, already implemented in the RELAP5-3D models package and the the Bell-Delaware procedure for evaluating the heat transfer coefficient on the shell side of the IHX, as has been done for its design [12]. For the latter, since it is not directly available into the system code, it has been implemented by using proper control functions which allow to evaluate the heat flux as boundary conditions for the heat structures simulating such component. Considering the solar molten salt HITEC has been foreseen as working fluid for the IHTS of the HCPB EU-DEMO, a dedicated binary file has been generated to implement its thermo-physical properties into the code fluid libraries [18]. The model reproduces accurately the shell side of the heat exchanger, while the inlet and outlet boundary conditions have been simulated by adopting time dependent volumes and junctions, see Fig. 7. Moreover, the thermal modelling approach here adopted has been assessed by performing a benchmark with the experimental data coming from the experiences conducted on the HETRA facility [18], [19].

4.3. Thermal power and transient loads

The thermal power adopted for simulating the normal operational scenario including the ramp-up /down takes into account both the FW heat flux and the nuclear heating as reported in [20], [21]; the latter is re-scaled to the required TBR [22]. More specifically, assuming as required TBR (TBR$_{req}$) the value of 1.05, suggested in [23] and since the obtained TBR design value has been 1.2 [9], the nuclear heating is re-scaled to meet the needed design update (rearrangement of the materials) to comply with the TBR$_{req}$ and assuming – as first approximation, the nuclear heating is directly proportional to the TBR. Fig. 11 shows the thermal power profile for the analysed loop and Fig. 12 shows the DEMO fusion power highlighting the two transition phases between pulse and dwell.

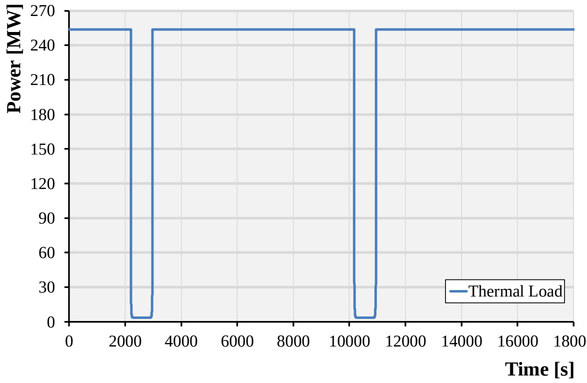

Fig. 11: Loop thermal power profile.

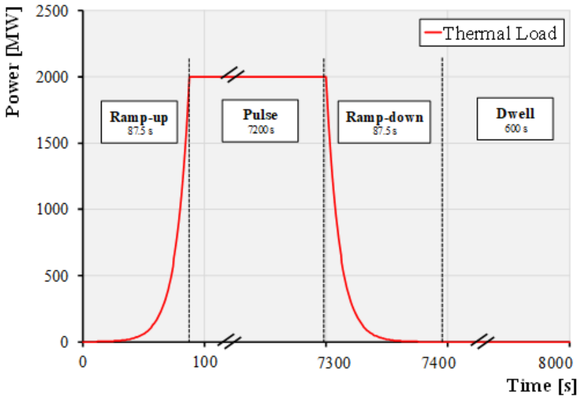

Fig. 12: DEMO duty cycle.

5. Normal operational conditions results

As concerns the simulation of the normal operational conditions, it has been mainly intended to preliminarily investigate the capability of the model to predict the thermal-hydraulic phenomena occurring into the system studying a possible strategy to control both the helium and HITEC mass flow rate in order to maintain the inlet temperature to the BB equal to 573.15 K as required in [22]. Firstly, in order to qualify the developed nodalization, the pressure drops calculated by the code have been compared to the theoretical ones. Fig. 13 and Fig. 14 illustrate the various 'pressure probing sections' for the cold and hot piping, respectively. The probing section 6 and 7 are representative of the BB inlet and outlet, respectively. Fig. 15 reports the aforementioned comparison.

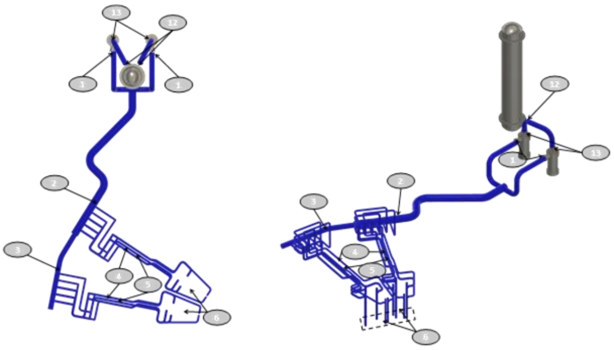

Fig. 13: Cold piping with pressure probing sections.

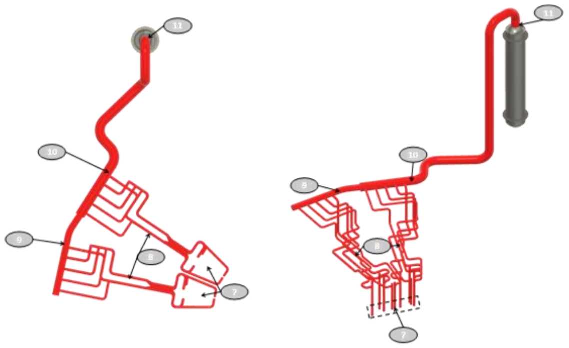

Fig. 14: Hot piping with pressure probing sections.

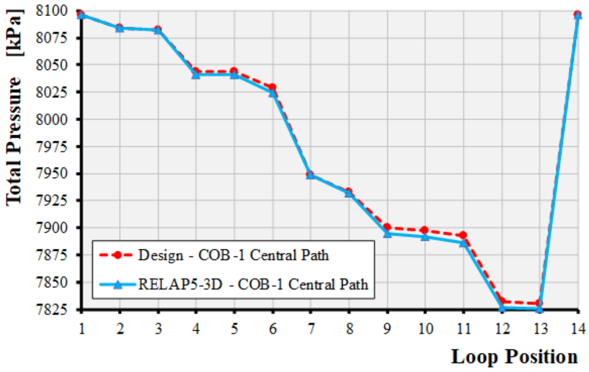

Fig. 15: Pressure drops along the COB-1 central path.

The results show a good accordance between theoretical values and the RELAP5-3D ones; in fact the total pressure drop predicted by the code is 2.58 bar with respect to the 2.67 bar theoretically evaluated (deviation of 3.41%). A parametric study has been thereafter performed analysing the normal operational conditions. The main objective of this preliminary study has been to assess the dynamic response of the system when it switches from pulse to dwell and vice versa. In particular, four cases involving a combination of different mass flow rates on both helium and HITEC sides has been set-up with the aim of understanding the potential maximum variations that relevant quantities such as pressure and temperatures can experience for a given Balance of Plant control.

The four identified cases are:

I. both the helium and the HITEC mass flow rate are kept constant at the nominal pulse value during the entire period;
II. the helium flow rate is the same that in (I), while the HITEC one follows the same functional shape of the BB thermal power;
III. consists in changing the helium mass flow rate according to the same functional shape of the BB thermal power, while the molten salt mass flow does not change;
IV. both the helium and the HITEC mass flow rates evolve like the power functional shape.

Fig. 16 and Fig. 17 report a graphic representation of the dynamic behaviour of the helium and HITEC mass flow rates, respectively.

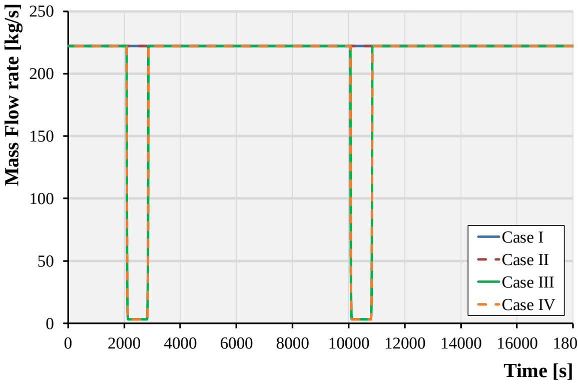

Fig. 16: Helium mass flow rate.

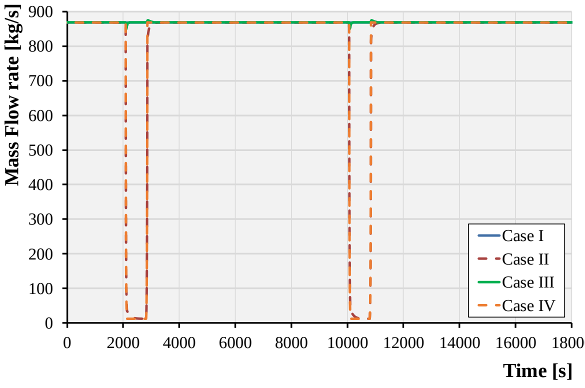

Fig. 17: HITEC mass flow rate

The trend of the temperatures in cold and hot legs is shown in Fig. 18 and Fig. 19, respectively; whilst in Fig. 20 the cold leg pressure is displayed.

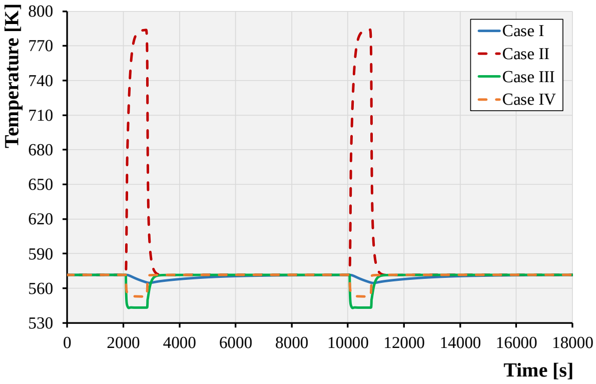

Fig. 18: Cold Leg temperature.

In both case (I) and (II), when the dwell starts, temperatures and/or pressure show high and fast changes. In particular the former presents too large increase of the pressure, while in the latter case the huge thermal-hydraulic variations affect the whole dwell phase as well as the following pulse period. Indeed, the system is able to recover the design values just before the beginning of the next dwell. This is due to the control of PHTS that, keeping the helium mass flow rate at its maximum value, extends the time needed to heat up again the BB structures. Case (III) and (IV) present less marked deviation of the relevant quantities thanks to the helium mass flow rate control which basically follows the BB thermal load profile. However, such regulation seems to be very challenging since it implies a quick and fast variation of the primary mass flow rate.

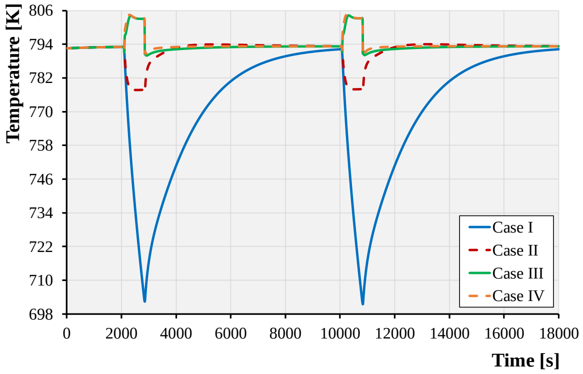

Fig. 19: Hot Leg temperature.

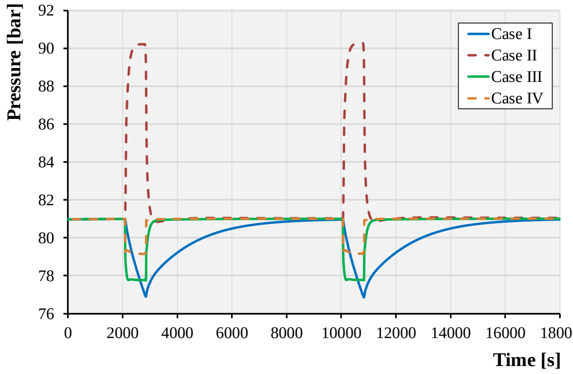

Fig. 20: Cold leg inlet pressure.

Starting from these outcomes, a more feasible controlling strategy has been proposed and analysed. In this case, the helium mass flow rate evolves assuming a viable rate of change of 12.5 % per minute, reaching the minimum value of 83.34 kg/s during the dwell. The molten salt mass flow rate is evaluated by the system code with a dedicated proportional-integral controller aimed at maintain the required BB inlet temperature to 573.15 K, see Fig. 21.

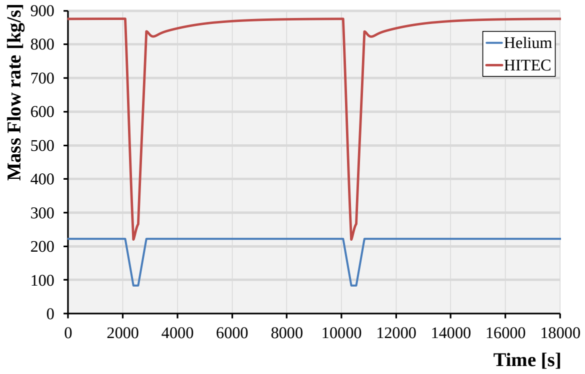

Fig. 21: Helium and HITEC mass flow rate for the proposed controlling strategy.

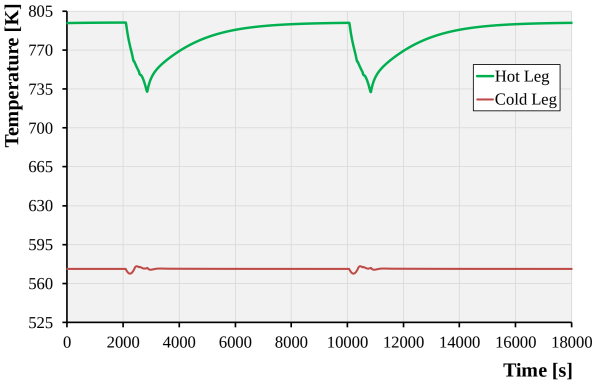

Fig. 22: Hot and cold leg temperature for the proposed controlling strategy.

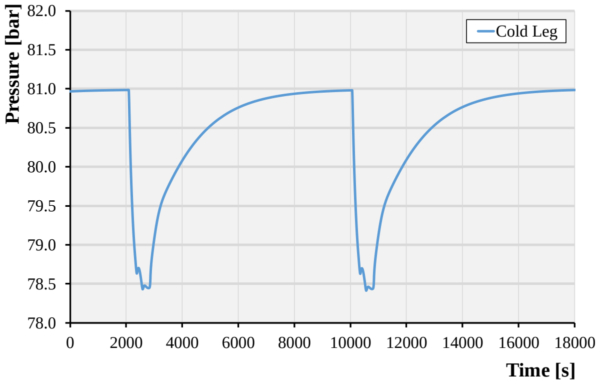

Fig. 23: Cold leg inlet pressure for the proposed controlling strategy.

The proposed control system allows reducing the main quantities excursion when switching between the two operational phases respect those envisaged for the parametric study. Indeed, this can be observed for both the hot and cold temperatures depicted in Fig. 22 and the cold leg inlet pressure, which is shown in Fig. 23. However, even if the BB inlet temperature can be considered satisfactorily controlled, the hot leg temperature fluctuations seems still too large (about 60 °C) to let the system operate in a very reliable and safe mode.

6. DEG-break in hot leg: preliminary results

In order to assess the robustness of the developed computational model, it has been investigated a DEG break occurring in that portion of the hot leg where the cross section is the greatest, namely 1.114 m^2.

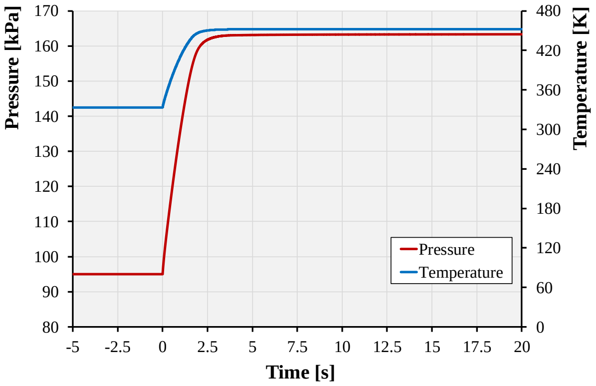

Fig. 24: Pressure and temperature evolution in the TCR under the investigate DEG break scenario.

To simulate such an accidental scenario the model has been extended to include the TCR, that is reported in [25] and from which it has been subtracted the equipment volumes. The available volume is about $1.18{\cdot}10^5$ m^3 and it has been simulated as an adiabatic hydraulic volume. The rooms have been modelled by using a SINGLE VOLUME component where the air temperature has been set to 333.15 K, while the initial pressure has been considered equal to 95 kPa.

The break has been simulated by using the VALVE component, which opens at time 0 s (starting from the end of the pulse conditions). Due to the large size of the rupture, the transient is extremely fast and after about 2.5 s from the break occurrence, the pressure reaches its maximum of 163 kPa, which is below the prescribed limit of 200 kPa. The equilibrium temperature inside the tokamak cooling rooms is about 450 K, see Fig 24.

It is worth to underline that this study has been focused on the first seconds following the break in order to make a preliminary assessment of the dynamic pressure loads on the civil structures. The long term transient behaviour will be investigated in a future work.

7. Conclusions

The research activity here presented concerns the development of a computational model of the representative and safety relevant cooling loop for the HCPB BB PHTS, which has been devoted to assess its thermal-hydraulic behaviour during the normal operational conditions, considering the ramp-up/down when switching from pulse to dwell and some different strategies to control the PHTS mass flow rates.

The PHTS control system proposed allows to reduce the main quantities excursion when switching between the two operational phases compare to those evaluated for the four cases within the parametric study. Nevertheless, the hot leg temperature variations strongly suggest thermo-mechanical analysis using the obtained results to assess their damaging due to the thermal fatigue. Hence, further investigations on the most suitable system control strategy (bypass or pressure relief and throttled inlet compressor) seems needed with the support of the Balance of Plant experts.

Moreover, preliminarily investigations of an ex-vessel LOCA scenario have been carried out, in which a DEG break occurs in the hot leg, to test the robustness and the prediction capabilities of the model. The results obtained simulating the normal operational scenario are in good agreement with the design data and the model seems suitable to investigate both operational and accidental transients suggesting the possibility to extend the thermal-hydraulic analyses to further the some of the scenarios following the PIEs already identified for the EU-DEMO HCPB reactor.

Acknowledgments

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