SAND2006-5312C

High Heat Flux Testing of a Helium-Cooled Tungsten Tube with Porous Foam*

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Abstract

Utramet, Inc. fabricated one-piece heat exchanger tubes of chemical vapor deposited (CVD) tungsten (W), each with an internal porous mesh fused along either 51mm or 38mm of the axial length of a tube 15 mm in outer diameter. The open porous mesh has a structure of joined ligaments that combines relatively low resistance to flow and a large area for heat transfer. In tests at the Electron Beam Test Stand (EBTS) at Sandia National Laboratories, the maximum absorbed heat load was 22.4 MW/m^2 with helium at 4MPa, flowing at 27g/s and with inlet and outlet temperatures of 40˚C and 91˚C and a pressure drop of ~0.07 MPa. The preparation and testing of the samples was funded through a Phase I grant by the US Department of Energy's Small Business Innovation Research Program. The paper reports the surface temperature distribution indicated by an infrared camera, test conditions, a post-test examination in a scanning electron microscope and other details.

Keywords: helium cooling, plasma facing components, tungsten, high heat flux

1. Introduction

Preferences for high efficiency energy conversion with a Brayton cycle and elimination of water as a coolant due to safety related issues have led to designs for future power-producing magnetic fusion plants with helium-cooled plasma facing components (PFCs). For example, the recent design for ARIES-CS[1], a compact stellerator, uses a helium-cooled ferritic steel first wall with a coating of oxide-dispersion strengthened ferritic steel to permit a peak temperature of 700˚C and a He system pressure of 8 MPa. Norajitra and co-workers have advanced a design for a DEMO divertor with helium-cooled tungsten (W) modules.[2] The use of helium (He) as a coolant and the requirement of using a refractory material, particularly W, present significant technical challenges. Also, designs with He-cooled FWs made of ferritic

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000

steels with a moderate heat load of 0.5 MW/m^2, maximum temperature of 470°C and with 8 MPa He system are being developed as part of the Test Blanket Module program for ITER (International Thermonuclear Experimental Reactor).

These PFCs receive most of their heat from a combination of electromagnetic radiation and bombarding particles on surfaces facing the plasma. Neutrons also deposit some additional volumetric heating. The consequence of the high mass flow rate needed for adequate heat removal is a high He density at acceptable flow velocities and therefore high pressure. Some minimum thickness of several millimeters (3 mm is a typical value) for the surface of the He-cooled PFC to be exposed to the plasma is necessary to provide robustness including some allowance for anticipated erosion due to particle bombardment. While a greater thickness increases the structural mass of the PFC, local stresses also increase because the greater thickness increases the surface temperature (and also the overall nuclear heating) and the stiffness against bending that might relieve some stress. A pressure of 8 MPa in a tubular cooling channel with an 8-mm inside diameter and 3-mm wall causes a stress of ~11 MPa. Other operating stresses for He-cooled PFCs come from (1) the thermal gradient through the thickness between the heated surface and the coolant, and (2) the differential strain between the directly heated ("top") surface of a tube and the sides and bottom of the tube, and (3) limitations to the deformation of an individual coolant channel that arise from the channel being part of a larger panel.

1.1 Helium-cooled PFCs

Consider a design for a fusion reactor in which we have already fixed the thickness of the heated wall of the PFC and the outlet temperature of the helium cooling loop. A higher heat transfer coefficient in the PFC corresponds to a lower maximum surface temperature of the PFC and some reduction in the system pressure (helium density) or flow rate (pumping power). Fins, micro channels, stacked micro-plates and porous media are among the clever ideas advanced to increase the heat transfer coefficients in He-cooled structures.[3] In applying such solutions to refractory structures, the technical challenges include either or both of the following: 1) intricate machining of fins or channels to produce a large area for heat transfer, and 2) joining of parts to the coolant channel wall, as in a brazing that provides good thermal contact between the particles themselves and between the particles near the wall and the wall. Another concern with such solutions is that the increased surface area and the reduced volume for flow can drastically increase the pressure drop.

For long channels, a simple approach with internal packed beds will not work and the solutions for He cooling have advanced significantly over the last decade. Here are two examples of clever solutions using packed beds. In both cases, the length of the flow path through the region of high flow resistance was minimized. Both efforts were funded by the Department of Energy's Small Business Innovative Research (SBIR) Program and tested at Sandia.

Thermacore, Inc. (Lancaster, PA) developed a design for guard heat sinks to be used around an RF antennae on DIII-D.[4] In this application, a packed brazed bed of copper balls filled the annular region of a coaxial tube. The brazed contacts within the bed and between the copper balls and the tube walls provided radial thermal conductance from the outer heated wall into the packed bed. The core of the heat sink, inside the annulus was divided into a top and bottom. Half of this core served as the inlet manifold He and the other half served as the outlet manifold and there was little flow resistance along these open channels. The He flowed from the inlet side to the outlet side along a relatively short circumferential path through the packed bed and was fed and collected from divided channels in the center of the pipe. In tests performed at Sandia with steady state He flow, this test article removed a heat load of 29.5 MW/m^2 (peak at top of tube) with the heat load applied over an area of 2.0 cm^2 area and 6 MW/m^2 over a 21.6 cm^2 area.

In the second concept, also developed by Thermacore, the plasma facing surface is a circular (or hexagonal) W headpiece brazed to a refractory alloy tube.[5] The headpiece has a hemi-spherical interior well filled with a packed bed of W particles, also brazed. Such modules could be incorporated in a hexagonal array to cover a large surface such as the divertor in a fusion reactor. Helium enters at the center of a packed bed and then flows outward a relatively short distance across the radius of the packed bed and returns along the stalk of the module. In tests at Sandia, this refractory module removed a heat load of 29.5 MW/m^2 with the heat load applied over an area of 2.0 cm^2 area and 6 MW/m^2 over a 21.6 cm^2 area.

In a somewhat similar design approach, Norajitra and others at FZK developed a hexagonal module with He that flows through holes in a hemispherical cap to form jets that impinge on the back of a W headpiece with return flow down the circumference of the module. This development proceeded through fabrication and testing of a module array in Germany.[2]

1.2 Recent Innovation

Ultramet, Inc., a small business in Pacoima, CA, has significantly advanced the technology for He-cooled refractory heat sinks with an integrated structure that overcomes both of the technological issues (joining and limited open volume for flow) noted above. Using chemical vapor deposition (CVD) of W, Ultramet can fabricate the refractory heat sink, for example, a W tube, and its interior porous W mesh as an integral unit. The bonding occurs as a part of the CVD process that coats the porous mesh. The mesh itself is formed initially from carbonization of an open-celled plastic foam that leaves a skeletal structure of inter-connected ligaments that are then coated with W in the CVD process. The result is an open structure with relatively low flow resistance and pressure drop. Compared to a packed bed of balls or irregular solids, the relatively large interconnected free volume around the ligaments is available for helium flow, with the expectation that the pressure needed to drive flow through this foam would be much less than for a packed bed.

As with fins, if the thermal conductance is low (thin fin or ligament coating), then a large thermal gradient forms down the fin or ligament near the wall and relatively little heat transfer to the He occurs further away from the wall, which makes any additional length of a fin ineffective. In theory, control of the thickness of the W coating can provide a first order control of the thermal conductance of the ligaments.

2. Specimens and Testing

Ultramet produced four tubular CVD tungsten (W) samples. The two basic goals of the testing in the Plasma Materials Test Facility at Sandia National Laboratories were (1) to determine the what steady sate heat load that these helium-cooled refractory heat sinks could handle and (2) to characterize the pressure drop through the porous W foam under various flow conditions. The preparation of tungsten tube with porous tungsten cores and the testing at Sandia reported here was also supported by the DOE SBIR Program.

2.1 CVD Tungsten Specimens

Figure 1 shows the main features of the tubes; inset is an SEM photo of a piece of the W foam. Each W tube is 152 mm (6 in.) long with respective inner and outer nominal diameters of 12.7 and 15 mm (0.5 and 0.62 inches). The actual outer diameters varied due to the nature of the CVD process. Specimen PN1 for which we report high heat flux test data had an outer diameter of 16.8 mm. In the heat exchanger section of the CVD W tube, a cylinder of porous CVD W foam fills the cooling channel. Its axial length is either 38 or 51 mm (1.5 or 2.5 in.) and its outer perimeter is integrally bonded to the tube. The porous W foam provides both a large area for heat transfer and good thermal conductance along the W coated ligaments of the foam. Overlapping each end of a W tube and integrally bonded to it at each end are CVD niobium tubular fittings 19.1 mm (0.75 in.) in diameter. These ductile niobium tubes were joined to the piping of the test chamber using Swagelok® compression fittings.

The inherently brittle nature of the tungsten base metal for these specimens was recognized by both Ultramet and Sandia. Under the combination of thermal stresses from the heat loads and primary stresses due to the helium coolant pressure during the tests, rupture of the specimens was understood as a possible if not likely outcome.

As noted previously, the development of a suitably robust refractory alloy for applications in fusion technology is a significant technical challenge and potentially difficult obstacle for this development path. There is some promising work that involves nano-scale structures but is not a subject of discussion in this paper.

2.2 Testing

Sandia performed two types of tests on the helium-cooled Ultramet CVD W specimens, both done in the Electron Beam Test Facility (EBTS). EBTS is a 30 kW electron beam (e-beam) in Sandia's Plasma Materials Test Facility.[8] Sandia performed flow tests, without e-beam heating, to characterize the pressure drop through specimens and high heat flux tests to measure the thermal performance of these specimens.

EBTS is equipped with a He loop with a nominal inlet temperature of 25°C and capable of He gas pressure to 4MPa and flow rates to 22 g/s at 4MPa. In the tests reported here, a low pressure "delta P" meter connected with 6-mm pressure lines to fittings at each end of the specimens provided the data on pressure drop. Prior to the collection of data, we ran the He system for 20 minutes with an in-line 5-μm gas filter to collect any particles that might lodge in the CVD W foam. We measure the He flow rate using the pressure drop through a calibrated aperture and calculated the mass-corrected flow data for He. (Ultramet also performed preliminary pressure drop tests in air at much lower flow rates, but these data are superseded by the He flow data.) We measured the temperatures of the inlet and outlet He streams with RTDs.

Due to time constraints, we performed high heat flux tests on a smooth tube without a porous mesh and only one specimen (PN1) with a porous core. During the high heat flux tests, we applied the heat loads only over the 38-mm length of the tube with the porous W foam inside. W, a very dense material, reflects about 2/3 of the relatively low energy electrons (20-30 keV depending on the power level of the beam). We measured the absorbed power using calorimetric data based on the flow rate and the He temperatures at the inlet and outlet of the chamber. With the incident power coming down normal to the axis of the tube, the heat load has a cosine distribution over the tube with the peak heat load along the top of the tube. From the absorbed power, the cosine distribution and the heated surface area observed on the W tube, we calculated the absorbed heat flux. The values given later are the peak absorbed heat load in MW/m^2 at the top of the tube.

Before applying any heat loads to the He-cooled tube, we used the filament leakage current from the e-beam to heat a W tube slowly without any coolant flow. With the good conductivity of the W, the temperature of the specimen was quite uniform. We calibrated the low range (300-1300°C) one-color spot pyrometers and the processed images from the IR (infrared) camera by setting the emissivities so that the surface temperature from the pyrometer and that of the processed IR image agreed with the measured temperature from one or two spring-loaded Type K TCs (thermocouples) pressed against the underside of the W tube. We also used a mid-range (740-1400°C) two-color pyrometer and a high range (1500-3500°C) two-color pyrometer, which do not require independent calibrations of their emissivities. These pyrometers are noted as 1C (one color), 2Cm and 2Ch in Fig. 2.

3. Results and Discussion

The single He-cooled W tube (PN1) we tested, with W foam in 38 mm of its length, removed impressively high steady state heat loads. Moreover, the porous foam core that provided this excellent heat removal had a relatively low pressure drop.

3.1 High Heat Flux Tests

For specimen PN1 with a 38-mm length of W foam, the maximum absorbed heat load was 22.4 MW/m^2 with He at 4 MPa, flowing at 27g/s, inlet and outlet temperatures of 40˚C and 91˚C respectively, and a pressure drop of ~0.07 MPa. Fig. 2 shows the observed peak surface temperature versus peak absorbed heat load for tubes PN1 and PN4 in the tests at 1 and 4 MPa. (The term “peak” here denotes the location of both the maximum heat load and maximum temperature along the top of the tube.) Table 1 gives the maximum heat loads and conditions for the tests at all He pressures. Although, the surface heat load varies in a cosine distribution over the top half of the tube, the value we are calling the peak heat flux would also be the average absorbed heat flux on a bank of tubes based on their frontal area.

Tests were performed at He pressures of 1.02, 2.06, 3.04 and 4.03 MPa, and respective mass flow rates of 5.4-5.8, 11.4-11.8, 17.0-17.5 and 23.4-27.0 g/s. Fig. 2 shows only the data for He pressures of 1 and 4 MPa to simplify the plot. The heated area always extended across the full diameter of the tube. At the lower heat fluxes, the heating pattern covered the full 38-mm length of the W foam in PN1. To obtain the higher heat fluxes, we shortening the heated length to ~19 mm.

The transition from full to half the heated length of the W foam, at the heat load of 15MW/m^2, there is an offset in the temperature curve for PN1 and the temperature from the mid-range two-color pyrometer actually dropped. This drop might be explained in part if the reticule of the pyrometer included a somewhat cooler area at the perimeter of the reduced heating area. The offset of the high range pyrometer may reflect a real offset in the peak temperature due to axial conduction in the tube. With the heated length of 19 mm, some heat flowed axially along the tube into the regions that are not directly heated but are bonded to the W foam.

3.2 Pressure Drop

The pressure drops for these specimens is relatively low. Fig. 3 shows data for various flow conditions for specimen PN1 with the porous W foam region 38 mm long and specimen PN3 with W foam 51 mm long. The curves fit a dependence on the square of the mass flow as expected. The flow for PN3 (4 MPa) overlap the data for PN1 at 2 MPa up to 16 g/s, the highest flow rate for the PN1 data. In Fig. 3 the data for PN1 above 13 MPa were deleted as were the data below 15 MPa for PN3 to show the trends for both data sets.

The supply pressures were 0.99-1.05, 1.98-2.08, 2.98-3.15 and 3.98-4.16 MPa for the PN1 tests and 3.98-4.12 MPa for the PN3 test. Flow tests were done on all four specimens (PN1-PN4). The pressure drop in the open tube, PN4, is of course essentially negligible in this test.

3.3 Post Test Examination

We considered fracture of the heated specimens a likely result, as noted previously, and this was the case for specimen PN1, which fractured on the cool down after the 60 s heating pulse at the highest heat load. PN1 fractured into many fragments; only a few were larger than a few square centimeters.

We examined three of these large fragments in our JEOL 6300 scanning electron microscope. Our objective was to find any indication that the high surface temperatures incurred during testing had led to a recrystallization of some portion of the wall of the tungsten tube. No such indications were found.

Figure 4 shows a fracture surface (part of wall) on one fragment. The features shown were typical for the fracture surfaces around each of the three fragments. The fracture surfaces all showed elongated, radially-oriented grains with at least two distinct deposition zones in the wall, i.e., a circumferential boundary roughly halfway through the wall thickness. The faceted surfaces of the fractured wall are typical of a brittle fracture.

The fragmentation of the sample underscores a well-recognized conclusion that the utilization of tungsten as a structural material in fusion plants will require the development of some form of tungsten (either an alloy or a modified micro-structure) that can resist brittle failure. However, the high heat removal in these tests is an impressive result for the potential of He-cooled refractory systems for plasma facing components in fusion devices.

4. Conclusions and Future Work

Ultramet has demonstrated integral bonding of tungsten tube with an internal 38-mm-long tungsten porous mesh. This integrally bonded tungsten heat sink demonstrated outstanding heat removal with a peak absorbed heat flux of 22.4 MW/m^2 with He at 4 MPa, flowing at 27g/s. Equally impressive are the high heat loads of 12, 9.5 and 5.7 MW/m^2 removed a He pressures of 3, 2 and 1 MPa respectively. Moreover, the very open porosity of the mesh enables this excellent thermal performance with a relatively low pressure drop.

One important consequence of this work is the demonstration for the potential of effective He cooling at significantly lower system pressures. While the higher pressure He systems may be needed for coupling to an efficient power conversion cycle, there may be applications at the lower pressure for He-cooled probes or specialized heat sinks.

Another potential consequence is that at high temperatures and pressures, the improved heat transfer may permit cooling of a first wall at significantly lower mass flow rate, to reduce the pressure drop, while still maintaining acceptable surface temperatures. For example, in our tests, at a system pressure of 4 MPa, a flow rate of 24.8 g/s gave a pressure drop for a 38-mm flow length of W foam of 0.71 MPa, which corresponds to a linear pressure drop of 1.87 MPa/m. We can make a simple estimate of the linear pressure drop at 8 MPa and an operating temperature of 1000˚C by correcting for density, calculating the flow velocity and increasing the pressure drop in proportion to the kinematic viscosity. At the same mass flow, the large increase in pressure drop (~18X) would preclude using a long foam-filled tube. However, let us consider application of these W heat sinks to a first wall with a heat flux of 3 MW/m^2, about $1/8^{th}$ of the maximum heat load tested. Using a mass flow rate of 0.0031 g/s ($1/8^{th}$ of 24.8) in these channels, gives a linear pressure drop of 0.53 MPa/m, which would probably be acceptable for roughly one-meter-long tubes spanning the plasma-facing section of a first wall.

A more detailed treatment of the data summarized here has been prepared by Ghoniem and Sharafat (University of California, Los Angeles). They and co-workers in DMS (Digital Materials Solutions in Granada Hills, CA) are using the data from the Ultramet-Sandia tests to calibrate a parametrized model for pressure drop and heat transfer in W porous media. DMS has issued a report on this modeling and will be publishing a paper in the Technology of Fusion Energy Conference in Albuquerque, November 2006. Also, DOE has approved a Phase-II SBIR Grant for further work on the W porous media development by Ultramet and DMS.

5. Acknowledgements

The authors wish to acknowledge the help of Fred Bauer and Ken Troncosa of Sandia National Laboratories in the operation of the EBTS and the performance of the testing at Sandia and to acknowledge the help of Tim Stewart of Ultramet, Inc. in the preparation of the four tungsten tube specimens.

6. References

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Tables

Table 1. Heat removal data, PN1

Pressure	He flow rate	peak absorbed heat load	peak surface temp.
(MPa)	(g/s)	(MW/m^2)	(C)
1	5.4	5.7	1416
2	11.4	9.5	1487
3	17.0	12.0	1605
4	27.0	22.4	2295

Figs.

1. Sketch of CVD mockup with inset SEM photo of tungsten porous foam.
2. Peak surface temperature (temp-peak) versus absorbed peak heat load (q"abs.-peak) for He pressures of 1 and 4 MPa.
3. Pressure drop versus He mass flow rate for PN1 (38 mm foam) at 1-4 MPa and PN3 (51 mm foam) at 4 MPa.
4. SEM photo of fractured wall of specimen PN1. (25X)

FIGURES YOUCHISON SOFT2006

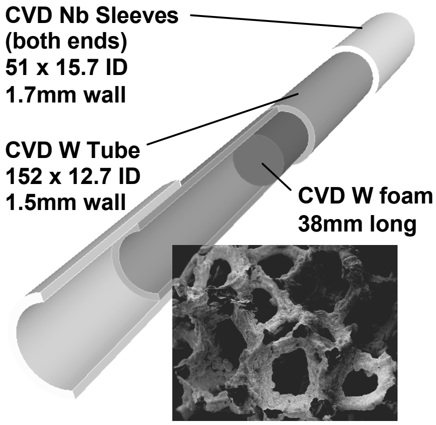

Fig. 1

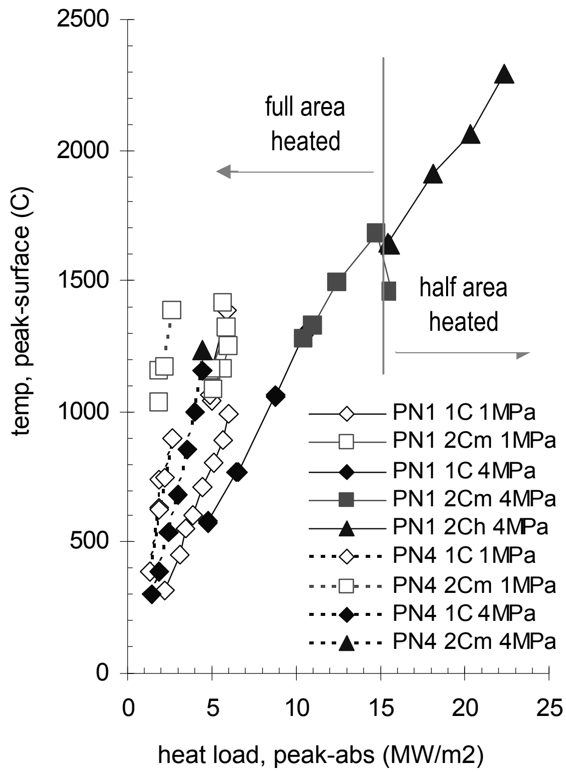
2500
2000
1500
1000
500
0
0
5
10
15
20
25
temp, peak-surface (C)
heat load, peak-abs (MW/m2)
full area
heated
half area
heated
PN1 1C 1MPa
PN1 2Cm 1MPa
PN1 1C 4MPa
PN1 2Cm 4MPa
PN1 2Ch 4MPa
PN4 1C 1MPa
PN4 2Cm 1MPa
PN4 1C 4MPa
PN4 2Cm 4MPa

Fig. 2

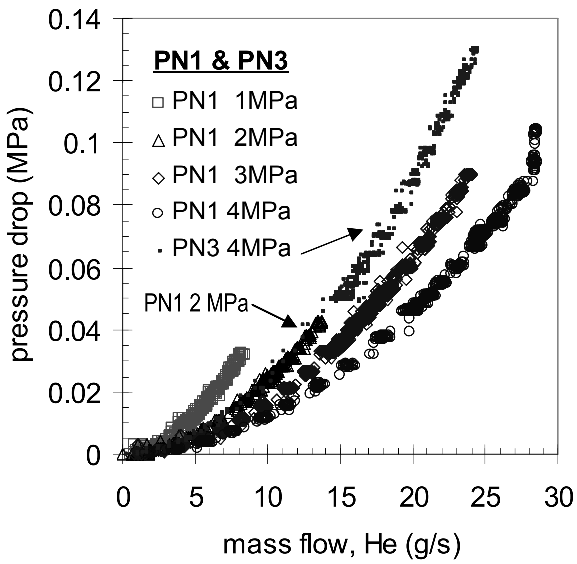
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
pressure drop (MPa)
PN1 & PN3
PN1 1MPa
PN1 2MPa
PN1 3MPa
PN1 4MPa
PN3 4MPa
PN1 2 MPa
0
5
10
15
20
25
30
mass flow, He (g/s)

Fig. 3

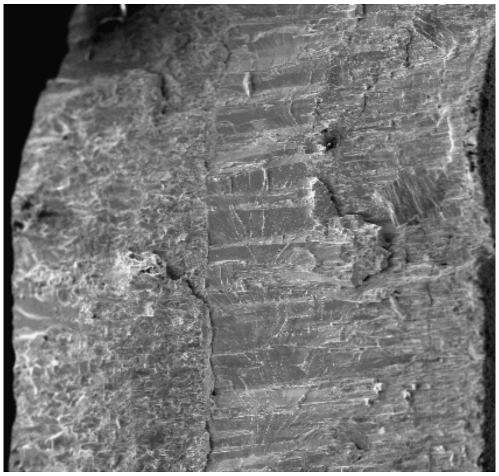

Fig. 4