GA–A22333

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This is a preprint of a paper to be presented at the High Heat Flux Engineering III Conference, August 4–5, 1996, Denver, Colorado, and to be printed in the *Proceedings.*

GENERAL ATOMICS PROJECT 4437
AUGUST 1996

Design, fabrication, and testing of helium cooled high heat flux module

C.B. Baxi, K.M. Redler, and J.P. Smith

General Atomics, P.O. Box 85608, San Diego, California 92186-9784

ABSTRACT

Helium cooling is an attractive alternative to water cooling for high heat flux components. Helium offers advantages from safety considerations, such as excellent radiation stability and chemical inertness.

General Atomics (GA) has considerable expertise in use of helium cooling due to its high temperature gas cooled reactor experience. In order to prove the feasibility of helium cooling at high heat flux levels of above 5 MW/m^2, GA designed, fabricated ,and tested a helium cooled module.

The module was sized to have a heat flux surface of 25 mm wide and 80 mm long due to test setup limitations on maximum deposited power. With a smooth flow channel, a flow rate of 0.23 kg/s, and a pumping power of 2300 W was required to keep the copper module surface temperature below 500^{o}C at a heat flux level of 10 MW/m^2. Hence, different techniques were examined to enhance the heat transfer, which in turn reduced the flow and pumping power required. It was concluded that an extended surface was the most practical solution. An optimization study was performed to find the best parameters. The module with an optimized extended surface geometry was estimated to require a flow of about 0.032 kg/s and a pumping power of 50 W to remove 20 kW of power. This is more than an order of magnitude reduction in pumping power required compared to the smooth channel.

The module was made from dispersion strengthened copper. The fabricated geometry was slightly different than the optimized design due to constraints of machining. The fabrication was done by electro discharge matching. The testing was carried out at the electron beam test facility of Sandia National Laboratory, Albuquerque (SNLA). The specifications of the loop and the electron beam testing facility were: 4 MPa pressure, 32 g/s of helium flow, and 30 kW beam power. The testing was carried out during August 1993 and again in December 1994. The testing confirmed the design calculations. Some of the test results obtained in the second series of tests are:

Heat Flux (MWm^2)	Area (cm^2)	Surface Temperature (^{o}C)
9.	20.	400.
18.	5.8	700.
34.	2.0	540.

It was necessary to reduce the area of heat flux deposition at higher heat flux due to limitations in the power capability of the electron beam. It is estimated that a heat transfer coefficient of about 40,000 W/m^2-C was achieved during these tests.

The pumping power calculated from flow rate and pressure drop measurement was about 160 W for the test with 9 MW/m^2 surface heat flux, which was less than 1% of the 18 kW power removed. As a result of this effort we conclude that, helium cooling of high heat flux components is feasible without requiring a very large helium pressure or a large pumping power.

Keywords: Glidcop, high heat flux, fusion, helium

1. INTRODUCTION

Helium is considered an attractive alternative to water due to its safety advantages[1] for cooling of high heat flux components. However, there is a misunderstanding that helium can not be used to remove large 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 GA decided to design, fabricate and test a helium cooled module capable of withstanding a heat flux of about 10 MW/m^2. The helium loop parameters of the testing facility at SNLA limited the heated size of the module to 25 mm wide and 80 mm length. The material selected for fabrication of the GA divertor module was dispersion strengthened copper made by GLIDCOP.

2. PUMPING POWER AND FLOW

Pumping power and volumetric flow rate are two important parameters which determine the feasibility of using helium to cool high heat flux components. If a module is subjected to a peak heat flux of $q''_{\max}$ and is cooled by helium at an inlet temperature of θ_{i}, the peak surface temperature $T_{\max}$ will be (nomenclature is at the end of the paper):

$$T_{\max} = \theta_{\mathrm{i}} + Q/V\rho_{\mathrm{o}}Cp + q''_{\max}/(\kappa/\delta) + q''_{\max}/\alpha \ , \tag{1}$$

Hence, the volumetric flow rate V required to remove power Q at an inlet helium temperature of θ_{i}, and peak wall temperature $T_{\max}$ is:

$$V = \frac{Q}{\rho_{\mathrm{o}}Cp\left[T_{\max} - \theta_{\mathrm{i}} - q''_{\max}(\kappa/\delta) - q''_{\max}/\alpha\right]} \ . \tag{2}$$

Further, if the pressure drop is ΔP, the pumping power W required for such a system is:

$$W = V \cdot \Delta P \ . \tag{3}$$

Using the definition of Stanton number, the ratio of pumping power to power removed can be written as:

$$\frac{W}{Q} = \frac{(q''_a)^2}{8\varepsilon(T_{\mathrm{a}} - \theta_{\mathrm{i}})^3\rho_{\mathrm{o}}\rho_{\mathrm{a}}} \ \frac{f}{St^3} \ , \tag{4}$$

Equations (2) and (3) show that the volumetric flow rate and pumping power can 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 even larger than indicated by Eqs. (3) and (4), because, in the case of non-uniform heat deposition, the enhancement has to be applied over an area with high heat flux only. In most practical applications, the peak heat flux is over a small area of the component. Any enhancement technique used to obtain a higher heat transfer coefficient also results in an increase in friction factor. However, as seen from Eq. (4), the Stanton number (non dimensional heat transfer coefficient) has an exponent of 3, compared to an exponent of 1 for friction factor. The net result is to decrease the flow and the pumping power required to attain the same thermal performance.

3. DESIGN

Standard correlations for heat transfer coefficient, friction factor and inlet and exit losses from Refs. 2 and 3 were used for thermal design of the module. Properties of helium were based on Ref. 4.

Bergles[5] has discussed 13 different methods for heat transfer enhancement. From practical considerations, this study was limited to following heat transfer enhancement techniques:

1. Two dimensional roughness and three dimensional roughness[5]: these concepts have been considered for the Gas Cooled Fast Breeder Reactor.[1] With this method the heat transfer coefficient can be increased by a factor of up to 3 at the expense of increasing the friction factor by a factor of 7.

2. Impinging jets[6]: this concept, although effective for small areas is not practical for large areas, and

3. Extended surfaces.[5]

Extended surfaces increase the effective heat transfer coefficient by three mechanisms:

a. Reduced flow area increases the flow velocity at a given flow rate.

b. The hydraulic diameter is small, and

c. 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. All the factors listed above also contribute to increase in friction factor and pressure drop. However, as seen from Eqs. (2) and (3), the net effect is to reduce the required flow and pumping power.

Table I shows how the enhancement techniques reduce the flow and pumping power requirements. To optimize the fins, a computer program was developed since there are too many variables which determine the surface temperature of the module (flow rate, fin pitch, thickness, height, material thermal conductivity). A study was performed to find the best height, pitch and width which resulted in minimum pumping power. Thus the optimized design consisted of a pitch of 1 mm, a height of 10 mm and pitch to thickness of 2.5. For this geometry, pumping power for a copper module at a heat flux of 10 MW/m^2 is 50 W, *i.e.*, 0.25% of the power removed. Table I shows that optimized fins provide a factor of 45 improvement over use of a smooth channel!

Further improvement (but very small) can be obtained by offset fins.[2] The principle behind this concept is use of developing boundary layer in the entrance region to obtain higher heat transfer coefficient. Analysis shows that the pumping power can be reduced to 40 W. Thus only a slight improvement can be obtained with the added complexity to the design.

A two-dimensional finite element thermal stress analysis of the module was performed with the COSMOS[8] code to verify the accuracy of one-dimensional calculations and to ensure that the module can withstand the induced stresses.

Table I: Summary of analysis for GA module

Thermal analysis was performed using different concepts to achieve a surface temperature of 500°C. Heat flux $q_i'' =$ 10 MW/m^2; wall thickness = 3 mm, helium pressure = 4 MPa (580 psia). Material is Cu, the module is 8 cm long and 2.5 cm wide.

Concept	Flow Required	Heat Transfer Coefficient (MW/m^2 °C)	Pressure Drop (MPa)	Pumping Power W (%)
Smooth Tubes	0.23	0.026	0.064	2300. (11.5)
2-D Rough Tube	0.12	0.028	0.066	1180. (5.9)
2-D Rough Tubes	0.072	0.029	0.044	480. (2.4)
Jets	0.026	0.04	0.1	490. (2.45)
Optimized Fins	0.026	0.04	0.012	50. (0.25)
Offset Fins	0.025	0.04	0.01	40. (0.20)

4. FABRICATION

Attempts to fabricate the module by brazing were not successful due to the difficulty of brazing complex geometries of dispersion strengthened copper. Therefore, the module was fabricated from dispersion strengthened copper by the electric discharge machining process. Connecting the module to the helium test loop required end conflate flanges. Brazing appeared the best way to guarantee a leak tight seal between the copper module and a stainless conflat flange adapter. After the braze cycle, a helium leak test was performed. No leak was seen at the maximum sensitivity of the machine, 1×10^{-9} torr l/s. The conflat flanges were then e-beam welded onto the stainless conflat flux adapters. The flanges were welded after the brazing due to experience that the knife edges being sometimes damaged at the brazing temperature. The unit was once again helium leak tested. The assembly was hydraulically tested to 6.2 MPa. The pressure was held for 5 min with no decay and no leaks. The module was baked in a vacuum furnace to 300°C.

The fabricated module differed from the optimum design in two respects:

1. The fin height was half of optimum size.

2. Due to imperfections in the some of fins, part of the flow could bypass.

The fabricated module had following dimensions:

Heated length = 80 mm
Width = 25 mm
Fin height = 5 mm, pitch = 1 mm, thickness = 0.4 mm

The fabricated module is shown in Fig. 1

5. TEST RESULTS

The tests were conducted at plasma testing laboratory of the Sandia National Laboratory, Albuquerque in August 1993 and again in December 1994. The heat source was an electron beam with a maximum power of 30 kW. The loop pressure was 4 MPa and the maximum flow rate available was about 30 g/s. Only part of the incident beam power is absorbed by the high heat flux surface. The module was baked in moist air at 300°C to increase the emissivity of the surface. The absorbed heat flux is calculated from the flow,

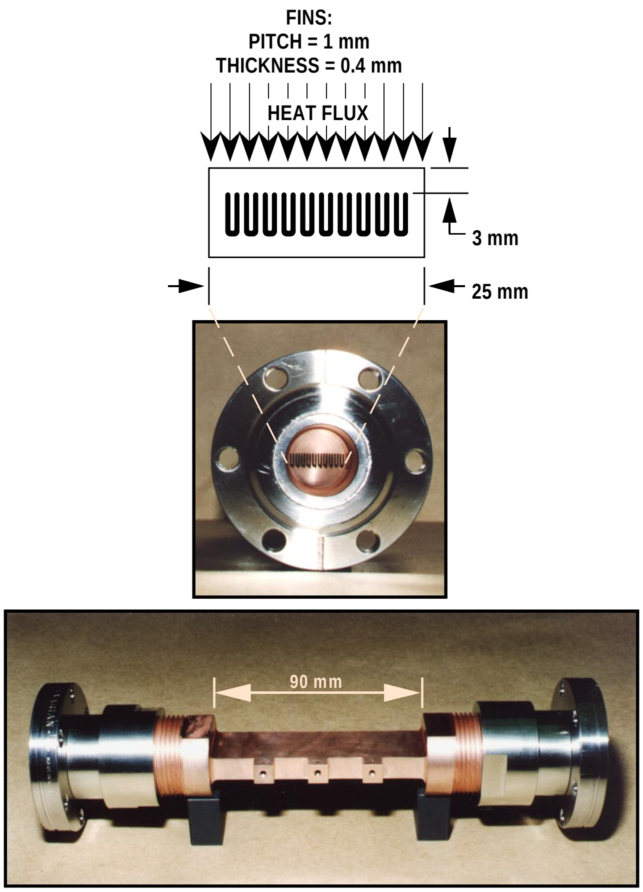

Fig. 1. GA helium cooled copper module.

inlet and outlet temperature of the helium. These measurements indicated that 70% to 80% of the beam power was absorbed by the module.

The first test was an isothermal flow test to access the relation between loop pressure, pressure drop through the module, and the flow. Figure 2 shows the results of this test. This test confirms the first design parameter that 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 result indicated that the module could be tested to the design heat flux.

During the first series of high heat flux tests the heat flux area and heat flux were gradually increased. In all, 92 test shots were taken to cover the experimental plan. During the 1993 tests, tests were terminated when a surface heat flux of about 10 MW/m^2 was reached (it was found to 9 MW/m^2 after analysis was completed). In 1994 further testing was done to find the relation between heat flux area, heat flux level, and surface temperature.

Figure 3 shows the relation between absorbed heat flux, area on which the heat flux was incident and the resulting peak temperature of the module. The maximum heat flux test was at an absorbed heat flux of 34 MW/m^2 over 2 cm^2 area. Although the module was designed for a peak surface temperature of 500°C, tests showed that it can withstand 700°C safely. For the peak temperature of 700°C, the module can withstand a heat flux of 45 MW/m^2 over a 2 cm^2 area and 15 MW/m^2 over the entire area of 20 cm.

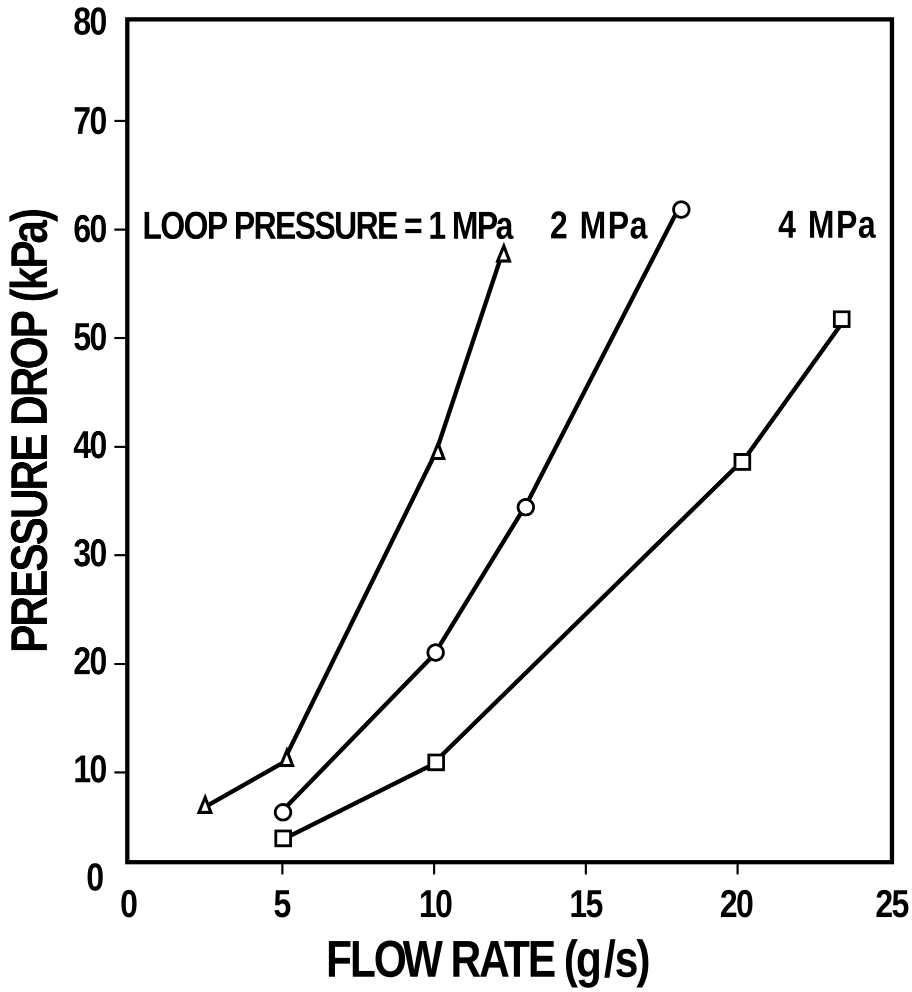

Fig. 2. Relation between flow rate and pressure drop at various loop pressures.

6. CONCLUSIONS

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

1. Large heat fluxes can be removed with helium cooling at moderate pressures and reasonable pumping powers.

2. The peak heat flux is a function of the area.

3. A peak heat flux of 34 MW/m^2 was achieved on 2 cm^2 area. The GA module can withstand up to 45 MW/m^2 over small areas and about 15 MW/m^2 over the entire heat flux area.

7. ACKNOWLEDGMENTS

The funding for the design and fabrication of module was provided by General Atomics. Authors wish to thank D. Youchison of SNLA for taking keen interest in the testing.

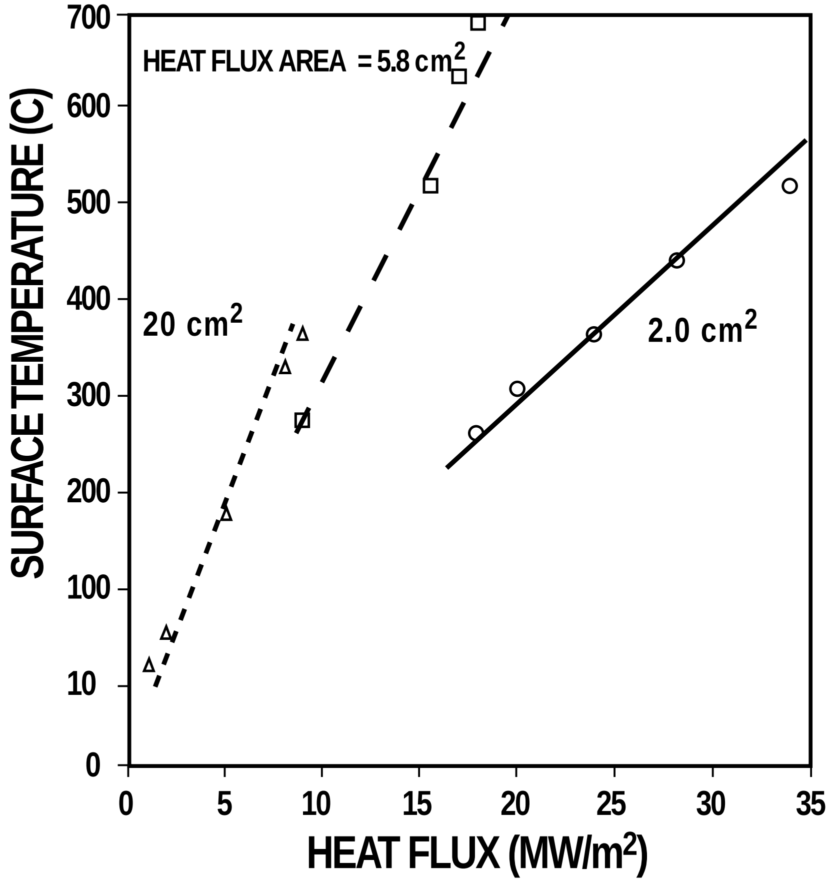

Fig. 3. Surface temperatures measured during high heat flux tests. The heat flux area is the parameter.

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9. NOMENCLATURE

Cp = specific heat of coolant
f = friction factor
ΔP = pressure drop
Q = total power removed
q'' = heat flux
St = Stanton number
T = Wall temperature
V = volumetric flow rate of helium
W = pumping power
α = heat transfer coefficient
θ = coolant temperatures
κ = thermal conductivity of the module
δ = wall thickness
ε = circulator efficiency
ρ = density of helium

Subscripts:

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