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Numerical Study on Multiple Jet Impingement Cooling System for Nuclear Fusion Reactor Divertor

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1. Introduction

Nuclear fusion technology is one of the promising technologies to meet the increasing energy demand. Divertor is an essential component of fusion reactor, which removes the fusion reaction ash, unburned fuel, and plasm impurities that result in an extremely high heat flux load. Multiple jet system has been regarded as an effective divertor cooling system which shows heat removal capacity at least 10 MW/m^2.

In the last decade, a large number of researches have been conducted for the divertor cooling [1]. Various types of cooling device have been proposed for divertor including plate, T-tube, and finger types. And, it was found that Helium (He) cooled divertor design is feasible at a reasonable pumping power. Rimza et al. [2] studied both experimentally and numerically the heat transfer characteristics of a divertor finger module with sectorial extended surfaces. Koncar et al. [3] analyzed the effects of nozzle sizes on heat transfer efficiency of multiple impingement cooling system of finger type.

As mentioned above, Koncar et al. [3] tested various cases with different nozzle sizes, but there was a lack of systematic analysis on thermal performance. In the present work, thermal performance of a finger type multiple jet impingement cooling system has been evaluated for various geometric parameters using three-dimensional Reynolds-aeraged Navier-Stokes (RANS) equations. The objectives of this research are to analyze the flow structures of multiple jet cooling system, and to investigate the effects of geometric parameters of the divertor cooling system on the heat transfer.

2. Numerical method

In the present study, thermal-hydraulic characteristics of a finger type cooling module for a He-cooled divertor were analyzed by solving three-dimensional RANS equations using commercial computational fluid dynamics (CFD) code, ANSYS-CFX 15.0, with shear stress transportation (SST) turbulence model. Fig. 1 shows geometry of the finger type multiple jet impingement cooling system investigated in this work. As shown in Fig. 1, the computational domain consisted of one fluid domain and three solid domains (tile, thimble, and cartridge). The working fluid (He) was considered as an ideal gas. Mass flow rate was set at the inlet boundary. Heat flux of 11.6 MW/m^2 was applied at the top surface, and the periodic conditions were applied at the periodic boundaries. In solid domains, material properties of the tile and thimble were set using temperature dependent expressions. Conjugate heat transfer in the solid and fluid domains of the divertor was calculated.

An unstructured tetrahedral grid system with prism layer meshws were used in this study. Pentahedral meshes were focused at the wall region to resolve the high temperature gradient, and the meshes were also concentrated in the regions where impingement occurs. A grid dependency test was carried out in a range of node number from 580,000 to 1,920,000 for the reference geometry, and the optimum number of element was found to be approximately 1,540,000.

3. Design variables and objective function

Fig. 1 shows geometric parameters investigated in this work: the ratio of center hole diameter to reference cartridge diameter (D_1/D), and the angles of hole 1, hole 2, hole 3, and hole 4 at the x-axis, θ_1, θ_2, θ_3, and θ_4, respectively.

To evaluate the thermal performance of cooling system of the divertor, the normalized heat transfer coefficient (HTC/HTC_{ref}) was considered as the objective function:

$$HTC = \frac{q_{wall}}{(T_{wall} - T_{inlet})} \tag{1}$$

where q and T indicate the heat local wall heat flux and the temperature, respectively.

4. Results and discussion

Fig. 2 shows the effects of the parameters on the overall heat transfer coefficient (HTC) of the He-cooled divertor. It was observed that the heat transfer

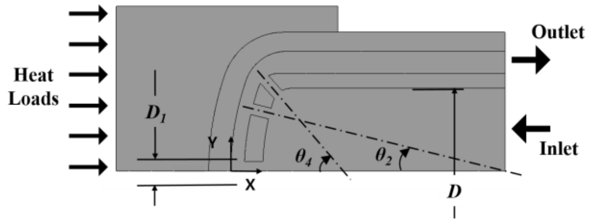

Fig. 1. Computational domain and design parameters.

coefficient generally decreases with the increase in D_1. At θ_1=9.97*deg*, HTC was increased by 2.32% in comparison with the reference geometry. It is found that the HTC slightly decreases with the increase in θ_2. The heat transfer coefficient generally increases with the increase in θ_3. The relative variation of HTC was only 0.67% in the tested range of θ_4. The heat transfer coefficient was more affected by the diameter of center hole, θ_1, and θ_3 than θ_2 and θ_4.

Figs. 3-5 show effects of D_1/D, θ_1, and θ_3, on flow field. Distributions of velocity contour for D_1/D=0.099 and D_1/D=0.175 are shown in Fig. 3. Diameter of the center hole in Fig. 3(a) is much smaller than that in Fig. 3(b), resulting in the reduction in the low-velocity region which improves the overall heat transfer.

Fig. 4 represents the turbulent kinetic energy distributions with different θ_1. With the increase in θ_1, the area of high-turbulent kinetic energy near the outlet of hole 1 increases, which enhances the turbulent kinetic energy, and thus increases the heat transfer at the target plate.

The velocity distributions depending on θ_3 are shown in Fig. 5. Concentration of high-velocity region appears in the hole 3 at θ_3=18.61*deg*, resulting in improvement of the overall heat transfer coefficient.

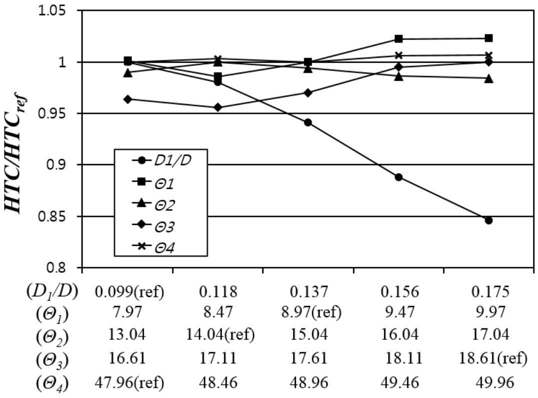

Fig. 2. Effects of geometric parameters on heat transfer coefficient.

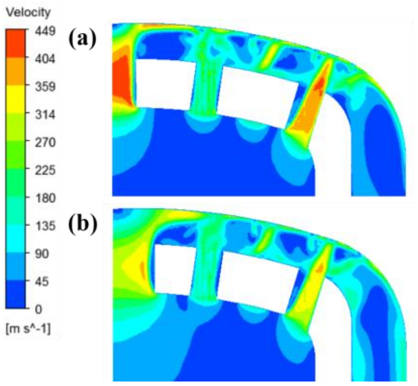

Fig. 3. Distributions of velocity contour: (a) D_1/D=0.099 and (b) D_1/D=0.175.

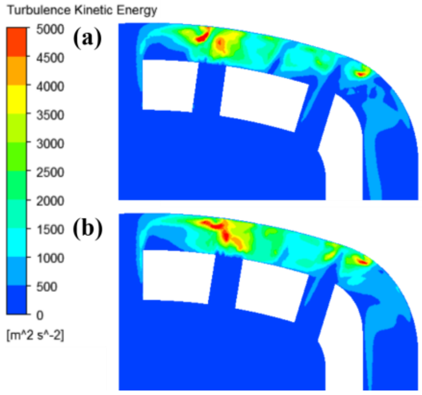

Fig. 4. Turbulence kinetic energy distributions: (a) θ_1=8.47*deg* and (b) θ_1=9.97*deg*.

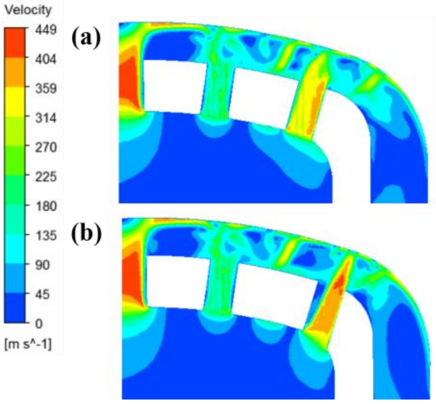

Fig. 5. Distributions of velocity contour: (a) θ_3=17.11*deg* and (b) θ_3=18.61*deg*.

5. Conclusions

A parametric study was carried out to investigate the effects of the geometry of the finger type module of impinging jet divertor cooling system on heat transfer by using three-dimensional RANS equations. The parameters related to the size and locations (θ_1, θ_3, θ_2 and θ_4) of the jet holes were considered as geometric parameters and the effects of these parameters on heat transfer were evaluated. The heat transfer coefficient was more affected by the diameter of center hole, θ_1, and θ_3 than θ_2 and θ_4.

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