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Optimal design of divertor heat sink with different geometric configurations of sectorial extended surfaces

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HIGHLIGHTS

- Effect of design variables in enhancing heat removal potential with pumping power assessed.
- The optimization objective is to minimize the thimble temperature.
- Investigation of optimum design parameters for various Reynolds number.
- Practicability of the optimum designs is verified through structural analysis.
- Benchmark validation of divertor finger mock-up against in-house experiment and good agreement is achieved.

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ABSTRACT

Cooling of fusion reactor divertor by helium is widely accepted due to its chemical and neutronic inertness and superior safety aspect. However, its poor thermo physical characteristics need high pressure to remove large heat flux encountered in fusion power plant (DEMO). In the perspective of DEMO, it is desirable to explore efficient cooling technology for divertor that can handle high heat flux. Toward this, a novel sectorial extended surface (SES) was proposed by the authors Rimza et al. (2014) [2]. The present work focuses on design optimization of divertor finger mock-up with SES to enhance the thermal hydraulic performance. The maximum thimble temperature is considered as the vital design constraint. Various non-dimensional design variables, viz., relative pitch, thickness, jet diameter, the ratio of height of SES to jet diameter and circumferential position of the SES are considered for the present optimization study. The effects of design variables on thermal performance of the divertor are evaluated in the Reynolds number (Re) range of 7.5×10^4–1.2×10^5. The analysis reveals that, the heat transfer performance of divertor finger mock-up with SES is improved for two optimum designs having relative pitch and thickness of 0.30 and 0.56, respectively. Also, it is observed that finger mock-up heat sink with SES performs better, when the ratio of SES height to jet diameter, reduces to 0.75 at the cost of marginally higher pumping power. The effects of jet diameter and circumferential position of SES are found to be counterproductive toward the heat transfer performance. To understand the stress distribution in the optimized geometries, a combined computational fluid dynamics (CFD) and structural analysis has been carried out. It is found that deviation in peak stresses among various optimized geometries is not significant. The CFD model has been benchmarked against in-house experiments and good agreement is achieved.

1. Introduction

Nuclear fusion is a promising energy option for the future, which is characterized by almost unlimited fuel supplies and best safety characteristics. In a design of future fusion power plant [1], divertor must handle a high heat flux (~10 MW/m^2). Thermal management of such high heat flux gives rise to numerous engineering issues, which affect the thermal hydraulic performance and lifetime of the divertor components. Therefore, the complete divertor target plate is divided into a number of small volumes known as cassettes and each cassette is made up of several small cooling finger mock-ups to reduce the possible thermal stress as depicted in Fig. 1. The most important design criterion is to keep thimble temperature

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Nomenclature

A	area of the jet (m^2)
D	diameter of jet (m)
h	height of extended surface (m)
J	pumping power ratio
K_{eff}	effective molecular thermal conductivity of fluid [$K_{eff} = K_l + K_t$] (W/m K)
K_l	laminar thermal conductivity of fluid (W/m K)
K_t	turbulent thermal conductivity of fluid (W/m K)
K	thermal conductivity of solid (W/m K)
k	turbulent kinetic energy (m^2/s^2)
$\dot{m}$	mass flow rate (kg/s)
μ_{eff}	effective molecular viscosity of the fluid [$\mu_{eff} = \mu_l + \mu_t$] (N s/$m^2$)
μ_l	laminar viscosity of the fluid (N s/m^2)
μ_t	turbulent viscosity of the fluid (N s/m^2)
p	pitch of extended surface (m)
P	pressure (Pa)
Q_T	total incident power (Watt)
q''	heat flux (MW/m^2)
SES	sectorial extended surface
t	thickness of extended surface (m)
T	temperature (K)
u_j	velocity components in three spatial directions (m/s)
W	pumping power (Watt)

Greek symbol

ε	rate of dissipation (m^2/s^3)
Δ	differences
δ	relative
μ	dynamic viscosity (N s/m^2)
ρ	density of fluid (kg/m^3)

above ductile brittle transition temperature (~600 °C) and below the brazing filler temperature (1050 °C). Also, it is required to maintain the pumping power of the coolant to be below ~10% of incident power.

Over the past few decades, the study of fluid flow and heat transfer in cooling channel with extended surface has become one of the active research areas. The extended surfaces enhance the cooling effect by increasing the total surface area, and occasionally generating secondary flows. In the past, various investigations have been performed on the effects of geometrical parameters on the flow friction and heat transfer in the cooling channel. Toward this, heat transfer characteristics of divertor cooling finger mock-up have been investigated with sectorial extended surfaces (SES) by Rimza et al. [2]. They revealed that, addition of SES greatly increases performance of the finger mock-up as compared to a smooth channel. A variety of heat transfer enhancement techniques have been evaluated by Baxi [3] and Baxi and Wong [4] to improve the heat transfer performance of the divertor. From their studies, they found that helium cooled divertor design for fusion machines is feasible, at a reasonable pumping power. The mass flow rate and pumping power required can be minimized by a combination of enhancement techniques and use of high pressure gas. Hageman et al. [5] investigated a plate-type divertor with fins, and found that the heat transfer performance of divertor increases to a great extent by the addition of fins. Critical heat flux experiments for divertor application have been performed by Ezato et al. [6–8]. They discovered that, capability of divertor to handle high heat flux increases significantly, by the use of screw tube and saw toothed fin. Sharafat et al. [9] performed a numerical analysis to optimize the design of metallic heat exchanger tube for minimum pressure drop through the porous media and for uniformity of surface temperatures. Youchison et al. [10] reviewed the convective heat transfer through helium cooled porous metal divertor modules. They found that, the porous metal helium divertor exceeded its design specifications, and survived at the maximum heat flux of ~29 MW/m^2. An optimization study was performed by Rader et al. [11], to assess the thermal performance of the modular divertor with fin. Their results revealed that the performance of the divertor enhances with variation in geometric configuration. Optimization of T-tube divertor design concept of modular helium cooled units was investigated by Bruke et al. [12]. Based on their studies, the design was modified by changing the dimensions of the slot-jet, inner cartridge and tungsten armor to accommodate higher heat fluxes. Experimental and numerical investigations on plate type divertor with the use of metallic foam have been conducted by Gayton et al. [13].

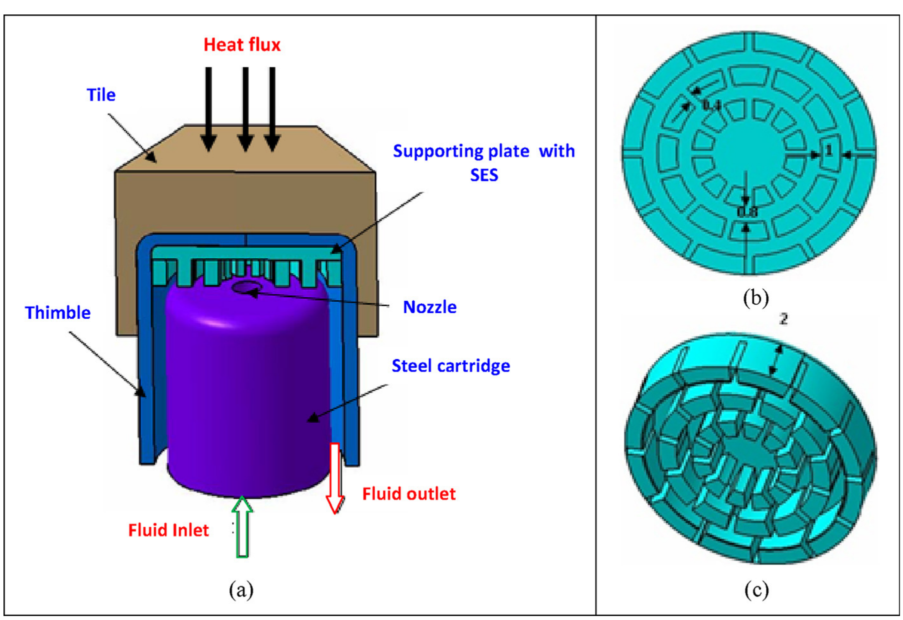

Fig. 1. (a) Schematic of divertor finger mock-up, (b) plan and (c) 3-D view of SES (all dimensions in mm).