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# Design, Fabrication, and Testing of a Helium-Cooled Module for the ITER Divertor*

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The International Thermonuclear Reactor (ITER) will have a single-null divertor with total power flow of 200 MW and a peak heat flux of about 5 MW/m$^2$. The reference coolant for the divertor is water. However, helium is a viable alternative and offers advantages from safety considerations, such as excellent radiation stability and chemical inertness.

In order to prove the feasibility of helium cooling at ITER relevant heat flux conditions, General Atomics designed, fabricated, and tested a helium-cooled divertor module. The module was made from dispersion strengthened copper, with a heat flux surface 25 mm wide and 80 mm long, designed for twice the ITER divertor heat flux. Different techniques were examined to enhance the heat transfer, which in turn reduced the flow and pumping power required to cool the module. It was concluded that an extended surface was the most practical solution. An optimization study was performed to find the best extended surface parameters. The optimum extended surface geometry consisted of fins: 10 mm high, 0.4 mm thick with a 1 mm pitch. It was estimated to require a pumping power of 150 W to remove 20 kW of power. This is more than an order of magnitude reduction in pumping power requirement, compared to smooth surface.

The module was fabricated by electric discharge machining (EDM) process. The testing was carried out at SNLA during August 1993. The testing confirmed the design calculations. The peak heat flux during the test was 10 MW/m$^2$, applied over a surface area of 20 cm$^2$. The pumping power calculated from flow rate and pressure drop measurement was about 160 W, which was less than 1% of the power removed. It is planned to test the module to higher temperature limits and higher heat fluxes during coming months.

As a result of this effort we conclude that helium cooling of the ITER divertor is feasible without requiring a very large helium pressure or a large pumping power. Our preliminary studies show that a helium cooling system for the ITER divertor can be designed at a pressure of 5 MPa with a pumping power of about 10 MW.

## 1. INTRODUCTION

Although the reference coolant for the ITER divertor is water [1], helium is considered an attractive alternative due to its safety advantages [2]. However, there is a concern that helium can not be used to remove ITER-relevant heat fluxes, that use of helium would result in large manifolds, require large pressure, and would result in large pumping power.

The purpose of this task was to examine these concerns and find a practical solution to them. Hence General Atomics decided to design, fabricate and test a helium-cooled divertor module for ITER-relevant heat flux conditions. The module was to be tested at the plasma materials testing laboratory of Sandia National Laboratory, Albuquerque (SNLA). The peak heat flux for the ITER divertor is 5 MW/m$^2$. The maximum pressure and flow rate for the helium loop at SNLA are 4 MPa and 0.025 kg/s. The GA divertor module was designed for twice the peak heat flux expected on the ITER divertor. This heat flux level and the helium loop parameters limited the heated size of the module to 25 mm wide and 80 mm long. The material selected for fabrication of the GA divertor module was dispersion strengthened copper with a peak surface limitation of 500°C.

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## 2. PUMPING POWER AND FLOW

Pumping power and flow rate are two very important parameters which determine the feasibility of using helium to cool fusion divertors. Using the standard relations for pressure drop, energy balance, pumping power, and the definition of dimensionless heat transfer coefficient, Stanton number (St), (nomenclature is at the end of the paper), the volumetric flow rate V, required to remove power Q, at an inlet helium temperature of $\theta_i$, and peak wall temperature $T_{max}$ is:

$$V = \frac{Q}{\rho_a Cp\left[T_{max} - \theta_i - q''_{max}\left(\frac{\delta}{\kappa} + \frac{1}{\alpha}\right)\right]} \quad (1)$$

and the ratio of pumping power, W, to power removed, Q, is:

$$\frac{W}{Q} = \frac{q_a''^2}{8\varepsilon\left(T_a - \theta_a\right)^3 \rho_i \rho_a Cp^3}\left(\frac{f}{St^3}\right). \quad (2)$$

Equations (1) and (2) show that the pumping power and volumetric flow rate could be reduced by:

1. Increasing the density by increasing the coolant pressure
2. Using heat transfer enhancement techniques, which increase the heat transfer coefficient.

In practice, the benefit obtained by enhancement techniques is larger than indicated by Eqs. (1) and (2), because the enhancement has to be applied over an area with high heat flux only. This area may be only 10% in the case of the ITER divertor. Any enhancement technique used to obtain a higher heat transfer coefficient (e.g. roughening the walls) also results in an increase in friction factor. However, as seen from Eq. (2), the Stanton number (nondimensional heat transfer coefficient) has an exponent of 3, compared to an exponent of 1 for the friction factor. The net result is to decrease the flow and the pumping power required to attain the same thermal performance.

## 3. TEST MODULE DESIGN

The test module dimensions were controlled by the beam power and flow loop parameters of the SNLA facility. The maximum pressure and flow rate for the helium loop at SNLA are 4 MPa and 0.025 kg/s and the maximum beam power is 30 kW. These parameters, and the size of the test vacuum chamber limited the heated size of the module to 25 mm wide and 80 mm long.

Standard correlation's for heat transfer coefficient, friction factor, and inlet and exit losses from Refs. [3] and [4] were used for thermal design of the module. Properties of helium were based on Ref. [5]. All design calculations were done for an inlet pressure of 4 MPa and an inlet coolant temperature of 20°C.

The following heat transfer enhancement techniques were examined:

1. Two dimensional roughness [6]
2. Three dimensional roughness [6]
3. Impinging jets [7]
4. Extended surfaces.

It was concluded that use of extended surfaces was the most practical way to achieve the large enhancement in heat transfer in a practical way. Extended surfaces increase the effective heat transfer coefficient because reduced flow area increases the flow velocity, the hydraulic diameter is smaller, and the heat transfer area is increased. The overall effect can be (depending on the coolant, fin material etc.) an increase in the heat transfer coefficient by a factor of 5 to 10 over the smooth channel value for a given flow and channel cross section.

Since there are too many variables which determine the surface temperature of the module (flow rate, fin pitch, thickness, height, material thermal conductivity), the effect of each variable was examined. A computer program was developed to perform this study. An optimization study was performed to find the best height, pitch, and width which resulted in minimum pumping power. The details of the optimization are reported in Ref. [8].

Thus the optimized extended surface design consisted of a pitch of 1 mm, a height of 10 mm and a pitch to thickness ratio of 2.5. For this geometry, the pumping power for a copper module at a heat flux of 10 $MW/m^2$ is calculated to be 50 W, i.e., 0.25% of the power removed

The calculated flow rates and pumping power required for the module with and without enhancements are summarized in Table 1. This table shows that optimized fins provide a factor of 45 improvement over use of a smooth channel!

A calculation was performed for a module made from beryllium. Due to considerably lower (33%) thermal conductivity of beryllium, the beryllium module performance is not expected to be as good as a copper module.

Table 1
Summary of Analysis for GA Divertor Module

| Material | Concept | Flow Required (kg/s) | Heat Transfer Coefficient ($MW/m^2{}^\circ C$) | Pressure Drop (MPa) | Pumping Power [W (%)] |
|---|---|---|---|---|---|
| Cu | Smooth tubes | 0.23 | 0.026 | 0.064 | 2300 (11.5) |
| Cu | 2-D rough tube | 0.12 | 0.028 | 0.068 | 1180 (5.9) |
| Cu | 3-D rough tubes | 0.072 | 0.029 | 0.044 | 480 (2.4) |
| Cu | Jets | 0.026 | 0.04 | 0.1 | 490 (2.45) |
| Cu | Optimized fins | 0.026 | 0.04 | 0.012 | 50 (0.25) |
| Cu | Offset fins | 0.025 | 0.042 | 0.01 | 40 (0.20) |
| Be | Optimized fins | 0.040 | 0.04 | 0.035 | 200 (1) |

A 2-D finite element thermal stress anaslysis of the module was performed with the COSMOS [9] code to verify the one dimensional calculations.

## 4. MODULE FABRICATION

The module was fabricated from dispersion strengthened copper by an electric discharge machining process.

Connecting the module to the helium test loop required end fittings, preferably conflat flanges. Brazing appeared the best way to guarantee a leak tight seal between the copper module and a conflat flange. After the braze cycle, a helium leak test was performed. The assembly was hydraulically tested to 6.2 MPa. The pressure was held for 5 minutes with no decay and no leaks. The module was baked in a vacuum furnace to 300°C for 6 hours. The fabricated module is shown in Fig. 1

## 5. TEST RESULTS

The tests were conducted at the plasma material testing laboratory of the Sandia National Labora-tory, Albuquerque in August 1993. The heat source was an electron beam with a maximum power of 30 kW.

According to the test plan, the first test was an isothermal flow test to find the relation between loop pressure, pressure drop through the module, and the maximum flow. At the loop pressure of 4 MPa a flow of 23.3 g/s could be obtained at a pressure drop of 52 kPa. This indicated that the module could be tested to design heat flux. The heat flux area and heat flux were gradually increased. In all, 92 shots were taken to cover the experimental plan.

Following are results at the highest helium pressure (4 MPa). The pulse length was 60 seconds, which is adequate to achieve steady state. No damage was detected at the end of these tests.

| Flow Rate (kg/s) | Heat Flux ($MW/m^2$) | Peak Surface Temperature (°C) | Pumping Power [W (% of power removed)] |
|---|---|---|---|
| 0.022 | 10 | 380 | 157 (0.8) |
| 0.011 | 6 | 422 | 21 (0.2) |
| 0.0064 | 3 | 424 | 3.4 (0.06) |

Thus the measured temperatures were smaller than design predictions. The heat fluxes shown in the above table are based on the assumption that 83.3% of the beam power is absorbed on the surface of the module. This fraction was based on SNLA experience with copper surfaces in their electron beam facility. In practice (as indicated by the calorimetry), this fraction may be somewhat smaller.

A further series of tests at peak heat flux of up to 25 $MW/m^2$ are planned in August 1994 and if available will be presented at the meeting.

## 6. ITER DIVERTOR DESIGN

From the test results we concluded that an ITER relevant divertor design with helium cooling is feasible with a combination of heat transfer enhancement techniques and high pressure helium.

We performed a preliminary study of the ITER divertor with a power flow of 200 MW, an average heat flux of 1 $MW/m^2$ and a peak heat flux of 5 $MW/m^2$. We assumed that the helium inlet pressure was 5 MPa and the peak heat flux is over 10% of the divertor surface. Using the heat transfer enhancement techniques verified in this paper, we

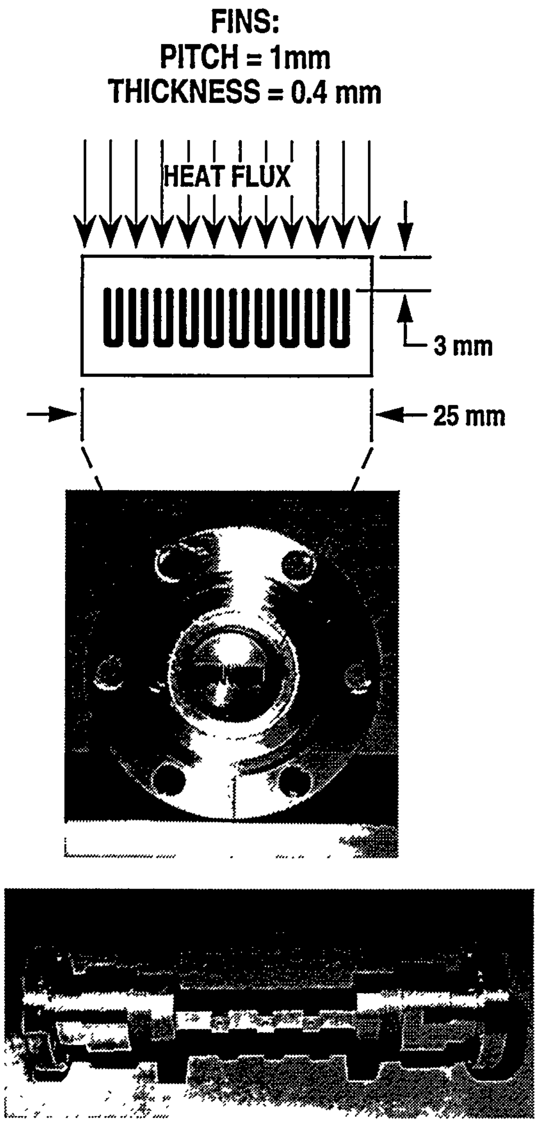


Figure 1. GA Divertor Module.

concluded that the flow required to cool such a divertor will be 180 kg/s and the pumping power will be about 10 MW.

## 7. CONCLUSIONS

As a result of this study, the following conclusions were reached:

1. ITER relevant heat fluxes can be removed with helium cooling at moderate pressures and reasonable pumping powers.
2. Helium cooling of fusion divertors can be achieved at pressures of about 5 MPa.
3. A helium-cooled divertor design for steady-state fusion machines is feasible, with a pumping power less than 5% of the power removed.

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## NOMENCLATURE

$C_p$ = specific heat of coolant
f = friction factor
$\Delta p$ = pressure drop
Q = total power removed
q" = heat flux
St = Stanton number
T = Wall temperature
V = volumetric flow rate of helium
W = pumping power
$\alpha$ = heat transfer coefficient
$\theta$ = coolant temperatures
k = thermal conductivity of the module
$\delta$ = wall thickness
$\varepsilon$ = circulator efficiency

Subscripts:
a = average
i = inlet
o = outlet
max = maximum