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On the impact of the heat transfer modelling approach on the prediction of EU-DEMO WCLL breeding blanket thermal performances

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The Water-Cooled Lithium-Lead Breeding Blanket is a key component of a fusion power plant, in charge of ensure Tritium production, shield Vacuum Vessel and magnets and remove the heat power deposited by radiation and particles arising from plasma. The last function is fulfilled by First Wall and Breeding Zone independent cooling systems.

Several layouts of BZ coolant system have been investigated in the last years to identify a configuration that might guarantee EUROFER temperature below the limit (550°C) and good thermal-hydraulic performances (i.e. water outlet temperature of 328°C). A research activity is conducted to study and compare different modelling approaches to simulate the heat transfer within the BZ liquid metal, assessing their impact on the numerical prediction of the WCLL blanket thermal performances. An approach will rely on the simulation of convective and diffusive heat transfer processes taking place within the liquid metal by means of a CFD tool based on the Finite Volume Method. Conversely, the other approach will roughly assume a pure diffusive heat transfer mechanism within the breeder, due to the very low velocities envisaged for its flow field. In this case the heat transfer performances will be preferably assessed by means of a commercial code based on the Finite Element Method.

The analyses have been carried out with reference to the so called "WCLL BB 2018 V0.6" equatorial cell. Advantages and issues from the thermal-hydraulic point of view are identified, the impact of the imposed boundary conditions and heat transfer properties, with the implemented correlations, on the respective results is critically discussed.

Keywords: WCLL, CFD, FEM, Breeding Blanket, Blanket Engineering.

1. Introduction

The Water-Cooled Lithium Lead (WCLL) Breeding Blanket (BB) is a qualified candidate for the European DEMO fusion power plant [1]. It must ensure an adequate neutron shielding, tritium breeding self-sufficiency, and energy extraction for the electricity production [2]. Lithium Lead (PbLi) is adopted as breeder, neutron multiplier and tritium carrier, EUROFER as structural material, and pressurized water at typical Pressurized Water Reactor (PWR) conditions, 15.5 MPa, as the First Wall (FW) and the Breeding Zone (BZ) coolant. The WCLL BB is designed according with the Single Module Segment (SMS) approach [3]. To guarantee the adequate mechanical properties, the EUROFER must be maintained at temperature lower than 550°C during the normal operation [4] [5].

The thermal-hydraulic studies have the responsibility to evaluate and to provide an adequate temperature map of the BB verifying that the maximum temperature of EUROFER structures is below the limit (550°C), to investigate PbLi heat transfer coefficient in BZ and to predict the thermal performances of BZ and FW coolant systems. The analyses are focused on the WCLL 2018 V0.6 equatorial elementary cell of the central outboard segment [6] [7]. A detailed three-dimensional model of the cell is developed, adopting two different methods. The first approach is based on the Finite Element Method (FEM), conversely, the second adopts the Finite Volume Method (FVM). Advantages and issues of these two different methods are critically discussed in the following. Different modelling strategies are considered to simulate the heat transfer between structures and fluids, and also the impact of the adoption of different materials thermo-physical properties on the thermal field calculation has been evaluated.

2. DEMO WCLL BB 2018 V0.6

Current WCLL BB design is based on EU-DEMO 2017 specifications [8] and CAD model, characterized by 16 sectors of 22.5°. Each sector includes two Inboard Segments (IB) and three Outboard Segments (OB). The BB consists of: the FW, an external box of EUROFER water-cooled with counter-current square channels and with a Tungsten layer of 2 mm facing the plasma, and the BZ, filled with liquid PbLi alloy that flows through channels, delimited by EUROFER structural stiffeners and refrigerated by Double Wall Tubes (DWTs). See Fig.1 for a synoptic view of the design.

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The elementary cell V0.6 has a toroidal length of 1500 mm, radial dimension of 1000 mm and total height of 135 mm. Its FW includes ten horizontal counter-current coolant channels. Its BZ presents the following design: radial-poloidal stiffening plates detached from the FW by 175 mm, with a total radial length of 365 mm; a radial-poloidal baffle plate placed at mid height of the cell allowing PbLi to flow in radial-poloidal-radial direction, entering from the bottom part through holes and exiting from the top part of the cell; six breeder channels, divided in 4 central (231×540 mm) and 2 side channels (233×540 mm), refrigerated by 22 DWTs.

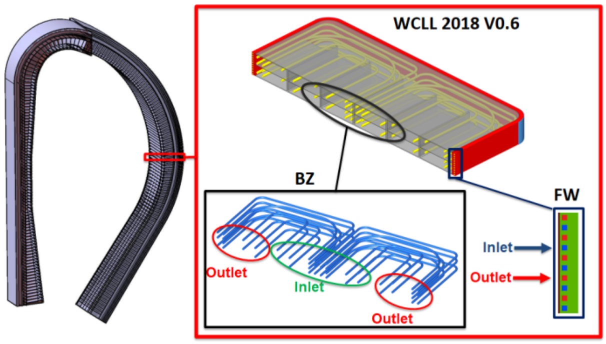

Fig. 1: WCLL 2018 V0.6 equatorial elementary cell

3. Problem formulation and numerical models

For this study, to mark up the thermal-hydraulics advantage and disadvantage focusing on the impact of the numerical prediction, different approaches to the numerical modelling are analyzed and compared. Four different models are compared to evaluate the thermal field of the WCLL 2018 V0.6 elementary cell.

Two of these use an approach based on a pure conductive analysis that roughly neglects the simulation of convective phenomena between the steel structure and the fluids (i.e. water and PbLi). Water domain is not modeled, and its effects are simulated by means of proper convective boundary conditions (BCs), while PbLi is modelled as a solid domain. In absence of buoyancy effects, due to the low velocities reached by PbLi (≈ 0.1-0.15 mm/s) heat conduction prevails and convection can be neglected, as demonstrated by several thermofluid-dynamic simulations considering both diffusive and convective contributions. This approach has been extensively used in literature [9] but, if buoyancy forces are considered, this assumption would no longer be true [10] [11].

The other two models use an approach based on a convective-diffusive analysis that might consider also the convective phenomena due to the fluids (i.e. water and PbLi). In particular, in one case water coolant is modelled as a fluid, keeping the PbLi domain as solid, while, in the other case, both water and breeder are modeled as fluids. This allows to highlight the main discrepancies between the different heat transfer modelling approaches as well as between the different numerical methods and, hence, codes adopted. To this purpose, the ABAQUS v6.14 commercial FEM code is adopted to simulate the pure diffusive model while the ANSYS CFX v19.2 FVM commercial code is used to run, besides from the diffusive model, also those accounting for convective phenomena.

The same material thermo-physical properties have been implemented in both the adopted codes. The properties of EUROFER and Tungsten are specified in terms of density, specific heat and thermal conductivity, while water and PbLi require also the dynamic viscosity [6]. Moreover, as to the PbLi, two different correlations for thermal conductivity are adopted to evaluate their impact on the thermal field. The relevant properties of Tungsten, EUROFER and water are summarized in Tab.1, Tab.2 and Tab.3; PbLi thermal properties are reported in [12] and the correlations related to the thermal conductivity are reported in Tab.4.

Table 1: Tungsten thermo-physical properties (T in K)

Equation	Unit
$\rho = 19300$	kg/m³
$c_p = 145$	J/(kg K)
$\lambda = 125$	W/(m K)

Table 2: EUROFER thermo-physical properties (T in K)

Equation	Unit
$\rho = 7874.3 - 0.361 \cdot T$	kg/m³
$c_p = -438.83 + 4.9838 \cdot T$ $-8.7371 \cdot 10^{-3} \cdot T^2 + 5.3333 \cdot 10^{-6} \cdot T^3$	J/(kg K)
$\lambda = 60.915 - 9.081 \cdot 10^{-2} \cdot T$ $+6.5 \cdot 10^{-5} \cdot T^2$	W/(m K)

Table 3: Water thermo-physical properties (T in K)

Equation	Unit
$\rho = -1.4226 \cdot 10^{-2} \cdot T^2 + 14.122 \cdot T$ -2693	kg/m³
$c_p = 9.8485 \cdot 10^{-3} \cdot T^3 - 16.39861 \cdot T^2$ $+9118.681 \cdot T - 1.6882247 \cdot 10^6$	J/(kg K)
$\lambda = -1.2024 \cdot 10^{-5} \cdot T^2 + 1.1846 \cdot 10^{-2} \cdot T$ -2.2804	W/(m K)
$\mu_d = (-8.095238 \cdot 10^{-4} \cdot T^2$ $+0.5722429 \cdot T + 29.67213) \cdot 10^{-6}$	kg/(m s)

Table 4: PbLi thermal conductivity [12]

Name	Equation	Unit
IAEA [13]	$\lambda = 11.9$ $+1.96 \cdot 10^{-2} \cdot (T[°C] - 235)$	W/(m °C)
Mogahed [14]	λ $= 0.1451 + 1.9631 \cdot 10^{-4}$ $\cdot T[K]$	W/(cm K)

To evaluate the WCLL 2018 V0.6 elementary cell thermal-hydraulic performances with the aforementioned FEM and FVM codes, 8 simulations are performed, as schematically represented in Fig. 2.

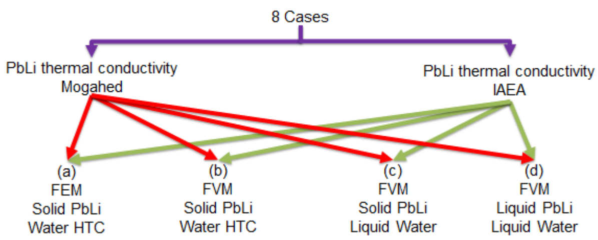

Fig. 2: Methods, models and analyses scheme

To this purpose, the radially varying volumetric density of nuclear deposited power reported in [15] and a normal heat flux of 0.5 MW/m^2 on the Tungsten plasma-facing surface have been adopted as thermal loads. Water mass flow rate for BZ and FW is calculated with the enthalpy balance for the EU-DEMO 2017 baseline, and the water heat transfer coefficient (HTC) is calculated with the Dittus-Boelter correlation assuming the water bulk temperature at 311.5°C and a mass flow rate for BZ and FW 0.8285 kg/s, respectively. In Tab.5 the BCs per different models are reported.

Table 5: Different models BCs

BCs	Values *a*	*b*	*c*	*d*	Units
FW HF	0.5	0.5	0.5	0.5	MW m^{-2}
Water (BZ-FW) T_{ave}	311.5	311.5	-	-	°C
Water (BZ-FW) T_{inlet}	-	-	295	295	°C
Water (BZ-FW) Pressure	15.5	15.5	15.5	15.5	MPa
FW Mflow	-	-	0.8285	0.8285	kg s^{-1}
BZ Mflow	-	-	0.8285	0.8285	kg s^{-1}
FW HTC	22012	22012	-	-	W m^{-2} K^{-1}
BZ HTC	11175	11175	-	-	W m^{-2} K^{-1}
PbLi T	327	327	327	327	°C
Total PbLi Mflow	-	-	-	0.1652	kg s^{-1}

4. Mesh sensitivity

For the two methods a mesh independency analysis is performed, in order to select spatial grids allowing accurate results to be obtained in a reasonable calculation time. As to the FVM models, the mesh independence is reported and proved in [6] and [16] for a blanket elementary cell with the same geometry and a similar DWTs distribution. Concerning the FEM model, a dedicated mesh independence analysis is performed varying the sizing of the grid elements, assuming a radially uniform nuclear heating to avoid the misleading effects of nuclear deposited power variation due to the change of the adopted mesh. The performed calculations are summarized in Tab.6 and the results are shown in Fig.3.

Table 6: FEM mesh sensitivity

#	Nodes	Elements	T_{max} EUROFER [K]	T_{max} PbLi [K]
A	1.71M	3.72M	516.0	517.6
B	1.92M	4.93M	519.2	519.8
C	2.21M	6.53M	519.8	520.3
D	2.49M	8.10M	520.2	520.6

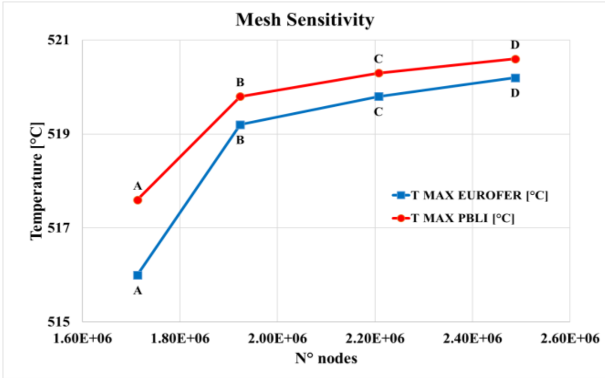

Fig. 3: FEM mesh sensitivity temperature results

They show that the finer mesh (D) provides significant improvements compared with others. There are significant variations from (B) to (A), and computational costs are not so wasteful compared with (C), therefore, the (D) mesh is adopted.

5. Results and discussion

Regarding the FEM analyses with two different PbLi thermal conductivity correlations (IAEA [13] and Mogahed [14], see Tab. 4 and [12]), as expected, results show similar spatial distributions of the thermal field that deeply differ as to their maximum values of ≈60°C. In case IAEA correlation is adopted, results (Fig. 4) indicate that the maximum temperature of 571.0°C is reached at the baffle plate while the stiffening plates experience a temperature of 562.7°C exceeding the imposed limit of 550°C. This calculation turns out to be very conservative due to the absence of the convective contribution and to the underestimation of thermal conductivity due to the IAEA correlation with respect to the Mogahed's one (mean percentage difference around 32%). Conversely, Fig. 5 shows the results obtained with Mogahed correlation, which predict a temperature limit of 509.3°C in the upper plate and a maximum temperature of 513.4°C in the baffle plate.

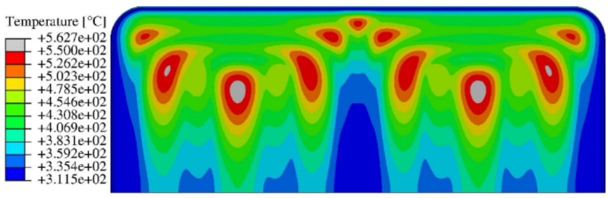

Fig. 4: FEM analysis upper plate temperature field – IAEA correlation

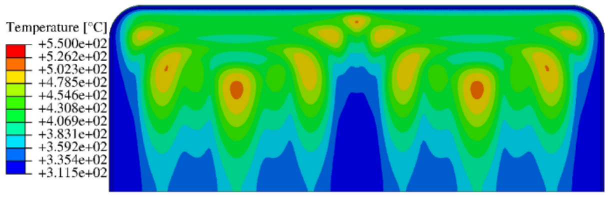

Fig. 5: FEM analysis upper plate temperature field – Mogahed correlation

The FVM analyses in a purely conductive model, where solid PbLi and proper convective BCs on the

DWTs and FW square channels have been assumed, return almost identical results to the FEM ones. The upper plate has the same hot spots locations as the FEM cases with both PbLi thermal conductivities. In Fig. 6 is reported the temperature field of the upper plate obtained with the Mogahed correlation, where, the maximum temperature predicted is 505.6°C. Moreover, the EUROFER T_{max} is 510.6°C, about 3 degrees less than the FEM case. Regarding Fig. 7, relevant to IAEA correlation, even in this case the upper plate reaches temperature above the limit (558.7°C), resulting 4 degrees less than that predicted by the FEM analysis. The T_{max} is in the baffle plate and amounts to 568.1°C.

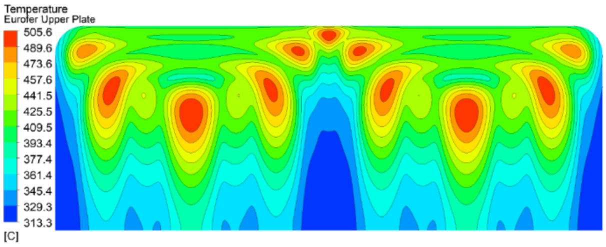

Fig. 6: FVM purely conductive analysis upper plate temperature field – Mogahed correlation

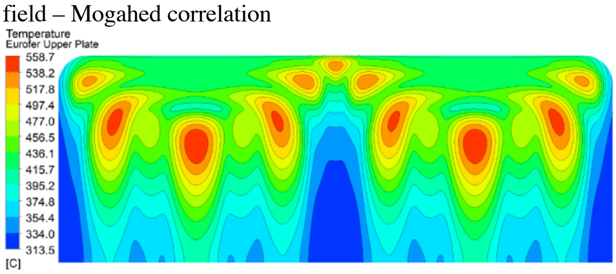

Fig. 7: FVM purely conductive analysis upper plate temperature field – IAEA correlation

The third set of analyses presents the integration of the water as fluid domain for the DWTs and the FW channels. For these analyses the FVM model is used. In these two cases, thanks to the improved modelling of water convective heat transfer the EUROFER temperature slightly decreases and a more realistic spatial distribution of the thermal field is obtained due to the increase of water coolant bulk temperature along the channels calculated by the code; in the Mogahed case the maximum temperature continues to stay below the imposed limit, reaching 504.4°C in the upper plate (Fig. 8) and 509.8°C in the baffle plate. Despite the predicted temperature increases of the IAEA case, the limit of 550°C is not overcome; it can be seen from Fig. 9 that the maximum temperature of the upper plate is 556.9°C while the baffle plate reaches at most 566.4°C.

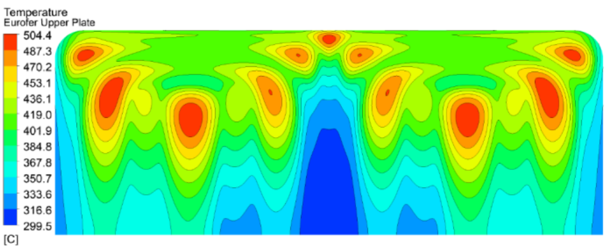

Fig. 8: FVM analysis with fluid water and PbLi solid domains upper plate temperature field – Mogahed correlation

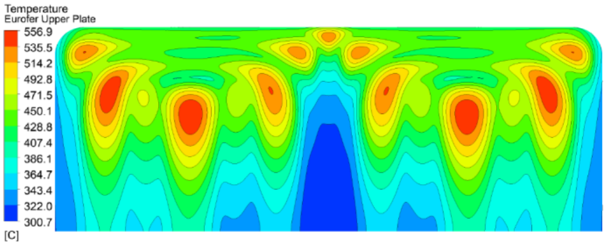

Fig. 9: FVM analysis with fluid water and PbLi solid domains upper plate temperature field – IAEA correlation

The last set of analyses, where also the PbLi is modeled as a fluid domain, are performed with FVM model. For the heat transfer, in addition to the convective contribution of water, there is also that of liquid PbLi, which contributes to a further reduction of the temperature field. In the analysis with Mogahed correlation, the contribution of the PbLi convection causes the temperature to decrease to 502.4°C in the upper plate (Fig. 10), and the EUROFER maximum temperature to be reduced down to 505.6°C. Regarding the IAEA correlation analysis, the predicted temperature of the upper plate decreases to 548.5°C (Fig. 11) satisfying the requirement, even if in the baffle plate this limit is slightly exceeded, as the temperature amounts to 559.6°C.

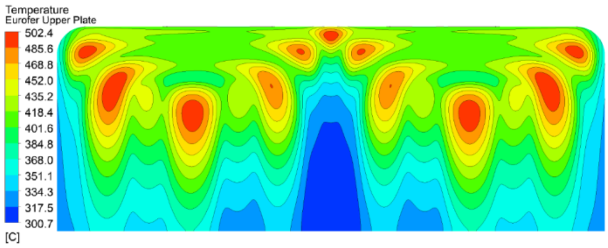

Fig. 10: FVM analysis with fluid water and PbLi domains upper plate temperature field – Mogahed correlation

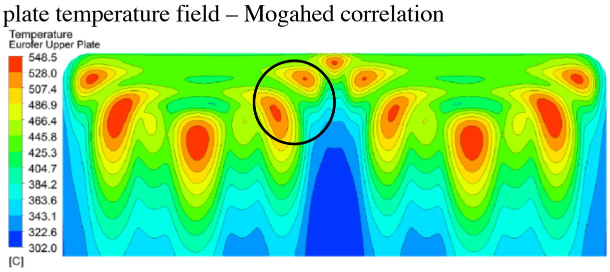

Fig. 11: FVM analysis with fluid water and PbLi domains upper plate temperature field – IAEA correlation

Collecting the obtained data (Tab.7), it is shown in Fig.12 that by refining the analysis and going gradually considering the convective heat transfer of the fluid domains into the models, the maximum EUROFER temperature of the model slightly decreases, as that of the stiffening plates.

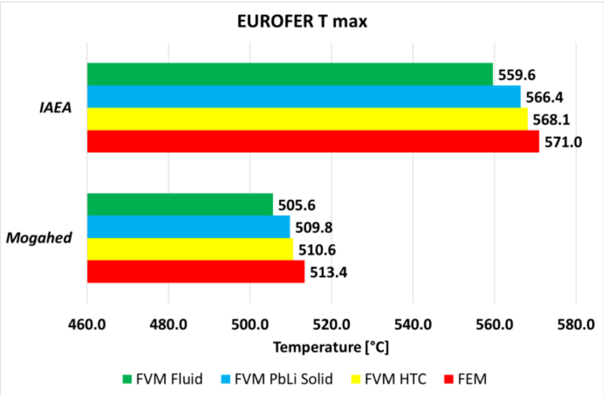

Fig. 12: EUROFER maximum temperature divided by PbLi thermal conductivity and per analysis method

As expected, FEM model is more conservative, returning higher temperatures of 1.5% in case of Mogahed PbLi thermal conductivity and 2% in the IAEA case. Finally, the impact of the correlation adopted for the PbLi thermal conductivity is significant, as results obtained with IAEA and Mogahed ones differ by ≈56 degrees, reaching a maximum for the FEM analysis (57.6°C) and a minimum for the FVM analysis (54°C) with the fluid domains of water and PbLi.

Table 7: EUROFER temperature calculated

Model	PbLi thermal conductivity correlation			
	Mogahed [14]		*IAEA [13]*	
	$T_{Upper\ Plate}$ [°C]	T_{max} [°C]	$T_{Upper\ Plate}$ [°C]	T_{max} [°C]
a	509.3	513.4	562.7	571.0
b	505.6	510.6	558.7	568.1
c	504.4	509.8	556.9	566.4
d	502.4	505.6	548.5	559.6

6. Conclusions

The research campaign carried out to investigate the effects of heat transfer modelling in the assessment of WCLL thermal performances has allowed to draw the following main conclusions.

The choice of the PbLi thermal conductivity correlation deeply affects the numerical predictions and, in particular, the Mogahed correlation returns a significantly lower thermal field than that obtained by means of the IAEA correlation. As a consequence of this, the EUROFER temperature meets the design requirements only whether predicted with the Mogahed correlation, exceeding the limit of 550°C in case IAEA correlation is adopted, no matter of the numerical method followed for its calculation (FEM and/or FVM). A definitive selection of the reference correlation to be adopted for fusion-relevant design purposes is, hence, strongly recommended.

As to the impact of numerical methods adopted for the thermal assessment, it can be concluded that between the FEM and the FVM, whether adopted for a pure diffusive heat transfer analysis, even if there is no substantial variation in the results obtained, there is a strong difference in the requested computational effort, since FVM calculations take typically a longer computing time than the FEM ones. Therefore, as a first instance, it is advisable to use a FEM calculation to get an idea of the thermal field under examination. Moreover, it has been noted from the analyses that the simulation of PbLi as a solid domain reduces the calculation times in FVM analysis. A simplification that can be, hence, used to investigate some critical phenomena that might occur in the DWTs water or in the FW channels, such as critical heat flux occurrence or excessive flow velocities.

Finally, regarding the approach adopted to model heat transfer occurring within water coolant and liquid breeder, it has been observed that the realistic simulation of coolant convection, instead of the assumption of convective boundary conditions, improves the prediction of the thermal field spatial distribution, slightly impacting its maximum values, while the proper simulation of PbLi flow with its convective-diffusive heat transfer process leads to slight changes in the predicted thermal field, both in terms of spatial distribution and maximum values, at least in absence of buoyancy effects.

In conclusion, a further investigation is recommended to assess the effects of buoyancy and MHD on the PbLi thermofluid-dynamic performances.

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