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DEMO WCLL breeding zone cooling system design: analysis and discussion

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The Water-Cooled Lithium-Lead (WCLL) Breeding Blanket (BB) is a key component in charge of ensuring Tritium self-sufficiency, shielding the Vacuum Vessel and removing the generated power of DEMO reactor. The last function is fulfilled by two independent cooling systems: First Wall (FW) that removes the plasma heat flux and Breeding Zone (BZ) that removes the deposited power of charged particle and neutron. Several layouts of BZ coolant system have been investigated in order to identify a configuration that guarantee Eurofer temperature below the limit (823 K) and good thermal-hydraulic performances (i.e. water outlet temperature 601 K). A research activity is conducted to study and compare four configurations, which rely on different arrangement of the stiffening plates (i.e. toroidal-poloidal and radial-poloidal), orientation of the cooling pipes (i.e. horizontal, vertical) and PbLi flow path. The analysis is performed using a CFD codes, thus a 3D finite volume model of each configuration is developed, adopting the commercial ANSYS CFX code. The objective is to compare the BZ cooling system layouts, identifying and discussing advantages and key issues from the thermal-hydraulic point of view, also considering feedbacks from MHD and neutronic analyses. The research activity aims at laying the groundwork for the finalization of the WCLL blanket design, pointing out relevant thermal-hydraulic aspects.

Keywords: DEMO, WCLL, Breeding Blanket, CFD, Thermal-hydraulics

1. Introduction

The Water-Cooled Lithium Lead (WCLL) Breeding Blanket (BB) is a candidate breeding blanket for DEMO fusion power plant [1]. It must ensure an adequate neutron shielding, tritium breeding self-sufficiency, and energy extraction for the electricity production. 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 First Wall (FW) and Breeding Zone (BZ) cooling systems. The WCLL BB is designed according with the Single Module Segment (SMS) approach [2]. To guarantee the adequate mechanical properties, the Eurofer have to be cooled at a temperature lower than 823 K during the normal operation [3] [4].

The thermal-hydraulic studies have the responsibility to evaluate and to provide an adequate temperature map of the BB verifying that maximum temperature of Eurofer structures is below the limit, to investigate PbLi flow path in BZ and to evaluate thermal-hydraulic efficiency of BZ and FW coolant systems. The analyses are focused on the equatorial elementary cell of an OB segment [5] [6]. A detailed three-dimensional finite volume model of the cell is developed, adopting the commercial CFD code ANSYS CFX 18.1. Different geometries are evaluated, concerning the stiffeners orientation and tubes layout to compare BZ cooling ability of different tubes layout and mark the advantage and disadvantage of the different configurations.

2. DEMO WCLL breeding blanket design

Current WCLL BB design is based on DEMO 2015 specifications [7] and CAD model, characterized by 18 sectors which each sector is 20° including two Inboard Segments (IB) and three Outboard Segments (OB). The BB consists of: FW, an external box of Eurofer water-cooled by counter-current square channels with a Tungsten layer of 2 mm that faces the plasma, and BZ, an internal box filled with liquid PbLi alloy that flows through channels, defined by Eurofer structural stiffeners, refrigerated by water that flows in several Double Wall Tubes (DWTs). See Fig.1 as sample referred to the design 2016v1.0.

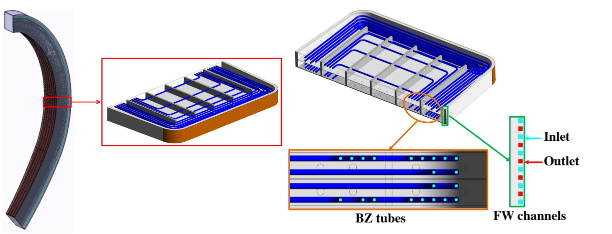

Fig. 1: WCLL BB 2016v1.0 segment with elementary cell: details of FW and BZ tubes.

Two different stiffener arrangements are considered for this comparative analysis, as reported in Fig.2, toroidal-poloidal and radial-poloidal [8] [9] [10]; consequently, this allows different DWTs layouts. Both elementary cells have toroidal length of 1500 mm, radial dimension of 1000 mm and total height of 135 mm. The number and size of the formed channels are different, due to the different stiffeners approach (Table 1).

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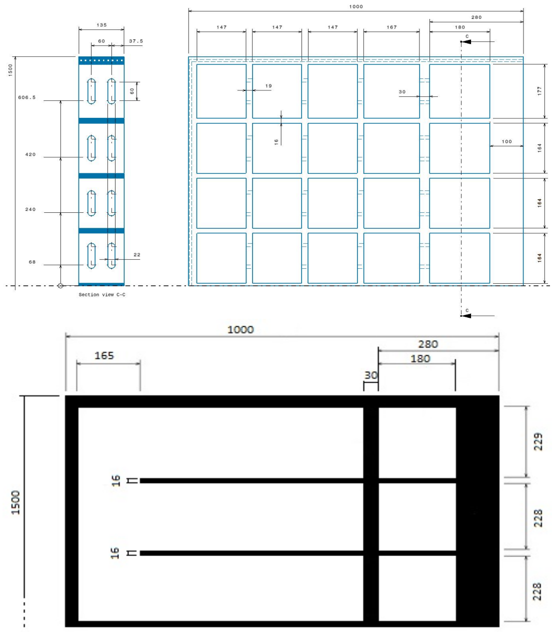

Fig. 2: WCLL 2017 half equatorial elementary cell geometry: a) toroidal-poloidal stiffeners (up), b) radial-poloidal stiffeners (down).

Table 1: BZ Geometrical parameters of WCLL elementary cell

Configuration		Channels [#]	Toroidal [mm]	Radial [mm]
Rad-Pol	Side	2	229	665
	Mid	4	228	665
Tor-Pol	Side	6	177	147
		2	177	167
	Mid	18	164	147
		6	164	167

2.1 Toroidal-poloidal stiffeners

This configuration fit with two different tubes layout, vertical (2017.T03) and horizontal (2017.T02).

Vertical layout has poloidal tubes that pass through the BZ of the whole segment of the WCLL. The tubes path starts from the upper part of the segment where the water flows downwards, passing into the channels formed by the intersection of the stiffeners, to reach the lower part of the segment, and curves in a U-shape to ascend towards the upper part, where there is the outlet manifold.

Horizontal tubes have a radial-toroidal-radial path. The tubes path starts from the manifold placed in the back part of the BZ elementary cell, go straight through predicted holes to the FW crossing the stiffeners (Fig.3) and curves in a U-shaped returning to the outlet manifold placed in the back part of the BZ [8] [11] [12].

2.2 Radial-poloidal stiffeners

The elementary cell fit with different horizontal tubes layout with U-shaped (2017.T01A) [10] or C-shaped (2018v0.2) DWTs. Both layouts, as the vertical tubes of the previous configuration, respect the manufacturability requirement to not cross the stiffeners. The tubes path starts from the manifold, it goes straight in radial direction reaching the FW, then the tubes bend differently: the U-shape curves within the channel composed by two stiffeners or Side Walls (SWs), and the C-shape has a greater length extension in front of the FW going beyond the width of the channel formed by two stiffeners.

3. Problem formulation and numerical model

For this study, to mark up the thermal-hydraulics advantage and disadvantage, different tubes layout with the relative stiffener orientation are analyzed and compared. The Reynolds Averaged Navier Stokes (RANS) equations have been solved for the single-phase fluid domains, using the k-ω Shear Stress Transport (SST) turbulence model. Thermal conduction is enabled allowing the heat transfer between the domains.

The material physical properties have been implemented in CFX. The physical 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. The relevant properties of Eurofer and water are summarized in the Table 2 and Table 3; PbLi thermal properties are reported in Ref. [13]. Regarding the properties of Tungsten, shown in Table 4, constant values are imposed due to the very limited variation (2-5%) in the temperature range [5].

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

Equation	Unit
$\rho = 7874.3 - 0.361 \cdot T$	kg/m^3
$c_p = -438.83 + 4.9838 \cdot T - 8.7371 \cdot 10^{-3} \cdot T^2 + 5.3333 \cdot 10^{-6} \cdot T^3$	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
$\rho = -1.4226 \cdot 10^{-2} \cdot T^2 + 14.122 \cdot \mathrm{T} - 2693$	kg/m^3
$c_p = 9.8485 \cdot 10^{-3} \cdot T^3 - 16.39861 \cdot T^2 + 9118.681 \cdot T - 1.6882247 \cdot 10^6$	J/(kg K)
$\lambda = -1.2024 \cdot 10^{-5} \cdot T^2 + 1.1846 \cdot 10^{-2} \cdot \mathrm{T} - 2.2804$	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: Tungsten thermo-physical properties

Equation	Unit
$\rho = 19300$	kg/m^3
$c_p = 145$	J/(kg K)
$\lambda = 125$	W/(m K)

The first layout is the vertical U-shape WCLL 2017.T03 with toroidal-poloidal stiffener orientation, is modelled on the central unit composed of four boxes [8]. Optimization analysis demonstrated that the minimum number of tubes to refrigerate the breeder unit is 14 amounting to a total 112 tubes per OB segment, an overview of the analyzed geometry is reported in Fig. 3.

The modelled domains are: Eurofer for structures and tubes and solid PbLi for breeder. The water-side heat transfer is modeled by the Heat Transfer Coefficient (HTC) as BC, and the pipes thermal resistance is calculated by the code. This method reduces calculation time. The passive cooling of the BZ from the FW is simulated by a negative heat flux, $q'' = -130\ kW/m^2$ at the surface in touch with the FW [11]. Periodic BC are imposed on the upper and lower surfaces of toroidal-poloidal stiffeners and tubes. The HTC is $h_{int} = 38793\ W/m^2\ K$, calculated from the Dittus-Boelter correlation assuming an average water velocity $u_{water} = 5\ m/s$ and considering a water bulk temperature of 584 K [11] [12]. To perform the analysis, a radial power density curve in W/m^3 depending on the radial direction is created into the PbLi and Eurofer structures, based on the results in Ref. [10].

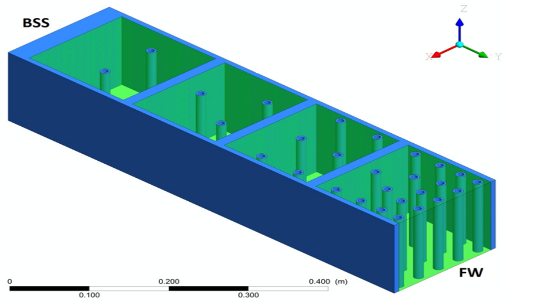

Fig. 3: WCLL 2017.T03 tubes layout for breeder unit geometry of toroidal-radial configuration

The second tubes layout is the configuration 2017.T02 of WCLL, analysis and boundary conditions (BCs) are reported in Ref. [11] [12] and only the results will be reported. The geometry is shown in Fig. 4.

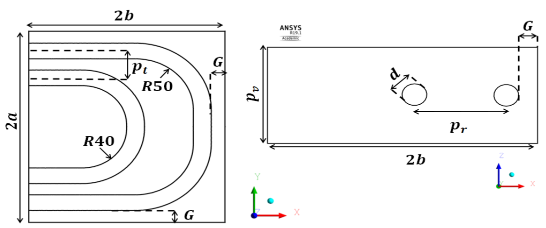

Fig. 4: WCLL 2017.T02 Cell geometry: radial-toroidal (left), radial-poloidal (right)

The third configuration analyzed is the WCLL V2017.T01A with three rows of U-shaped horizontal tubes [10] with radial-poloidal stiffeners orientation. This layout is carried out after optimization of Ref. [9] [10]. The analyzed geometry is the equatorial elementary cell of the OB segment based on the DEMO Baseline 2015. Dimensions and geometry are reported in Ref. [10]. In this analysis, the PbLi is set as solid domain to consider the MHD influence on the suppression of the buoyancy forces, as a conservative assumption. The BCs are reported in Ref. [10].

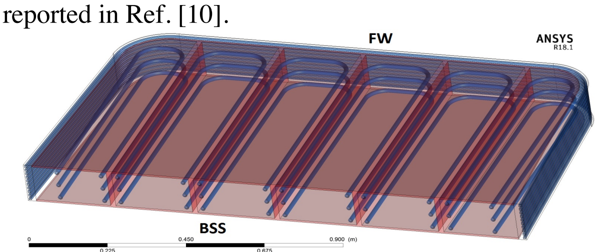

Fig. 5: WCLL 2017.T01A OB equatorial elementary cell geometry

The last configuration is the WCLL 2018v0.2 of the equatorial OB segment. The geometry of this configuration is reproduced considering the thermo-mechanical analysis provided in Ref. [9] and the dimensional analysis made by Ref. [8]. The breeding unit has a toroidal distance of 1500 mm, the radial dimension is 540 mm and the total height is 135 mm. The BZ coolant system consists of 20 C-shape DWTs, due to the optimal cooling performance obtained in Ref. [5]. The number of tubes to refrigerate the configuration is based on previous analyses reported in Ref. [5] and [10]. The elementary cell includes 10 square channels in the FW of 7×7 mm into the model. Volumetric power deposition curve in radial direction is modelled, according to Ref. [10]. Water mass flow rate for BZ and FW is calculated with the enthalpy balance for the DEMO 2017 baseline. An overview of the numerical model is reported in Fig.6.

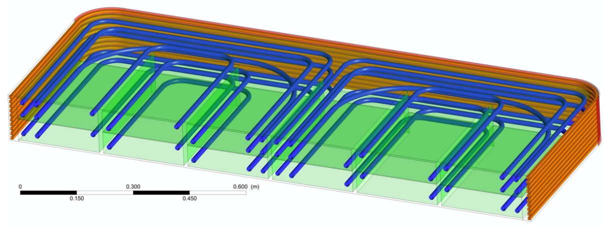

Fig. 6: WCLL 2018v0.2 OB equatorial elementary cell geometry

4. Mesh sensitivity

For all configurations a mesh independency analysis is performed for the finite volume model, allowing accurate results and reasonable calculation time, using meshes with different degree of detail. For WCLL 2017.T01A is described in Ref. [5] [10]. For WCLL 2018v0.2, the same criteria of the Ref. [5] has been adopted. For WCLL 2017.T02 is described in Ref. [11]. Concerning the WCLL 2017.T03 a mesh independence is performed using different degree of detail. A first preliminary independent analysis is conducted varying the global sizing and a second analysis is conducted varying the local size, increasing the tubes inflation layer in the breeder to evaluate the thermal boundary layer influence. The performed calculations are summarized in Table 5 and Table 6.

Table 5: Mesh independence, first analysis: mesh grid details and results

	Nodes	Element	Eurofer T Ave	PbLi T Ave
Coarse	479325	449728	669.66	667.70
Medium	2522325	2432192	670.02	668.37
Fine	7090409	6903744	670.17	668.55

Table 6: Mesh independence, second analysis varying the local size: mesh grid details and results

	Nodes	Element	Eurofer T Ave	PbLi T Ave
M1	2522325	2432192	670.02	668.37
M2	3130075	3030592	669.94	668.27
M3	4346745	4228544	669.92	668.24

Table 5 shows that a finer mesh does not provide significant improvements, therefore, having a significant number of elements, the Medium was adopted to evaluate the influence on the local sizing of the thermal boundary layer. The Table 6 shows that the increase in the number of elements of the boundary layer does not provide relevant refinement, consequently the M1 mesh was adopted.

5. Results and discussion

Regarding the WCLL 2017.T02, without the magnetic field, the channel is strongly dominated by buoyancy forces with high cooling performance due to the high velocity (around $v \sim 15\ ^{cm}/_{s}$) of the PbLi, that passes from a laminar flow to a turbulent flow. PbLi velocities are two order of magnitude higher than in forced convection. The highest temperature reached is $T = 715\ K$ (Fig. 7).

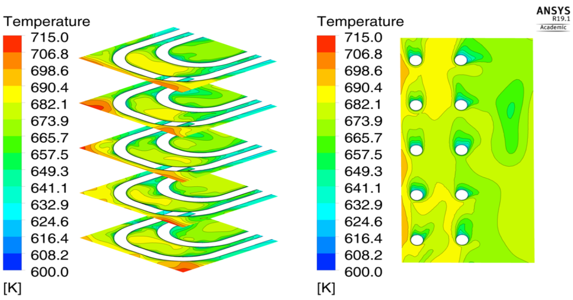

Fig. 7: OHD 5-cell stack temperature distribution on the horizontal planes passing through the pipe center (left) and the vertical central plane (right)

The MHD analysis returns a solution with: buoyancy forces almost suppressed and laminar flow. The temperatures are above the limit of 823 K (Fig. 8). Introducing the passive cooling of FW to the BZ with imposed heat flux of $q'' = -100\ kW/m^2$ and reducing the distance between cooling elements to $p_v = 40\ mm$ the temperature limit is met, but there are still hot spot in the corner due to the radius of the tubes. (Fig. 8).

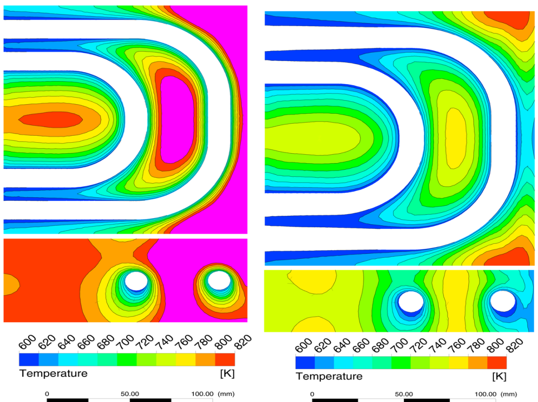

Fig. 8: Temperature distribution with MHD effect: flow without FW passive cooling (left), flow with FW passive cooling and reduced vertical tube pitch (right).

The results of WCLL V2017.T03 show a temperature field below the limit of 823 K for the Eurofer. As reported in Fig. 9, no hot spots are present inside the BZ and the temperature field is symmetric.

Evaluating the water thermodynamic cycle of DEMO, it results that the number of tubes is not enough to meet the required water velocity limit of 7 m/s. The number of tubes must be increased to more than 500 tubes per segment to reach velocity of 7 m/s inside the pipes (Fig. 10), thus increasing the amount of water and steel and reducing the amount of PbLi in the BZ.

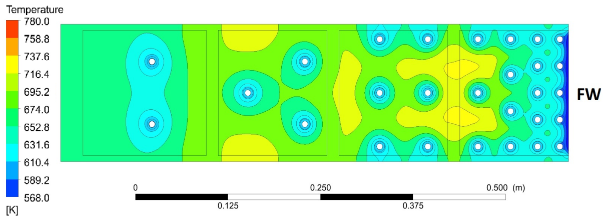

Fig. 9: Temperature distribution in the WCLL 2017.T03

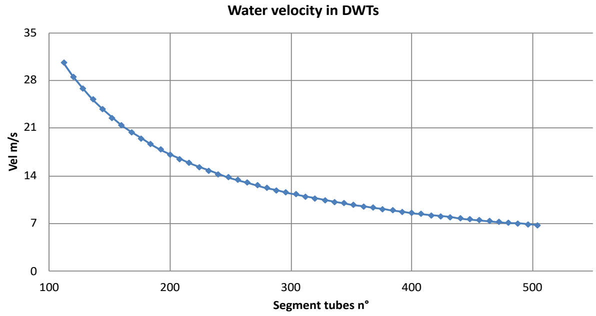

Fig. 10: Water velocity trend with increasing number of tubes

The third analysis, made on 2017.T01A, provides a symmetric temperature field into the BZ but, as it could be deduced from Ref. [10], three rows of tubes are not enough to satisfy the Eurofer temperature limit. As shown in Fig. 11, there are hot spots into the channels reaching temperature around 1200 K. The hot spots are related to the minimum curvature radius of the DWT (i.e. 50 mm) and the presence of the vertical stiffener plates. Indeed, they are placed about in the center of the DWT curvature and between two adjacent tubes, always close or in front of the FW. The mitigation of the high temperature zones would require a larger number of tubes in the elementary cell. No further analysis is conducted to find a solution for the hot spot suppression, being available the analyses on the same layout that are reported in Ref. [10].

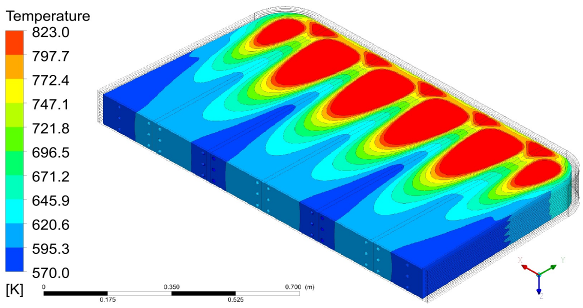

Fig. 11: WCLL 2017.T01A breeder temperature with hot spot

The WCLL 2018v0.2 is investigated to overcome the issues of version 2017.T01A. The analysis returns a solution with temperature symmetry in the toroidal direction, the Eurofer domain is slightly below the limit of 823 K (Fig. 12).

Although in the poloidal direction the buoyancy forces are almost suppressed, as seen in Ref. [12], no hot spot in that part of BZ occurs. High cooling performances are reached due to BZ and FW water outlet temperature, that is around 601 K (FW T~608 K and BZ T~600 K). It also results that there is a difference between the power deposited and the power extracted in the FW, phenomena investigated in Ref. [5].

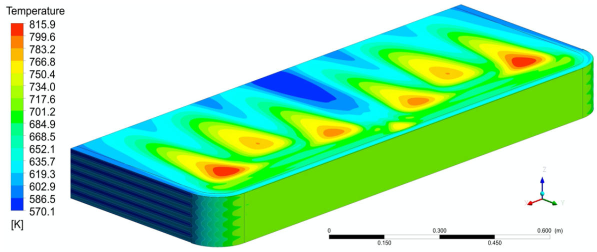

Fig. 12: WCLL 2018v0.2 Eurofer and Tungsten domain temperature

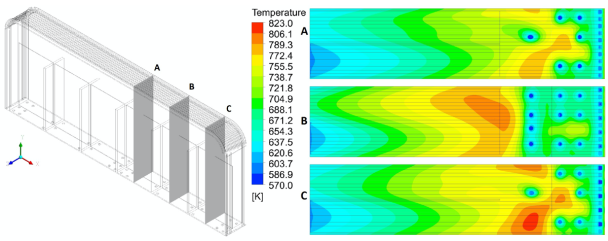

Fig. 13: WCLL 2018v0.2 temperature field radial poloidal view, A) plane at 121.5 mm from the center; B) plane at 364.5 mm from the center; C) plane at 607.5 mm from the center.

6. Conclusions

Temperature symmetry in toroidal direction is achieved for all configurations, but the cooling performance is satisfied only for three of them, not exceeding the Eurofer limit of $T_{max} \leq 823\,K$. As reported in the analyzed cases, the cell layout is significantly simplified by using horizontal tubes. Regarding the stiffener approach, the radial-poloidal arrangement is selected as the reference layout, due to the lower volume of Eurofer structures. Moreover, buoyancy forces are expected to contribute in enhancing the heat transfer compared with the poloidal flow case, even accounting the MHD dampening, due to larger characteristic length along the temperature gradient.

The WCLL 2017.T02 and 2017.T03 configurations reported promising temperature results but: in the first layout the amount of pipes required to cool down the hotspot is too high, thus creating a very large number of slots for the passage of the tubes not guaranteeing however the suppression of hot spots at the corners, and in the second layout more than 500 tubes are needed, reducing the PbLi inventory inside the segment, penalizing the TBR performances. The WCLL 2017.T01A configuration, considering the previous analyses, presents a hot spot of T~1200K, which requires a higher number of tubes to mitigate it.

The WCLL 2018v0.2 configuration presents a symmetric temperature field and below the required limit. BZ and FW have high cooling performance with a reduced number of tubes, without crossing stiffeners. This configuration is the selected design for the further analyses concerning the MHD effect and an optimized mass flow rate to enhance the cooling performances.

Acknowledgments

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