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Development of a high-heat flux cooling element with potential application in a near-term fusion power plant divertor

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HIGHLIGHTS

- Laminate jet impingement system introduced for high pressure operation (17 MPa+).
- Numerical thermo-fluid analysis on baseline geometry.
- Cascade impingement shown to reduce divertor mass flow rate requirements and increase fluid temperature change.
- Numerical thermo-fluid analysis validated using scaled experiments with air.

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ABSTRACT

A low temperature jet impingement based heat sink module has been developed for potential application in a near-term fusion power plant divertor. The design is composed of a number of hexagonal CuCrZr sheets bonded together in a stack to form a laminate structure. This method allows the production of complex flow paths using relatively simple manufacturing techniques. The thermo-fluid performance of a baseline design employing cascade jet impingement has been assessed and compared to a non-cascade case. Experimental validation of the numerical work was carried out on a scaled model using air as the working fluid. Local heat transfer coefficients were obtained on the surface using surface temperature data from thermochromic liquid crystals.

1. Introduction

A low temperature heat sink concept employing jet impingement has been developed for potential applications in a future fusion power plant. The design differs from other jet impingement approaches proposed in the literature [1–4] in its use of a cascading fluid flow path. Geometrically it is composed of a number of sheets stacked together and bonded in a laminate structure. By forming the geometry in this way complex three dimensional flow paths can be produced without compromising manufacturability.

For the structural material of the plates the alloy CuCrZr was chosen. This material offers the best heat flux handling capacity at the temperatures envisaged for operation and has been extensively researched in the fusion community. Due to the small 200–350 °C temperature window predicted for CuCrZr under DEMO relevant conditions [5] water is the preferred coolant for the design.

A baseline concept employing a hexagonal sheet structure has been developed and its thermo-fluid performance assessed using both numerical and experimental methods. The goal is the development of a heat sink capable of withstanding heat fluxes in the 10–20 MW/m^2 range whilst also maximizing the temperature change of the fluid.

2. Design features

2.1. Operational pressure

In current tokamak devices the heat flux handling capacity of the divertor has been of primary concern. As we move towards a fusion power plant maximizing the outlet temperature of the divertor also becomes important.

To achieve this with liquid water as the coolant we must increase the system pressure and reduce the mass flow rate requirements.

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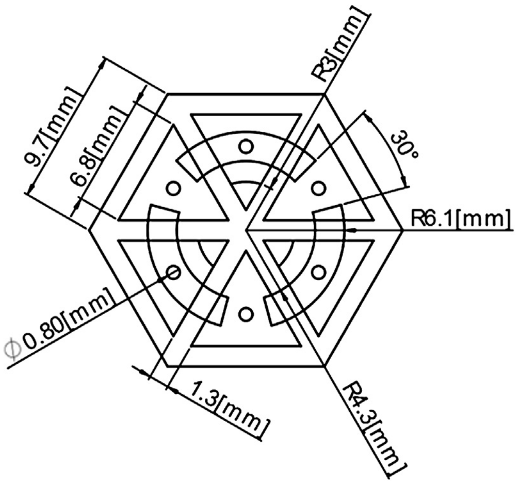

Fig. 1. Dimensions of baseline hexagonal heat sink concept.

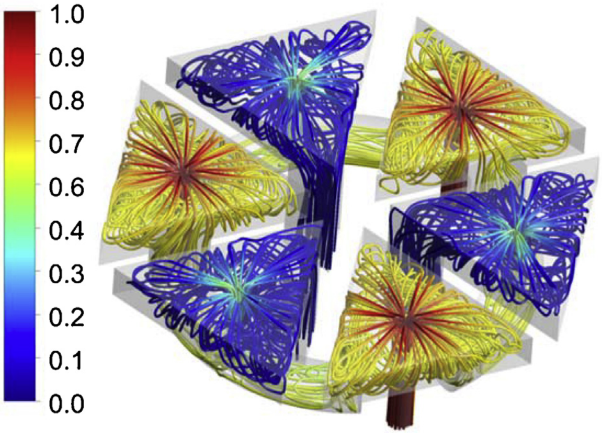

Fig. 2. Normalized total pressure drop through baseline fluid flow path.

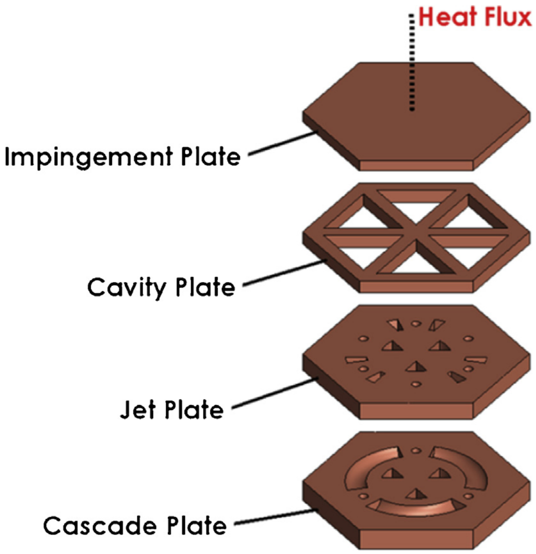

Fig. 3. Reference sheet composition and stacking order for baseline design.

In a closed divertor coolant loop peak temperature will also be limited by the heat sink material. For CuCrZr under DEMO relevant conditions this is approximately 350 °C [5]. Above 16.5 MPa the saturation temperature of water is greater than this value. Operating at pressures in excessive of 16.5 MPa means that peak fluid temperatures are limited structurally, rather than by the fluid. If a combined divertor to blanket coolant loop is utilized increasing the pressure further is beneficial.

To handle such pressures in a laminated sheet structure the hexagonal surface was divided into a number of triangular cavities. This was preferable over a multi-hexagonal structure as it limited stress concentration regions. A plan view of the baseline concept designed for a pressure of 20 MPa is depicted in Fig. 1.

2.2. Fluid flow-path

To cool the hexagonal surface a single impinging jet is employed in each of the triangular cavities. These are positioned at the centroid of the triangle. As the wall jet moves out from the stagnation region it eventually meets the cavity wall where a secondary impingement occurs.

A streamline plot of the normalized total pressure drop for the baseline concept is shown in Fig. 2.

Initially only three of the jets are supplied with fluid. These impinge within the cavity structure and then the flow splits as it exits. This spent flow from the primary impingement cavities then passes along internal channels to the three remaining jets. After the second impingement the fluid exits the structure through the central outlet channels.

This re-impinging of the same fluid element multiple times is called cascade impingement [6,7]. It is a system which enables additional pressure drop to be traded for a reduced mass flow rate.

Employing this method in the design is particularly effective due to the high operational pressure. As a result, multiple impingements can be performed before the total pressure drop becomes an appreciable percentage of the system pressure.

In Fig. 3 the four sheets composing the baseline design are shown, together with their stacking order.

Functionality of each of the laminate sheets in the final construction can be described as follows:

1. Impingement plate – withstand high incident heat fluxes normal to its surface.
2. Cavity plate – provide structural support to impingement plate for high system pressure.
3. Jet plate – provide inflow and outflow routes to cavities.
4. Cascade plate – provide multi-impingement flow-path and inlet and outlet routes to module.

Below the impingement plate it is important to try and minimize the rigidity of the structure to limit thermal stresses.

3. Thermo-fluid analysis

3.1. Methodology

Numerical simulations on the baseline geometry were performed using ANSYS 13.0 CFX. A conjugate model was employed in which it was assumed that the laminate structure could be treated as a single solid body.

A 120° periodic segment of the design was used for the simulations and meshed using ICEM. To accurately capture the gradients in the boundary layer 20 prism layers were grown to a height of 30 μm with a 1.25 growth ratio.

An incident heat flux of 10 MW/m^2 was applied to the impingement plate and all other external surfaces were assumed adiabatic. At the interface between the solid and fluid regions conservative heat influx was assumed.

At the fluid inlet the pressure was set to 20 MPa and the temperature to 150 °C. A mass flow rate was also prescribed and varied