Fusion Engineering and Design 114 (2017) 102–112

Contents lists available at ScienceDirect

Fusion Engineering and Design

journal homepage: www.elsevier.com/locate/fusengdes

Thermal-hydraulic performance of a multiple jet cooling module with a concave dimple array in a helium-cooled divertor

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ARTICLE INFO

Article history:
Received 13 September 2016
Received in revised form
20 November 2016
Accepted 6 December 2016
Available online 21 December 2016

Keywords:
Concave dimples
He-cooled divertor
Finger type cooling module
Multiple jet impingement
Nuclear fusion reactor
Reynolds-averaged Navier-Stokes equations

ABSTRACT

A numerical study was performed to evaluate the thermal-hydraulic performance of a finger type cooling module, where multiple jets impinge on the surface with concave dimples, in the divertor of a nuclear fusion reactor. Conjugate heat transfer was analyzed in both the solid and fluid domains using three-dimensional Reynolds-averaged Navier-Stokes equations with the shear stress transport turbulence model. The computational domain consisted of a single fluid domain and three solid domains: tile, thimble, and cartridge. The numerical results for the temperature variation on the tile were validated in comparison with the experimental data. A parametric study was performed with two design variables, the ratios of dimple diameter and dimple height to the nozzle diameter, and two dimple arrays (inline and staggered arrays). The parametric study showed that the heat transfer rate was increased by up to 2.62% by introducing concave dimples, and that the heat transfer and pressure drop performances increased with increasing diameter and height of the dimples for a specified dimple array.

1. Introduction

Cooling technology for divertors in nuclear fusion reactors is crucial for enduring a high heat flux of at least 10 MW/m^2, which is generated by unburned fuel, erosion particles, and helium ash. In this respect, many types of cooling systems have been developed for divertors. The finger type cooling module is one of the effective cooling devices developed for a divertor cooling system using helium (He) as a coolant. On the other hand, to increase the power of the fusion reactor, heat transfer in the divertor cooling module needs to be enhanced further by introducing heat transfer augmentation techniques, such as the use of turbulators, which promote the generation of turbulent kinetic energy.

Divertor cooling systems are generally classified into three types according to the coolant: water-cooling, liquid metal-cooling, and He-cooling systems. The water-cooling system has an advantage of using well established technology in water-cooled nuclear fusion reactors. In the case of the liquid metal-cooling system, the coolant can withstand higher heat flux than other coolants, but the material properties of the liquid metal are not well established. A He-cooling system uses He as the coolant, which is also used for cooling all the other components of the fusion reactor. Therefore, it has the advantages of simplifying the balance of the fusion reactor and eliminating the risks of hydrogen generation.

A number of cooling devices have been proposed for a He-cooling system, e.g., plate, T-tube, and finger types [1], as shown in Fig. 1. The plate type cooling device uses a jet flow to cool the heated wall, as shown in Fig. 1(a). This device uses larger units that reduce the total pressure drop and number of units than the others. However, there is some instability due to a difference in the dynamic stress between the top and bottom sides. T-tube and finger type devices also use a helium jet issued from narrow slits and holes, respectively, as shown in Fig. 1(b) and (c). In the case of the T-tube type device, the cooling performance can be improved by reducing the thickness of the sacrificial layer, but there is a clear limitation in reducing the thickness. Therefore, among these cooling devices, the present study examined the finger type cooling device.

Finger type cooling devices can be classified into two main concepts; a He-cooled modular divertor with slot array (HEMS) and a He-cooled modular divertor with jet cooling (HEMJ) [2], as shown in Fig. 1(c). Both concepts consist of a small hexagonal tungsten tile as a sacrificial layer and a thimble composed of a tungsten alloy. To improve heat transfer in the cooling module, the HEMS requires an additional device, such as a tungsten slot at the bottom of the thimble, which makes the system more complex, increases the dif-

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http://dx.doi.org/10.1016/j.fusengdes.2016.12.008
0920-3796/

Nomenclature

D	Diameter of dimple (m)
f	Dimensionless pressure drop
H	Height of dimple (m)
HEMJ	He-cooled modular divertor with jet cooling
HEMS	He-cooled modular divertor with slot array
k	Fluid thermal conductivity (W/mK)
Nu	Nusselt number
$\overline{Nu}$	Area averaged Nusselt number
P	Static pressure (Pa)
q	Local heat flux (W/m^2)
RANS	Reynolds-averaged Navier-Stokes
RMS	Root mean square
SES	Sectorial extended surfaces
SST	Shear stress transport
T	Local temperature (K)
V	Average axial velocity (m/s)
x, y, z	Cartesian coordinates (m)
ρ	Density (kg/m^3)

Subscripts

d	Dimple
f	Fluid
in	Inlet
j	Jet
max	Maximum
out	Outlet
t	Tile
$thimble$	Thimble
w	Wall

ficulties in its fabrication, and enhances the manufacturing cost. Therefore, HEMS was not defined as a reference design concept. In contrast, the HEMJ concept requires multiple small jet holes at the top of the steel cartridge, rather than using extra devices to enhance the heat removal capacity. The HEMJ concept has been studied more broadly for fusion power plants in Europe. Therefore, the HEMJ concept using multiple jets was employed for the finger type cooling module studied in the present work.

Several studies, both experimentally and numerically, have been performed on finger type cooling modules using multiple jets in He-cooling systems for divertors. Koncar et al. [3] reported the results of a computational study on the heat transfer performance for different edge shapes of tile in a finger type module. Weathers et al. [4] and Krussmann et al. [5] presented the distributions of the heat transfer coefficient, temperature, and pressure drop in air and helium flow loops, respectively, in finger type cooling modules, and showed that these performance parameters agreed well with the experimental data. Koncar et al. [6] studied numerically the heat transfer distribution in a finger type cooling module with different nozzle sizes of the jet cartridge. Their results indicated that the heat removal capacity of the central jet could be improved using a smaller diameter center hole. Koncar et al. [7] carried out a numerical analysis to evaluate the parameters, i.e., heat transfer coefficient, pressure drop, and structure temperature, with five different cooling systems based on the diameter and number of jet nozzles. They reported that the maximum values of the thimble temperature and Mises stress decreased without nozzles in the fourth row and without nozzles in the fourth row and equal jet cross sections, respectively.

Dimples are popular heat transfer augmentation devices used in a range of cooling passages because they can delay the development of a thermal boundary layer and promote the production of turbulent kinetic energy with minimal pressure loss [8]. Several studies have examined the effects of the dimples on the heat transfer and flow characteristics. Kim and Kim [9] evaluated numerically the heat transfer performance of four configurations of the dimple array, i.e., concave-inline, concave-staggered, convex-inline, and convex-staggered, in a micro jet-dimple cooling system. Rao et al. [10] performed an investigation both experimentally and numerically on heat transfer and friction in a dimpled channel for different shapes of dimples, such as sphere, teardrop, ellipse, and inclined ellipse. Kim and Kim [11] investigated numerically the effects of the dimple height and diameter on the heat transfer and pressure drop in a channel with a staggered-convex impinging jet-dimple array. In contrast, a few studies on the divertor cooling examined the cooling system with heat transfer augmentation devices. Rimza et al. [12–14] evaluated the effects of sectorial extended surfaces (SES) on the heat transfer characteristics of jet impingement in the finger type module of a He-cooling system. They reported that the cooling modules with SES showed better heat transfer performance than that without SES. Obviously, the modification of shape and configuration of the heat transfer augmentation devices in the cooling system affects the cooling performance.

As mentioned above, heat transfer augmentation devices, such as dimples, are efficient for enhancing heat transfer in heat exchanging systems. However, the dimples have not been introduced in He-cooled divertor to enhance the cooling performance of the multiple jet cooling system. The present work examined the flow structure and heat transfer in a finger type module for divertor cooling with different shapes and configurations of concave dimples on the impinging surface using three-dimensional Reynolds-averaged Navier-Stokes (RANS) equations. The Nusselt number on the impinging surface and pressure drop through the module were evaluated for two geometric parameters (diameter and height of the dimples), and two configurations (inline and staggered dimple arrays).

2. Geometry of the cooling module

Fig. 2 shows the geometry of a single finger type module developed at the Karlsruhe Institute of Technology [15], which was investigated in this work. Table 1 lists the geometric parameters of the reference cooling module. The single module was comprised of three parts: tile, thimble, and cartridge, as shown in Fig. 2(a). A small hexagonal tile of tungsten was employed as a thermal shield and sacrificial layer. A thimble made of tungsten alloy was brazed to the tile. A steel cartridge with jet nozzles was placed concentrically inside the thimble. As shown in Fig. 2(b), the coolant fluid enters through the inlet of the cartridge. Multiple jets issue from the nozzles impinge on the thimble surface, and the coolant flows between the cartridge and thimble to exit the cooling module.

3. Numerical analysis

Three-dimensional analyses of the flow field and heat transfer in the finger type cooling module were performed using commercial software ANSYS CFX 15.0 [16]. The steady RANS equations were discretized using the finite volume method. The shear stress transport (SST) turbulence model [17] was used as the turbulence closure model, which integrates the benefits of the k-ε and k-ω models. The blending function ensures a smooth transition between the k-ω model in the near-wall zone and the k-ε model in the rest zone. Conjugate heat transfer in both the solid and fluid domains in the cooling module was calculated.

Figs. Fig. 22(a) and Fig. 3 3 present the computational domain, where the present numerical analysis was performed. A circumferentially 60° element of the entire module indicated in Fig. 2(a) was