

Development of heat sink concept for near-term fusion power plant divertor

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Abstract. Development of an efficient divertor concept is an important task to meet in the scenario of the future fusion power plant. The divertor, which is a vital part of the reactor has to discharge the considerable fraction of the total fusion thermal power (~15%). Therefore, it has to survive very high thermal fluxes (~10 MW/m²). In the present paper, an efficient divertor heat exchanger cooled by helium is proposed for the fusion tokamak. The Plasma facing surface of divertor made-up of several modules to overcome the stresses caused by high heat flux. The thermal hydraulic performance of one such module is numerically investigated in the present work. The result shows that the proposed design is capable of handling target heat flux values of 10 MW/m². The computational model has been validated against high-heat flux experiments and a satisfactory agreement is noticed between the present simulation and the reported results.

1. Introduction

Helium cooled divertor design is one of the potential options for future fusion reactors [1]. Since, helium is chemically and neutronic inert which is favorable from a safety aspect. On the other hand, due to deprived thermo physical property of helium a highly efficient design and cooling technique is desirable for the reactor divertor to sustain the heat flux ~10 MW/m². The present paper describes the detailed design study of a new divertor heat exchanger concept for the tokamak application. The effects of critical thermal hydraulic parameters on the heat transfer characteristics of the module are presented as a function of Reynolds number (*Re*).

Different type of helium cooled concept have been reported for the plasma-facing surface for the power plant application. Pizzuto et al. [2] studied the High Efficiency Thermal Shield (HETS) concept for tokamak design. The result showed that the HETS solution is feasible in order to achieve a good heat transfer at the low cost of pressure drop. Diegele et al. [3] investigated the modular divertor for future fusion power plant with an improved heat transfer technique. In their investigation, they found that modular concept has the potential of removing high heat flux (~10 MW/m²) at reasonable pumping power. Experimental and numerical investigation on divertor finger mock up was investigated by Rimza et al. [4-6]. They discovered that, the potential of divertor to handle heat flux increase largely, by the use of the extended surfaces. High Efficiency Thermal Shield (HETS) is based on a finger mock-up concept for tokamak design. In the present study, a new efficient divertor heat exchanger design concept has been



proposed to provide a larger scale divertor concept that would minimize the number of units. Hence, the cost of manufacturing will also decrease. The effect of critical hydraulic parameter on the thermal hydraulic performance of divertor heat exchanger has been investigated using Fluent 14.0 [7].

2.0. Solution Methodology

2.1. Proposed Design

Plasma-facing surface of divertor is fabricated of tungsten with sacrificial layers (4 mm) as shown in figure 1. Tile is joined on the thimble by brazing and fabricated by high ductility tungsten alloy. A high temperature filler material Pd-Ni 40 (1511 K) has been used as a brazing filler between the mating surfaces [8]. To cooled the hot thimble, a jet cartridge carrying the multiple jets is placed concentrically inside the thimble. All the geometrical parameters of a divertor heat exchanger are shown in the Table 1.

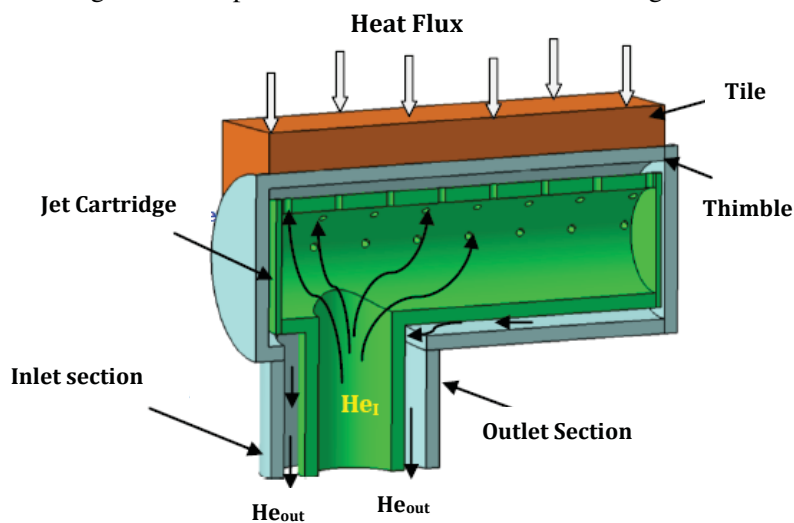


Figure 1. Diagram of proposed divertor heat exchanger.

Helium (He) enters through the inlet section of the cartridge, and accelerates through the multiple jets (\varnothing 0.6) and flows radially outwards through outlet section as shown in figure 1. The most important design criterion is to keep thimble temperature above ductile brittle transition temperature ($\sim 600^{\circ}\text{C}$) and below the brazing filler temperature of the mating surface (1511 K). The pumping power ratio should be lower than $\sim 10\%$ of incident power [4].

Table 1. Detailed geometrical parameters of a divertor heat exchanger.

Divertor	Dimension (mm)		Material
	Diameter	Thickness	
Tile	16.8	4	Tungsten (W)
Thimble	16	1.25	Tungsten Alloy (WL-10)
Jet Cartridge	11.5	1.25	Indian RAFMS

2.2. Initial Boundary Conditions

The computational domain of interest considered for the present numerical simulation is depicted in figure 1. Due to symmetry, only 180° sector model has been considered for the present simulation. The domain

consists of three solid volumes viz., tile, thimble, cartridge and one fluid volume. The material properties of the tile and thimble are modeled as temperature-dependent [9]. Helium is specified as an ideal gas. The boundary conditions for 3D simulations are as follows:

- Adiabatic boundary conditions are applied on outer sides of the domain.
- The top surface of the domain is applied with constant heat flux $\sim 10 \text{ MW/m}^2$.
- Specified mass flow rate, temperature and pressure (600°C and 10 MPa) are assigned at the inlet manifold [4].

Pressure-velocity coupling between the incompressible Navier-Stokes and continuity equations are resolved using the SIMPLE algorithm [10]. The effect of accompanied by adapting the k - ϵ realizable model. The convective and diffusive fluxes are combined using the second order upwind scheme. To declare convergence, the errors and discretized momentum and continuity equation, are set to a value below 10^{-4} , whereas for energy equation it is set to below 10^{-6} .

3.0. Results and Discussion

3.1. Model Validation

To test the validity and enhance the level of confidence in numerical solutions, the present simulation has been validated against the results of Končar et al. [11]. Systematic studies for various mass flow rates with different heat flux, inlet pressure and temperatures have been performed. The predicted results are compared with experimental as well as numerical results and are presented in figure 2, for a fixed flow rate of 13.7 g/s .

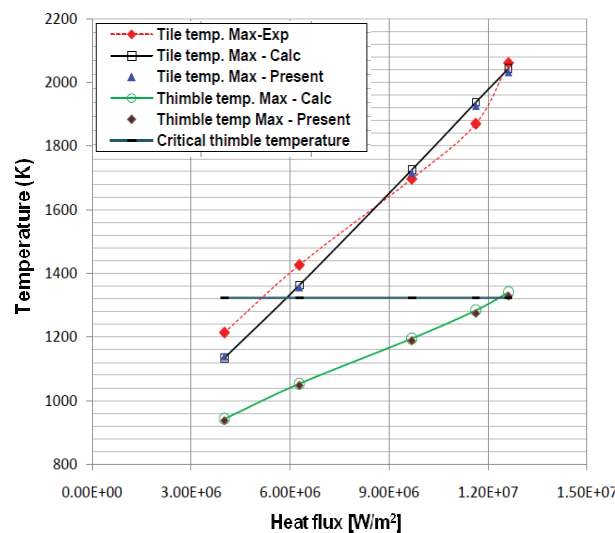


Figure 2. Comparison of present maximum tile and thimble temperature and reported results as a function of heat flux.

The temperature increase more or less linearly with heat flux, as expected. The temperature distributions along the tile, thimble, helium temperature difference of the present simulation at different heat fluxes are in satisfactory agreement with the reported results.

3.2. Assessment of Thermal-hydraulic Performance

The prime motive of this study is to find the required mass flow rate at a reasonable pressure drop for cooling of heat exchanger. Towards this, numerical studies have been performed at various mass flow rates, viz., 10, 13, 15, 20 and 25 g/s, corresponding to the Re numbers is 1.2×10^4 , 1.5×10^4 , 1.8×10^4 , 2.4×10^4 and 3.0×10^4 . Temperature distributions on the surface of tile and thimble for various Re Numbers for design heat flux (10 MW/m^2) is depicted figure 3(a). It can be noticed that, the tile and thimble temperatures decrease with Re numbers. This implies that increasing the Re Numbers makes eddies stronger, and increase the fluid mixing causing the highest heat transfer rate in the modular heat exchanger. The results show that tile and thimble mating surface filler temperature are within design limits for Re numbers of $\sim 1.58 \times 10^4$. The temperature distributions in the modular heat exchanger, as predicted by the numerical model are depicted in figure 3(b). The temperature across the left corner of tile is slightly varied, presumably due to impact of jet velocity.

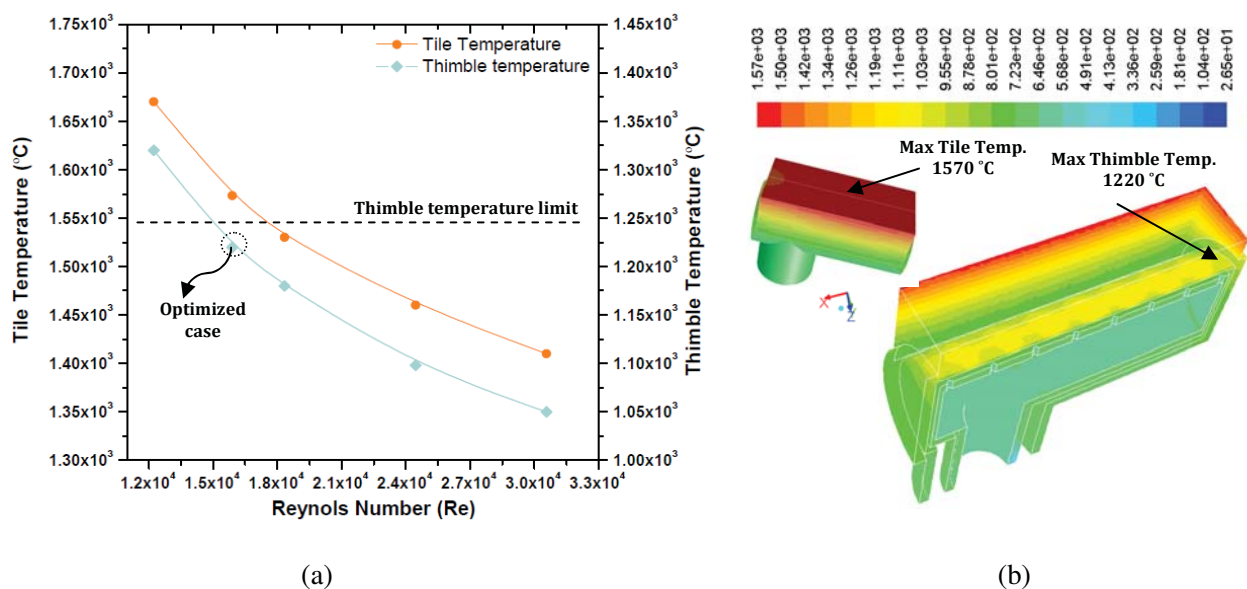


Figure 3. Comparison of (a) maximum tile & thimble temperature as a function of Re Numbers and (b) predicted temperature distribution over the heat exchanger at $Re \sim 1.58 \times 10^4$.

Pumping power ratio (J) is one of the most significant factors that reflect the hydraulic performance of the heat exchanger. It is the ratio of required pumping power to circulate helium in the heat exchanger to cool the hot target surface to the total incident power [4]. The Pumping power ratio for the modular heat exchanger is given by,

$$J = W/Q_T \quad (1)$$

where W is the pumping power for modular heat exchanger of divertor ($W = m \times \Delta P / \rho$), m is the mass flow rate of coolant, ΔP is the pressure drop in in divertor heat exchanger, ρ is the density of coolant, and Q_T is the total incident power.

Figure 4 presents the variation in the pumping power ratio as a function of Re numbers. It is clear that pumping power ratio increase continuously with Re numbers. The possible reason is that, the formation of

vortex and high velocity, turbulence level increases, leading to the associated increase in heat transfer. However, eddies and flow acceleration caused by high velocity, increase the pressure loss in the heat exchanger.

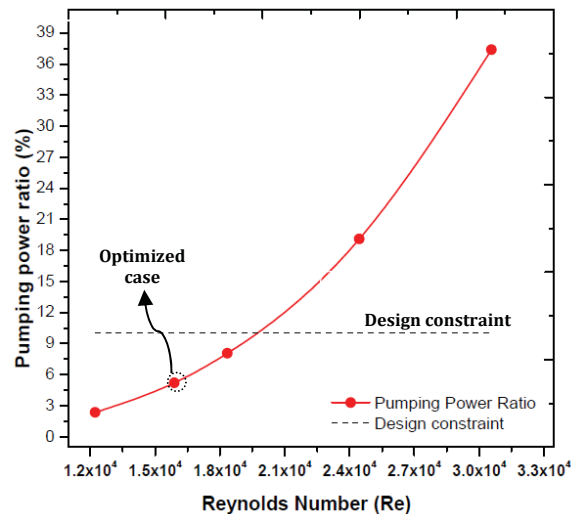


Figure 4. Variation in pumping power ratio as a function of Re Numbers

The results show that pumping power ratio is well within the design limit ($< 10\%$) at Re number 1.58×10^4 . It is observed that only $\sim 5\%$ pumping power ratio is required at prototypical Re numbers to maintain the desired thimble filler temperature constraints. From all these studies, it is clear that the proposed divertor heat exchanger has the capability to extract design load at acceptable pumping power ratio.

4.0. Conclusions

The three dimensional heat transfer characteristics of a new divertor heat exchanger proposed for fusion reactor are investigated through jet impinging technique. The main purpose of the present investigation is to evaluate thermal hydraulics performance of proposed heat exchanger. Numerical investigations showed that the proposed design is capable of handling target heat flux values of 10 MW/m^2 . The present analysis shows that proposed heat exchanger design should be accepted for Re numbers less than $\sim 1.58 \times 10^4$ (13 g/s) to make sure desired pumping power ratio and thimble temperature limits.

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