DESIGN AND FABRICATION OF A FLAT-PLATE MULTICHANNEL HE-COOLED REFRACTORY HX FOR DIVERTOR APPLICATIONS

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A flat-plate He-cooled divertor would provide a flat surface facing the plasma, would minimize the number of otherwise complex sub-modules needed to cool large areas, and could greatly reduce the complexity of the coolant manifold systems.

We recently designed and manufactured a unique flat-plate multichannel refractory metal heat exchanger (HX) that employs open-cell refractory foam to enhance heat transfer from the heated plate to the helium coolant. The structural material of the flat-plate HX box (102 mm wide and 165 mm long) is powder metallurgy molybdenum. Three flat-plate HX boxes were fabricated, two with a heated surface plate made of 4-mm thick Mo, TZM, and one 3-mm thick W. Four supply- and five return ducts, each 4.8 mm wide by 61 mm long run parallel underneath the heated plate. A thin sheet of Mo-foam (~2 mm × 70 mm ×80 mm; H/W/L) is sandwiched between the ducts and the heated plate. Advantages of using foam are detailed in a separate paper in these proceedings. The supply ducts push helium up towards the heated plate and then circumferentially through the foam into the neighboring return ducts. Key to optimizing the design was achieving uniform helium flow upwards to the heated plate along the entire length of the supply ducts, while simultaneously minimizing end-effects due to the short active duct length (~80 mm). A series of geometric features were designed to obtain relatively uniform flow distributions throughout the HX box. Here we report on the final design based on CFD analysis and thermo-structural finite element.

I. INTRODUCTION

Fusion power plants contain divertor target plates which must deliver heat at elevated temperatures in order to retain high overall efficiency[1]. The divertor target plates experience high heat fluxes (greater than 10 MW/m^2) and should use coolants, such as helium that are compatible with the blanket power conversion systems. An extensive body of research regarding refractory metal based helium-cooled divertors with enhanced heat transfer in plate and modular concepts using jet-arrays[2,3] or pin-fin arrays[4] has been published. Our concept differs from these in that foam is used as a porous medium for heat transfer enhancement as detailed in previous publications[5-7]. Here, we describe our efforts to expand the refractory foam based HX concept for flat-plate divertor applications. A flat-plate divertor concept would minimize the number of otherwise complex sub-modules[2] required to cool large areas as required in practice. In addition to the typical operating conditions and design requirements for fusion power reactor divertors listed in Table I, the design of this flat-panel HX was performed with the following considerations in mind:

- Helium flow to the heated plate to be as uniform as possible.
- Minimizing fluid flow end-effects due to a short active duct length.
- Coolant pressure drops had to be minimized.
- To enhance power conversion, high coolant exit temperatures were desired.

The overall technical objective of this program is to design, fabricate, and test tungsten heat exchanger panels for divertor concepts with high heat flux capabilities (>10 MW/m^2), low coolant pressure loss, and manageable thermal stress.

TABLE I. Typical Design Requirements for He-cooled Fusion Power Reactor Divertor Operation

Design Parameter	Value
Max. W-structure temperature	< 1300 °C
Min. W-structure temperature	> 800 °C
Inlet He temperature	600 °C
Outlet He temperature	700 °C
Max. heat flux	10 MW/m^2
Volumetric heating rate	15 MW/m^3
Allowable pumping power	< 10% thermal power
Sacrificial W-armor thickness	5 mm

II. DEVELOPMENT OF POROUS FOAM HEAT EXCHANGER DESIGN CONCEPTS

Between 2005 and 2006 Ultramet developed a flexible Nb-based joint for testing a “Foam in Tube" HX design concept. This design featured a 10 pores-per-inch (*ppi*), 20% density W-foam inserted into a 12.7 mm ID x 16.2 mm OD Nb tube. The W-foam was centered along 38 mm of the axial length. This concept was tested at Sandia National Laboratories (SNL), successfully withstanding heat flux loads up to 22.4 MW/m^2 near the centerline region with room temperature (RT) helium[5]. Photos of the fabricated "Foam in Tube" HX are shown in Figure 1.

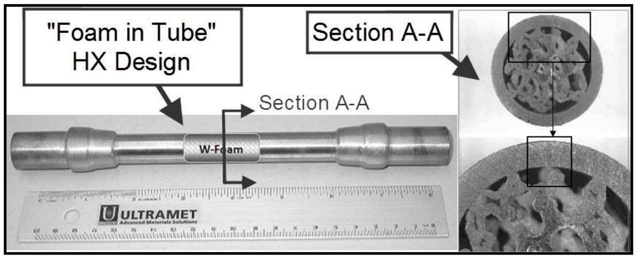

Fig. 1. Overall view (left) and section view (right) of "Foam in Tube" HX design, showing details of the CVD bond between the W-foam and tube wall (Section A-A).

In 2007 and 2008 a single channel HX concept, the "azimuthal He-Flow through Foam in Tube" shown in Figures 2 and 3, was designed and fabricated by Ultramet.[6,7] The decision to have the coolant flow azimuthally through the porous foam was made in an effort to reduce prohibitively large pressure losses witnessed when testing the axial configuration used in the "Foam in Tube" HX design. Initial testing at SNL with heat flux loads up to 8 MW/m^2, and 300 °C He coolant with flow rates between 23 to 100 g/s at 2 to 4 MPa pressures are planned with subsequent testing using 600 ^{o}C He coolant.

These porous foam HX concepts provided the foundation for the flat-plate multichannel HX design presented in this paper.

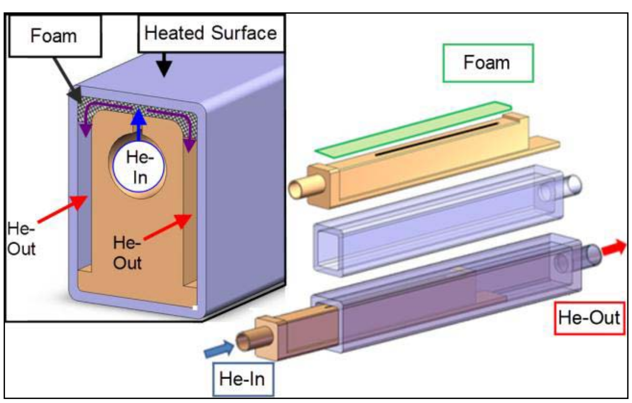

Fig. 2. Cross-sectional (left) and exploded (right) view of "azimuthal He-Flow through Foam in Tube" HX design concept.[8]

Fig. 3. Fabricated single channel "azimuthal He-Flow through Foam in Tube" HX.[8]

III. FOAM-BASED FLAT-PLATE HX CONCEPT

This single channel HX concept was further refined during 2008 to 2010 into a flat-plate, multichannel HX concept in order to better meet the needs of the large area fusion reactor divertors. Various concepts and design iterations were created using multiple He channels. An early flat-plate HX design concept is shown in Figure 4.

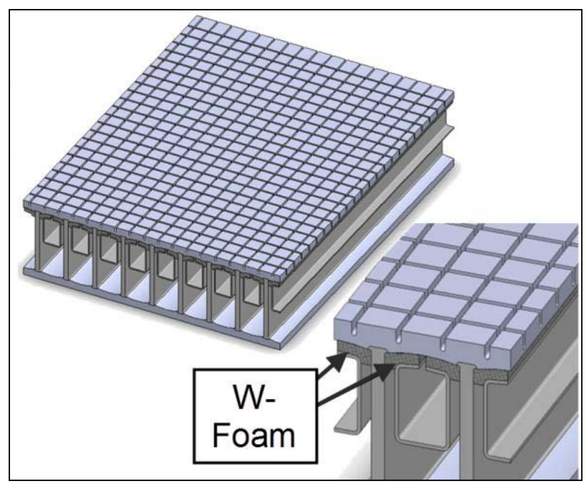

Fig. 4. CAD model of an early flat-plate divertor concept using foam to enhance heat transfer.

Eventually, a box-shaped design concept was developed that featured helium coolant distributed via a manifold into four inlet channels. The helium then flows azimuthally through a thin layer of foam, and is collected in neighboring outlet channels for return. This design concept utilizing azimuthal flow through multiple channels is shown in Figures 5 and 6.

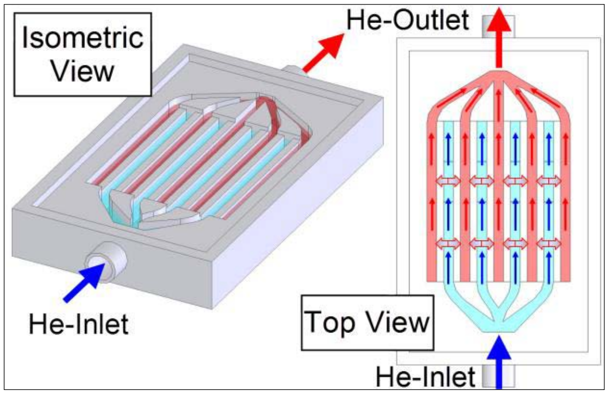

Fig. 5. Isometric view (left) and top view (right) of the HX box [note: print copy is b&w, but color online].

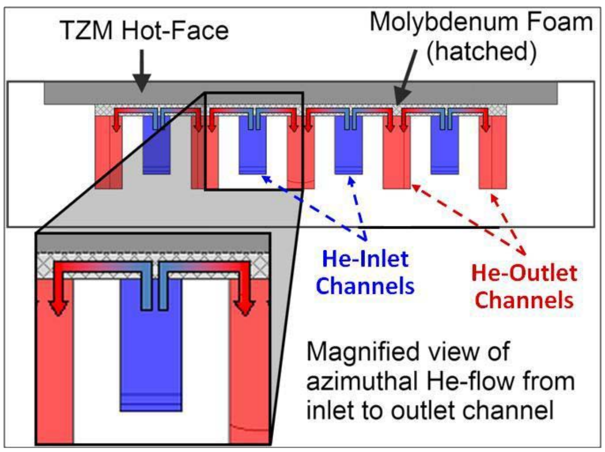

Fig. 6. Section view showing the azimuthal helium-flow.

III.A. Optimization of Flat Multichannel HX Plate

This design concept underwent a long computational fluid dynamics (CFD) based optimization process to create a design that would uniformly cool the heated region of the lid. Early designs using flat inlet channels showed non-uniform flow distributions in the foam region beneath the heated surface. CFD analysis showed that this was due to a lack of consistent helium flow upwards from the inlet channels into the foam region.

Multiple ideas were attempted in an effort to redirect the flow upwards and through the foam region uniformly: curved flow dividers placed on the inlet channel floors, non-uniform inlet/outlet channel widths and depths, slotted plates inserted between the flow channels and the foam, and many others. CFD analysis results of a sample design iteration are presented in Figure 7.

Finite element analysis (FEA) was performed to optimize thermal performance of the HX box subject to 4 MPa He-coolant pressure and various surface heat loads. All thermal analyses assumed perfect metallic bonding between the refractory foam and the heated surface, similar to the CVD bond shown in Fig. 1. FEA was performed using TZM (Mo-0.5Ti-0.08Zr) and pure molybdenum as lid material. Furthermore, the brazing of the lid to structure was also assumed to be a perfect bond. The analysis was performed for different lid thickness subject to heat fluxes up to 10 MW/m^2 and helium at 4 MPa. Heat fluxes were increased incrementally to establish the maximum thermal load that the HX could endure before failure.

Based on difficulty to manufacture such large HX structures from tungsten, molybdenum was chosen instead, because of Mo ease of machining compared with W. It is well known that Mo is not suited for fusion power applications because of activation concerns; however for demonstration of proof of principle Mo is well suited as a surrogate refractory material for tungsten.

Manufacturing considerations were taken into account during the design phase, with features being simplified and dimensions altered to accommodate the fabrication process.

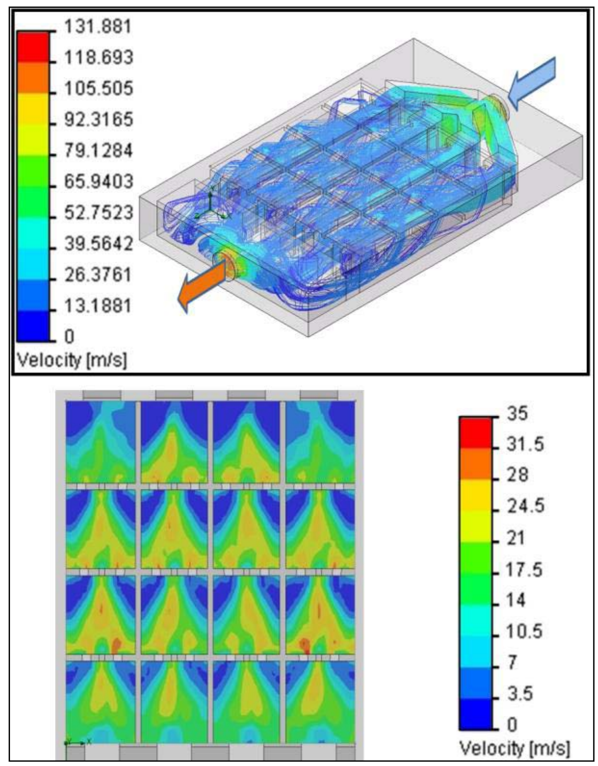

Fig. 7. CFD analysis for an early flat-plate HX concept (top) velocity streamlines and (bottom) He-velocity below heated surface [note: print copy is b&w, but color online].

III.B. Optimized HX Design used for Testing

The prototype design used for testing retains the four inlet channel concept. Steps of varying heights were added within the inlet channels in order to force the He flow upwards into the foam, and gradually reduce the space within the inlet channels. This allows the flow to be redirected in a controlled fashion, and resulted in a better flow distribution, and helped reduce pressure losses. Inlet and outlet manifolds serve the purpose of evenly dividing the flow between the multiple channels, and reducing pressure losses. Exploded and section views of the flat multichannel HX plate are provided in Figure 8.

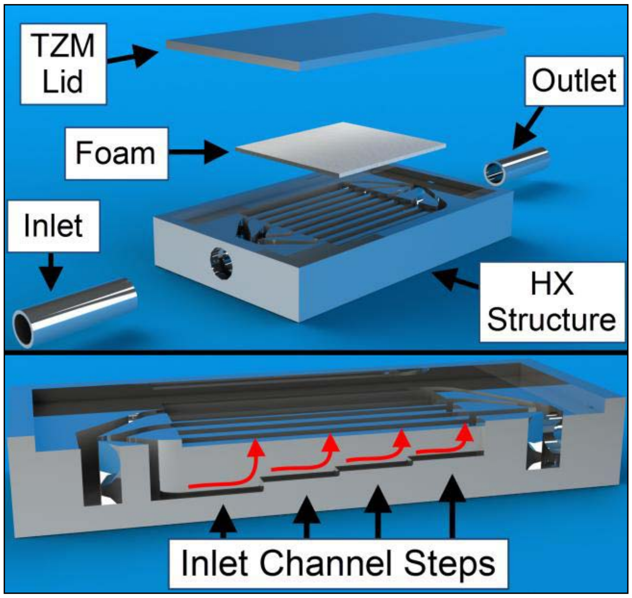

Fig. 8. Exploded view of HX prototype (top), and section view (bottom) of inlet channel steps for redirecting helium flow [note: print copy is b&w, but color online].

The total estimated pressure drop for the flat multichannel HX plate is estimated to be less than 100 kPa with room temperature He flowing at 100 g/s, and an inlet pressure of 4 MPa. FEA results anticipate that this design can withstand heat fluxes of 8 MW/m^2 before exceeding the operating temperature and stress limits for TZM and W lids.

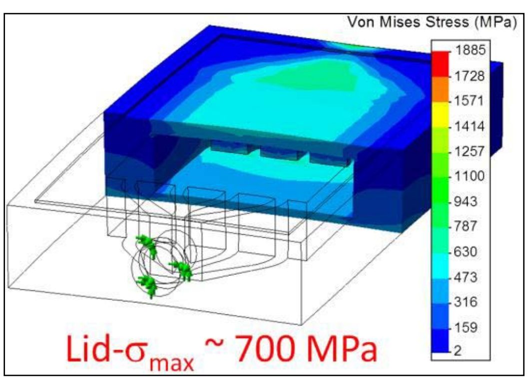

Fig. 9. FEA Von Mises Stress results for flat-plate HX prototype design [note: print copy is b&w, but color online].

IV. FLAT MULTICHANNEL HX FABRICATION

A prototype flat multichannel HX plate made of molybdenum and TZM alloy was fabricated for experimental testing. The primary HX structure shown in Figure 10 was created from a block of 1.0 inch thick pure molybdenum. The coolant channels were milled, and holes were drilled for the molybdenum inlet and outlet tubes. Milling operations were performed using Ultramet's Toyoda CNC grinder, supported by Mastercam 3D design software.[9]

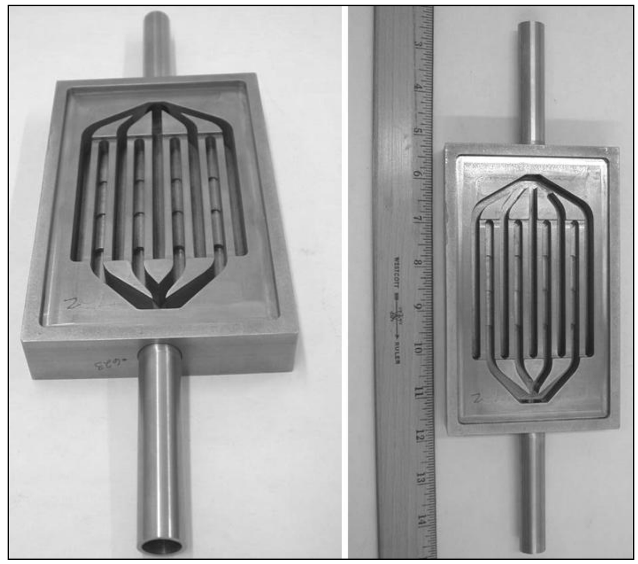

Fig. 10. Photos of the slotted molybdenum primary structure, including inlet/outlet molybdenum tubes.

A sheet of molybdenum foam was inserted into the recessed space that is directly over the slotted channel areas as shown in Figure 11.

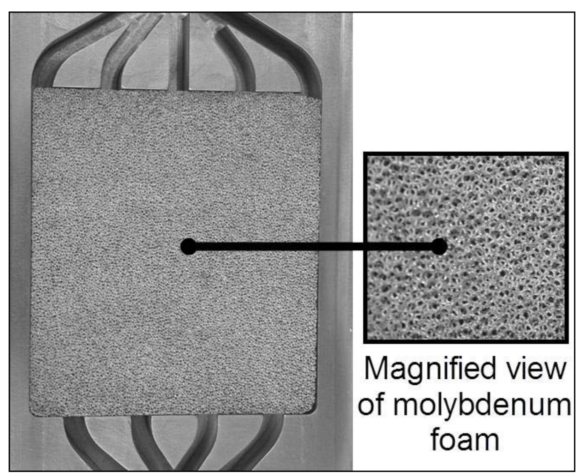

Fig. 11. Photos of the molybdenum primary structure with molybdenum foam recessed over the slotted area.

The TZM lid was attached to the HX body by brazing it to the surfaces it contacts the solid molybdenum. Photos of the multichannel HX with the TZM lid partially and fully in place are shown in Figure 12.

Fig. 12. Photos of foam-based HX with TZM lid partially in place (left) and with lid in place (right).

V. PLANNED EXPERIMENTAL TESTING

The flat multichannel HX plate prototype will be tested at the SNL Electron Beam Facility. Helium will be used as the coolant, with inlet conditions of 300 °C and 4 MPa for flow rates up to 100 g/s.

The electron beam will be used to apply a heat flux load onto an area of roughly 100 cm^2 on the TZM lid above the foam region. The plan is to ramp up the heat flux starting at 1 MW/m^2 until failure in order to determine the HX's performance. Through FEA testing on the HX structure, the anticipated maximum heat flux allowable without failure using a 4 mm thick TZM lid is between 8-10 MW/m^2.

Preliminary tests have been performed in order to test the gas flow loop that will be used for the experiment. Nitrogen was pumped through the HX at varying flow rates in order to measure the pressure losses within the system. These tests were performed using both 65 ppi and 100 ppi foam within the HX, with results given in table II.

TABLE II. Experimental Pressure Drop Through the Foam-Based HX

Nitrogen Flow Rate (L/min)	Pressure Drop (Pa)	
	65 ppi Foam	100 ppi Foam
34	23.7	39.9
39.6	34.9	--
45.3	48.6	85.9
51	64.8	117.1
56.6	84.7	137
62.3	98.4	--
68	119.6	--

VI. CONCLUSIONS

A helium cooled multichannel flat-plate HX for divertor development made of molybdenum and TZM was designed and fabricated. The divertor prototype uses a porous material (refractory foam) to enhance heat transfer efficiency. Helium flows through a 2-mm thick low-density open-cell molybdenum foam, which is located directly below the heated surface and above four parallel coolant inlet channels. Four inlet and five outlet channels are used to create an azimuthal helium flow behavior, which was optimized using CFD analysis to provide coolant to the heated region evenly with reasonable pressure losses (less than 100 kPa). FEA simulations suggest that the design HX should withstand heat fluxes up to 8 MW/m^2 before failure.

The prototype was manufactured at Ultramet successfully. Testing of the prototype is now underway at the SNL Electron Beam Facility in order to see if it meets the performance requirements desired.

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