CHAPTER 3
3.0. INTRODUCTION

As mentioned previously, 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 context of DEMO, it is essential to look at a competent cooling technology for divertor that can handle extremely high heat flux generated in interior of the core. Towards this, a new type of “Sectorial Extended Surface” (SES) has been proposed. This particular design is easy to manufacture and cost effective.

As detailed in Section 1.3.1, the plasma-facing components are fabricated with numerous small sized “finger” shaped mock-ups cooled by helium jets to reduce the stresses caused by temperature gradients and internal gas pressure. The present study is “focused towards finding an optimum performance of one such finger mock-up through systematic computational fluid dynamics studies. Heat transfer characteristics of finger mock-up have been numerically investigated with a sectorial extended surface”. Numerical investigations show that addition of SES greatly increases thermal-hydraulic performance of the finger mock-up. Detailed parametric studies on critical parameters that influence thermal performance of the finger mock-up have been analysed. Thermo-mechanical analysis has also been carried out through finite element based approach to know about possible stresses in the assembly as a result of large temperature gradients and gas pressure. It is seen that the stresses are within the permissible limits of
materials adopted for the present design. Benchmark studies have been performed for reported other designs that are experimentally tested through high-heat flux experiments [48] and a good agreement is obtained between the present simulation results and the reported results.

3.1. SOLUTION METHODOLOGY

3.1.1. Detailed Design of Finger Mock-Up

The entire divertor of tokamak is divided into a number of modules known as “cassettes”, which are independently cooled. The plasma facing components of the divertor are split into a number of ‘finger mock-ups’ in order to reduce the thermal stress, as presented in Figs. 3.1. Each mock-up consists of small hexagonal ‘tile’ (width 17.8 mm) made up of pure tungsten (W) material with sacrificial thickness (~ 5 mm) used as the thermal shield. A hexagonal form of small segments allows a higher packing density for heat dissipation. Tiles are brazed to another material of tungsten alloy (WL-10) known as the ‘thimble’ (Ø15×1mm). Tungsten Lanthanum Oxide (WL-10) is chosen as thimble material because of its encouraging property for the machining. The motive for the separation of these two components (tile and thimble) is that any crack originating from the tile surface does not reach the thimble and is stopped at the interface.

The brazing of the tile and thimble is performed with a nickel (Ni) alloy filler metal, STEMET® 1311 (Ni-based, 16.0 (Co), 5.0 (Fe), 4.0 (Si), 4.0 (B), 0.4 (Cr)) with a brazing temperature of 1050 °C. A cartridge (Ø11.2×1 mm) made up of Reduced Activation Ferritic Martensitic steel (RAFMS) carrying the nozzle is placed concentrically inside the thimble. Fluid enters through the nozzle and flows radially outwards through the space between cartridge and the thimble. These tungsten finger mock-up units are connected to the support structure by means of brazing which is preferred to be made of RAFMS [76]. Thermo-hydraulic performance of mock-up has
been studied with addition of sectorial extended surfaces, which is placed between cartridge and the thimble with a supporting plate of 1 mm thickness, as depicted in Fig. 3.1(b). The circumferential pitch are varied from first row to last row that leads to reduce the expense of machining to cover the top cooled surface. Extended surfaces are angularly constructed at every 30° sector, resulting in 36 numbers of extended surfaces with 1 mm thickness, 0.8 mm pitch, and 2 mm height. Circumferential gap between the extended surfaces is maintained at 0.4 mm.

![Fig. 3.1. Schematic of (a) He-cooled divertor finger mock-up and (b) 3-D and close up views of SES (all dimensions in mm).](image-url)
Fabrication has been simplified to a great extent by SES that can be simply machined out of a solid cylinder using typical available machining processes like Electrode Discharge Machining, Water jet Cutting or Milling. The most important design criterion is to keep thimble temperature above ductile brittle transition temperature (DBTT, ~600°C) and below re-crystallization temperature (RCT, ~1300°C). The brazing filler temperature of tiles and thimble should not exceed 1050°C [48] and pumping power should be lower than ~10 % of incident power.

3.1.2. Governing Equations

The steady state forms of continuity, momentum, and energy equations for an ideal gas fluid used for the present numerical simulation are described in Chapter 2. In the present simulation, Mach Number (M) is found to be less than 0.3 and temperature rise of helium in the divertor assembly is only about 60 K. Hence, the assumption of helium as an incompressible gas is justified. To resolve the Reynolds stresses, realizable k-ε turbulence model is employed, because it accurately predicts the performance for separation, recirculation, and flows involving boundary layers under pressure gradients [70] and also used to simulate flow and heat transfer in pin fin channel [77]. Pressure-velocity coupling between the incompressible Navier-Stokes and continuity equations is resolved using the “Semi Implicit Pressure Linked Equations" (SIMPLE) algorithm. To declare convergence at any iteration, the absolute errors in the discretization momentum and continuity equations are set to be 10⁻⁴ whereas for energy, it is set to be 10⁻⁷.

3.1.3. Boundary Conditions

A schematic of computational model with boundary conditions is depicted in Fig. 3.2. Due to the symmetry, a 30° sector model is considered for the present numerical simulation. Temperature dependent material properties are taken into consideration for the tile, thimble, and supporting
plate with extended surfaces [78] whereas constant material properties are considered for cartridge. The finger mock-up is cooled by helium jet at 10 MPa and 600 °C impinging onto the heated wall of the target surface. The inlet and outlet temperatures of the He coolant are limited by the DBTT of tungsten lanthanum oxide (600 °C) and the creep rupture strength of the RAFMS steel structure. High pressure of helium (~10MPa) has been used for efficient removal of heat from the hot target surface. The boundary conditions for the present 3D numerical simulations are as follows:

- Symmetry boundary conditions are imposed on the 30° cut sections.
- Adiabatic boundary conditions are imposed on outer sides of the domain.
- Top surface of the domain is imposed with constant heat flux (10 MW/m²).
- Mass flow rate and temperature of He gas are specified at the inlet.
- No-slip conditions are imposed on the walls and at the extended surfaces.

Fig. 3.2. (a) Finger mock-up with boundary condition and (b) grid domain of SES.
3.2. BENCHMARK VALIDATION

Benchmarking the numerical calculation against suitable experimental data is of vital importance in CFD studies. For the validation exercise, same geometric structure as reported in the literature [48] has been adopted. In the reported literature, helium-cooled concept based on multi jet impingement has been adopted. The coolant has an inlet temperature and pressure of about 873 K and 10 MPa. The thermal hydraulic performance of concept was analyzed at constant mass flow rate 13.5 g/s and heat flux is varied in the range of 4.01 -12.6 MW/m².

3.2.1. Grid Sensitivity Analysis

In a CFD simulation, establishing grid size towards independent nature of the solution is an essential first step. In this regard, efforts are made to determine the optimum mesh for the present numerical simulations. Different mesh sizes employed for the grid sensitivity study are shown in Table 3.1 along with maximum tile and thimble temperature. Temperature differences increase, because the grid spacing reduces with increase in the number of control volume. The reduction in the grid spacing reduces the discretization error in the solution and predicts the most accurate results as compare to coarse mesh.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Control Volume</th>
<th>Minimum grid spacing (mm)</th>
<th>Maximum tile Temperature (°C)</th>
<th>Maximum thimble Temperature °C</th>
<th>CPU time per Iterations (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>2.5×10⁵</td>
<td>0.2</td>
<td>1687</td>
<td>1087</td>
<td>3</td>
</tr>
<tr>
<td>M2</td>
<td>3.5×10⁵</td>
<td>0.15</td>
<td>1675</td>
<td>1064</td>
<td>5</td>
</tr>
<tr>
<td>M3</td>
<td>5×10⁵</td>
<td>0.1</td>
<td>1651</td>
<td>1004</td>
<td>8</td>
</tr>
<tr>
<td>M4</td>
<td>6×10⁵</td>
<td>0.08</td>
<td>1649</td>
<td>1003</td>
<td>12</td>
</tr>
</tbody>
</table>

Maximum ‘tile’ and ‘thimble’ temperature as reported in literature [48] are 1660.3°C and 1010.73°C respectively.
It can be noticed that the difference between temperature distributions of tiles and thimbles obtained from mesh M3 and M4 are small. The percentage of deviation in temperature between M3 and M4 are 0.12% and 0.09% respectively. Though the change is a small but computational effort is significantly higher for M4 as compared to M3, thus justifying the use of mesh M3 for further investigations.

3.2.2. Parametric Studies

Systematic parametric studies are performed using mesh M3 for various mass flow rates with different heat flux. This particular grid has been chosen after performing a detailed grid sensitivity study as discussed in Section 3.2.1. The outcomes of these parametric studies are depicted in Figs. 3.3(a) and (b). It is observed that temperature at tile & thimble and rise in temperature of helium gas continuously increase with increase in the heat flux whereas the pressure drop remains unchanged, as expected.

![Fig. 3.3.](image)

**Fig. 3.3.** Comparison between (a) helium pressure drop & temperature difference and (b) maximum tile and thimble temperature as a function of heat flux.
In the present simulations, temperature distributions across tile, thimble and rise in temperature of helium gas at various heat fluxes are found to be in good agreement with the reported results [48]. Analysis has been performed for nominal mass flow rate and is validated against the reported result. The temperature distributions in the solid and fluid regions are presented in Fig. 3.4. The maximum tile temperature occurs at the outer corner of the surface, and the maximum thimble temperature is noticed just above the central jet.

![Temperature distribution](image)

**Fig. 3.4.** Temperature distribution for mass flow rate of 6.8 g/s with a heat flux of 10 MW/m² (a) reported results and (b) present simulation.

### 3.3. RESULTS AND DISCUSSION

#### 3.3.1. Comparative Studies for Flow & Heat Transfer Analysis

Comparative studies for flow & heat transfer without SES and with SES have been carried out and presented for mass flow rate of 5 g/s with heat flux value of 10 MW/m². Figure 3.5(a)
depicts distribution of turbulence kinetic energy with the presence of SES. It is seen that maximum kinetic energy occurs at the nozzle entrance due to high velocity of coolant at the centre. The sectional top view of velocity distribution around SES is depicted in Fig. 3.5(c). Symmetric eddies are formed in between the extended surfaces due to flow obstruction, which is similar to flow across bluff bodies. Flow bypass occurs through the gap between the wall of the extended surfaces and the channel wall that is clearly seen from the figure. Formations of eddies leads to increase in turbulence activity and hence increase in the rate of heat transfer.

![Fig. 3.5.](image)

(a) Sectional top view of turbulence kinetic energy distribution \( (m^2/s^2) \) around SES (b) sectional view of 30° sector of SES (c) velocity distribution \( (m/s) \) with close up view.
Temperature distributions for without and with SES are shown in Fig. 3.6. It is observed that the temperature of tile and thimble are reduced for SES as compared to that without SES. The addition of extended surface in divertor finger mock-up increases heat flux distribution and heat transfer rate as compared to smooth channel as more surface area is available for fluid to interact with the hot surface.

![Temperature distribution of divertor cooling finger mock-up design](image)

**Fig. 3.6.** Temperature distribution of divertor cooling finger mock-up design (a) without SES and (b) with SES.

### 3.3.2. Extraction of Thermal parameters

The effective heat transfer coefficient (h	ext{eff}) for the case without SES is determined based on the average heat flux (Q/A_c) incident on the cooled surface and the temperature difference between the cooled surface wall and the bulk fluid as defined by,
\[ h_{\text{eff}} = \frac{Q}{(T_c - T_b)} A_c \]  

(3.1)

The test section without extended surface actual and effective heat transfer coefficient (\( h_{\text{act}} = h_{\text{eff}} \)) will be same due to unavailability of extended surface. However, the effective wall heat transfer coefficient for the test section with extended surface requires accounting the fin efficiency (\( \eta \)), because the surface temperature of the SES is spatially non-uniform. Therefore,

\[ h_{\text{eff}} A_c = h_{\text{act}} (A_p + A_e \eta) \]  

(3.2)

Efficiency (\( \eta \)) of the extended surface is given by [79]:

\[ \eta = (\tanh Ml)/Ml \]  

(3.3)

where, \( M = \sqrt{\frac{h_{\text{act}} P_0}{\lambda_e A_{ce}}} \) and 'l' is the length of SES.

Effectiveness (\( \zeta \)) of the extended surface is defined as the ratio of heat transfer rate by SES to that without extended surface and is written as:

\[ \zeta = A_e \times \eta / A_c \]  

(3.4)

The corresponding pumping power (W) is then determined by:

\[ W = m \times \Delta P / \rho \]  

(3.5)

Where the symbols have their usual meanings and are described in the nomenclature.

### 3.3.3. Assessment of Performance for Flow Parameters (without SES)

The prime motive of this investigation is to find optimum mass flow rate at an acceptable pressure drop for cooling of finger mock-up. Towards this, numerical studies have been
performed without considering SES at different heat fluxes value, viz., 8, 10, and 12 MW/m² over a wide range of mass flow rates (5 – 20 g/s). Temperature distributions on the surface of tile and thimble for various mass flow rates for given heat loads are depicted in Fig. 3.7(a) and (b) respectively.

Figure 3.7 shows that the tile and thimble temperatures are within design limits for lower heat flux value of 8 MW/m² with mass flow rate of ~ 10 g/s, whereas for higher heat flux (10 - 12 MW/m²), flow rate in the range of 14 – 19 g/s is required to keep thimble temperature within the design limits (1050 °C). From the above figure, it implies that without SES, cooling finger will require very high mass flow rate and hence pumping power will be high to maintain the desired constraint.

Fig. 3.7. Maximum temperature as function of mass flow rate at different heat loads (a) tile and (b) thimble.
Figures 3.8(a) and (b) represent heat transfer coefficient and pressure drop as a function of Reynolds number (Re). With increasing Re, both $h_{\text{eff}}$ and $\Delta P$ increases however, there is no appreciable effect observed with variation in heat flux due to the temperature variation of cooled wall surface.

![Graphs showing heat transfer coefficient and pressure drop](image)

**Fig. 3.8.** Effect of Reynolds number on (a) heat transfer coefficient and (b) pressure drop at different heat loads.

### 3.3.4. Performance Analysis with Extended Surfaces

Thermal-hydraulics performance of finger mock-up has been analyzed to find the effectiveness of SES at specified heat load conditions described in Section 3.3.3. Four cases (Flow with & without SES) are analysed with two-heat flux, viz., 8 and 10 MW/m². Coolant mass flow rate is varied from 5 – 20 g/s. Maximum temperature values on tiles and thimble without, and with SES at different mass flow rates are depicted in Fig. 3.9.
It is observed that, tiles and thimble temperature reduces with an increase in flows rate. The temperature values along the tiles and thimble with SES are significantly lower than that without SES. With the presence of SES, lesser mass flow rates (5 g/s for heat flux of 8 MW/m² and 7.3 g/s for 10 MW/m²) are adequate to keep thimble temperature within the desire limits.

![Graphs showing thimble and tile temperatures](image)

**Fig. 3.9.** (a) Comparisons of tiles and (b) thimble maximum temperature for with and without SES at different heat loads.

Figure 3.10 represents the variation of effective heat transfer coefficient (hₑₑₑ) and pressure drop for without and with SES at different Re. It is noted that ‘hₑₑₑ’ for both the cases increase with the rise in Re, but the rate of increase is higher in presence of SES. This is due to increase in the surface area that enhances turbulence in the flow of gas and hence improves the effective heat transfer coefficient. Similarly, the values of pressure drop increases in the presence of SES as compared to that without extended surfaces as seen from Fig. 3.10(b) as expected.
Fig. 3.10. Comparisons of (a) effective wall heat transfer coefficient and (b) pressure drop for with and without SES at optimized heat loads.

Fig. 3.11. (a) Comparison of efficiency (η) and (b) effectiveness (ζ) with SES.
Variation in efficiency ($\eta$) and effectiveness ($\zeta$) with mass flow rate are depicted in Fig. 3.11. It is seen that both $\eta$ and $\zeta$ are maximum at lower mass flow rate, and they start decreasing continuously as mass flow further increases. This particular behaviour is expected as both these factors inherently depend on heat transfer coefficient. From the above comparison, it is implied that extended surfaces potentially enhance the thermal performance of the finger mock-up.

3.3.5. Design Analysis of Divertor Finger Mock-up

The dependence of pumping power on the proposed design of finger mock-up has been investigated for various mass flow rates and is presented in Fig. 3.12. It is seen that, the pumping power continuously increases with mass flow rate for a constant heat flux 10 MW/m$^2$. Dashed line marks the design limit on pumping power.

![Fig. 3.12. Comparison of pumping power with and without SES as function of mass flow rate.](image)

From the figure, clearly the mass flow rate should not exceed 10 g/s for the finger mock up without SES, so as to limit pumping power within 10% limit. However, this limitation on flow rate leads to exceeding the temperature limits (Fig. 3.7b, Sec 3.3.3). Therefore, the reference
design is unable to tolerate 10 MW/m² unless extended surface is added to it. It is also seen that, with the addition of SES, even a lower mass flow rate of ~7.3 g/s is adequate to maintain the desired temperature and pumping power constraint.

The maximum heat flux to be accommodated by finger mock-up at allowable tile/thimble filler temperature constraint has been estimated as:

$$q^* = \frac{(T_c - T_i)}{\left(\frac{A}{h_{\text{eff}}A_c} + \frac{t}{\lambda_c}\right)}$$  \hspace{1cm} (3.6)

where \( t \) and \( \lambda_c \) denote the thickness and thermal conductivity of the thimble respectively.

Figure 3.13 depicts the variation of heat flux with mass flow rate for the cases with and without SES at 10 MW/m². It is observed that prototypical mass flow rates for fusion power plant (~7.3 g/s) with SES can accommodate a heat flux of 10 MW/m² whereas it is only ~4.5 MW/m² without SES. In order to accommodate high heat flux exceeding 10 MW/m² with the present design, melting limits of the tile/thimble brazing filler material should be increased.

![Graph showing comparison of mass flow rate without and with SES for different heat flux values.](image)

**Fig. 3.13.** Comparison of mass flow rate without and with SES for different heat flux values.
Parametric studies on pumping power without and with SES are analyzed for two different pumping power limits, viz., 10 – 15 % of the total power removed from the tile and thimble. The corresponding results are depicted in Fig. 3.14. It is observed that with extended surface, finger mock-up can tolerate up to a maximum heat load of 10 - 11.2 MW/m² at the expense of pumping powers 10% and 15 % of the incident power. However, without the extended surfaces, it can handle highest heat load of 5 MW/m² only.

![Fig. 3.14. Comparison of pumping power (a) without SES and (b) with SES as a function of heat flux.](image)

Figure 3.15 compare the effective heat transfer coefficient obtained for heat flux 10MW/m² with pumping power for with SES and without SES. From the figure, it is found that at identical required pumping power, the mock-up with extended surface offer a higher heat transfer coefficient and thereby higher heat transfer enhancement. From all these parametric studies, it is evident that the use of extended surface in the finger mock up significantly increase the thermal
performance associated with low additional pressure drop. To respect pumping power and thimble temperature limit, low mass flow rates (~ 7.3 g/s) is adequate for the present design.

![Graph](image)

**Fig. 3.15.** Comparison of effective wall heat transfer coefficient for without SES and with SES as function of pumping power.

### 3.4. THERMO-MECHANICAL ANALYSIS

In order to verify the practicability of design, thermo-mechanical investigations are carried out using finite element analysis tools [70]. Towards this, nodal temperatures and pressure obtained from the CFD optimization studies are imported to the FEM software for structural analysis. For the entire solid domain, temperature dependent material properties [78] are considered, and frictionless boundary condition is considered at the bottom.

Figure 3.16 shows temperature distribution around the extended surface as well as the von-Mises stress for the optimized geometry. Figure 3.16(a) illustrates the maximum temperature at top of the mock up and the temperature distribution around the extended surface is non-
homogeneous. It is seen that the maximum stress develops at the tile-thimble interface. However, all the stresses are within the permissible limit [3.16b].

Fig. 3.16. 30° sector cooling finger mock-up (a) Temperature distribution (K) (b) von-Mises Stress distribution.

3.5. CLOSURE

The fluid flow and heat transfer characteristics of divertor cooling finger mock-up are investigated through jet impinging technique with and without sectorial extended surfaces (SES). The main objective of the present study is to numerically evaluate how addition of SES affects the thermal hydraulics performance of finger type divertor. Towards this, systematic studies by modelling of one such cooling finger have been carried out. Grid sensitivity analyses have been performed through a 30° sector model, and the optimized grid has been obtained. In the second stage, flow and heat transfer features have been investigated and are compared with the
published experimental and computational data. The calculated and measured values of the tile and thimble surface temperatures show good agreement with the reported results. Numerical investigations showed that addition of SES greatly increases thermal-hydraulic performance of the finger mock-up. Performance analysis indicates that present mock-up design should be acceptable for mass flow rate less than 7.3 g/s (Re ~111000) to ensure desired pumping power and thimble temperature limits. Adding the array of extended surface doubles the maximum heat flux that can be accommodated by the divertor finger mock-up. Thermo-mechanical analysis has been carried out for the finger mock-up through finite element based approach. It is seen that, all the stresses are within the permissible limit.