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REVIEW OF HELIUM COOLING FOR FUSION REACTOR APPLICATIONS

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ABSTRACT

Helium cooling has been successfully used for fission reactors in the U.S. and Germany in the past. Helium is an attractive coolant for fusion reactors because it is chemically and neutronically inert and can be used directly for gas turbine cycle power conversion. In addition, as was shown during ITER and other fusion power plant evaluations, it is superior from safety considerations. On the other hand, some researchers are under the impression that use of helium cooling requires high pressure, large pumping power and larger manifold sizes due its low density at atmospheric pressure. In this paper it is shown that these concerns can be eliminated through the use of heat transfer enhancement techniques to reduce the flow, pumping power and pressure requirements. A number of proven heat transfer enhancement techniques such as extended surfaces, swirl tape, roughening, porous media heat exchanger and particulate addition are reviewed. Recent experiments with some of these methods have shown that expected heat fluxes of 10 MW/m^2 in fusion reactors can be removed by helium cooling at a modest pressure of 4 MPa. In this paper designs of divertor heat sinks made from copper, vanadium and tungsten with a peak heat flux of 5 to 10 MW/m^2, cooled by helium at a pressure of 4 MPa, are presented.

1. INTRODUCTION

Three coolants considered for next generation fusion machines are water, liquid metal and helium gas. From safety considerations helium is the best coolant due to its chemical and neutronic inertness. During ITER studies, safety evaluations clearly indicated the superiority of helium compared to other coolants in the presence of hot plasma facing components and tritium [1]. Also for fusion reactors, helium coolant could be used in a gas turbine cycle for power conversion. Hence a study was undertaken to investigate the feasibility of helium cooling for fusion divertors.

Volumetric flow rate and pumping power are the two important parameters which determine the feasibility and practicability of using helium. The volumetric flow rate determines the size of manifolds required, and pumping power impacts the efficiency.

The volumetric flow of helium required to remove Q Watts of power from a divertor L m long, with an inlet temperature of T_{in} and maximum heat sink temperature of T_{max} is [2]:

$$V = \frac{Q}{C_p \rho \left(T_{max} - T_{in} - \delta \cdot q_{max}/k - q_{max}/h\right)} \tag{1}$$

previous study [2] has shown that the pumping power, W is a function of key parameters as follows:

$$W = F\left\{L^{n1},\ q_{max}^{n2},\ Q,\ \frac{f}{h^3},\ \frac{1}{\rho^2}\right\} \tag{2}$$

where:

f = friction factor

h = effective heat transfer coefficient, W/m^2-C

k = thermal conductivity of the material, W/m-C

V = volume flow rate, m^3/s

L = length of the heat sink, m

n1, n2 = exponents larger than 3

q_{max} =maximum heat flux, W/m^2

T_{in} = inlet temperature of coolant, C

T_{max} = maximum permitted surface temperature, C

C_p = specific heat of helium, J/g-C

W = pumping power = $M(\Delta P/\rho)$, W

ΔP = pressure drop, Pa

δ= thickness of the wall facing heat flux, m

ρ = density of helium, kg/m^3

Volumetric flow rate and pumping power can be reduced by obtaining a large heat transfer coefficient. In order to increase the heat transfer coefficient, the friction factor is also increased, however the net effect is to decrease the pumping power. In practice, it is not necessary to increase the heat transfer coefficient (and thus friction factor) on the entire cooled surface but only in areas with large heat fluxes. In fusion machines, this area is less than 50% of the divertor surface.

It has been observed [2,3] in some experiments that it is easy to obtain large heat fluxes on small surface areas. There are two reasons for this. Firstly, the coolant temperature rise is negligible and secondly the conduction spreads the heat flux, thereby reducing the effective heat flux at the coolant interface. Hence, the authors of this paper caution against projecting the performance of experimental results for small surface areas to large areas.

2. HEAT TRANSFER ENHANCEMENT TECHNIQUES

The fusion community examined a number of heat transfer enhancement techniques in connection with the ITER design over the last few years [2–8]. In Table 1, hx is the factor increase in heat transfer coefficient, fx is the increase in friction factor. The hx and fx are relative to a smooth surface. These factors do not depend on size of the heat sink.

Methods 1 and 2 in the above list depend on the thermal conductivity of the material. Since future fusion machines will have to use low activity (and unfortunately low thermal conductivity) materials, these methods are, in the opinion of the authors of this paper, not attractive for fusion applications. GA has studied method 1, and a heat flux as high as 32 MW/m^2 was achieved at a heat transfer coefficient of 40000 W/m^2-C as reported in Ref. 2. Method 2 has attracted a lot of attention recently and is being studied by Thermacore [3]. Application of porous media with a low conductivity material has not been proved. Another objection to this method is the high cost of fabrication.

The jet impingement heat transfer method [4] tends to be very local and to present practical difficulties in manifolding. In addition, jet impingement requires high velocity which in turn leads to high pressure drop.

Table 1
Heat Transfer Enhancement Methods

		hx	fx	Ref.
1	Microfins	8	30	2
2	Porous media	5	20	3
3	Jet impingement	3	7	4
4	Particulate Addition	10	30	5
5	Swirl Tape	2	4	6
6	Two D roughness	1.8	3.8	7
7	Three D roughness	3.	7	7
8	Swirl Rod Insert	2.5	5	8
8A	Swirl Rod Insert with 2 D roughness	3.5	7	8

A number of studies on particulate addition [5] to gases to increase the effective specific heat of the fluid have been undertaken in the past. This method does increase the heat transfer coefficient without significantly increasing the pressure drop. However, the particulates must be removed from the coolant before the gas enters the helium circulator and must be added to the coolant after the circulator. This results in a cumbersome system. In addition, the solid particulates cause erosion of the cooling channel and often choke off the flow paths. Hence, this method has not gained much acceptance.

Swirl tape increases the heat transfer coefficient by increasing the effective flow velocity of the coolant and increasing mixing. There is a large amount of reliable data available on this method. C. Wong has demonstrated use of this method for a helium-cooled blanket [9].

Both 2D and 3D roughnesses increase the heat transfer coefficient by breaking the laminar boundary layer near the wall [7]. These geometries are easy to fabricate. Applications of these methods were extensively studied during development of the Gas Cooled Fast Breeder Reactor.

The swirl rod insert (SRI) is a variation of swirl tape proposed by GA during ITER development. This method uses a rod with fins in place of a twisted tape. This allows using a smaller hydraulic diameter and easy fabrication. The method increases the heat transfer coefficient by increasing the effective flow velocity and reducing the hydraulic diameter. SRI can be used in combination with wall roughness for single phase flow. GA fabricated and tested a vanadium module to demonstrate the effectiveness of this method [8]. The fabricated module used two dimensional (2D) roughness and was tested to about 5 MW/m^2 at the Sandia National Laboratory, Albuquerque (SNLA) helium loop. Details of this module are shown in Fig. 1. Comparison of analysis and experiment is shown in Fig. 2 which proves the validity of the analytical method.

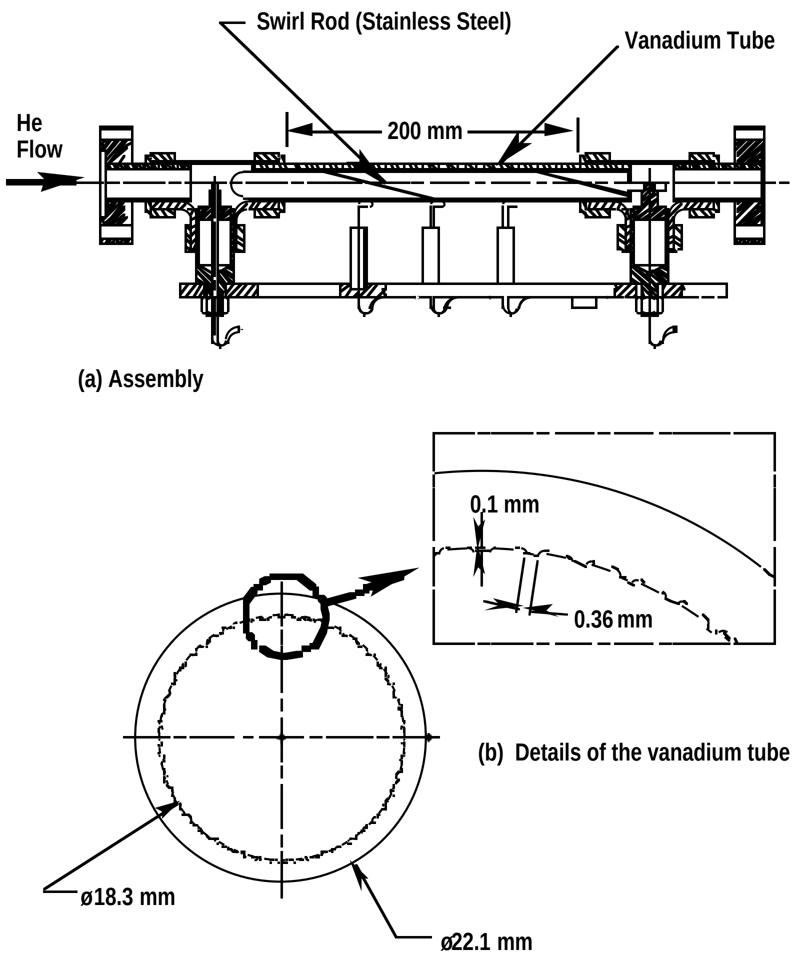

Fig. 1. Details of swirl rod insert (SRI) with 2D roughness for vanadium module.

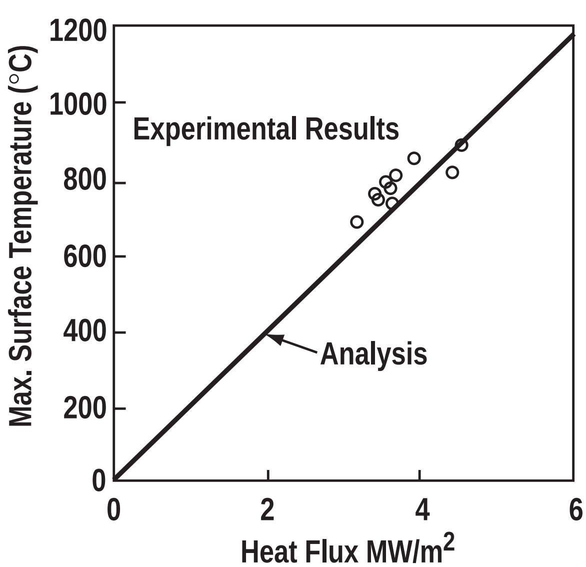

Fig. 2. Comparison of analysis and experiment for SRI with 2D roughness. Vanadium module with a 4 MPa helium coolant pressure.

3. DIVERTOR DESIGN

The highest heat flux in the fusion machine occurs in the divertor region. We will present designs with a peak heat flux of up to 10 MW/m^2. The design basis used will be:

1. Average Heat flux = 1 MW/m^2
2. Flow Length = 1.0 m
3. Inlet Helium Temperature = 20°C
4. Helium Pressure = 4 MPa (580 psia)
5. Heat Transfer Enhancement Technique: SRI with 2D roughness
6. For the heat sink made of copper the maximum temperature allowed will be 400°C; for heat sinks made from vanadium or tungsten it will be 800°C.

A computer program was developed to calculate the peak surface temperature, pressure drop and pumping power for a divertor module cooled by helium. The program was calibrated by comparison with a finite element model.

First we will consider divertor heat sinks made from vanadium. The easiest design will be a smooth tube. Consider a smooth tube made from vanadium, 1 m long with a wall thickness of 1.5 mm. Figure 3 shows the performance of such a heat sink for different tube diameters subjected to an average heat flux of 1 MW/m^2 and a peak heat flux of 5 MW/m^2. The flow has been chosen such that the peak surface temperature is 800°C. For a helium inlet condition of 20°C and 4 MPa, the pressure drop decreases with tube diameter and the pumping power fraction, W/Q, is approximately 10%. Clearly this is not acceptable.

A similar analysis of 8 mm ID, swirl-rod insert with 2D roughness is presented in Fig. 4. The roughness (ribs, as shown in Fig. 1) was applied only over 50% of the length and 50% of the perimeter. A parametric study was performed with the pitch of the fins on the rod insert increasing from 5 to 25 cm. The fin height on the rod is 1 mm. The pressure drop and pumping power both decrease with the pitch of the fins with little benefit obtained after a 25 cm pitch. The

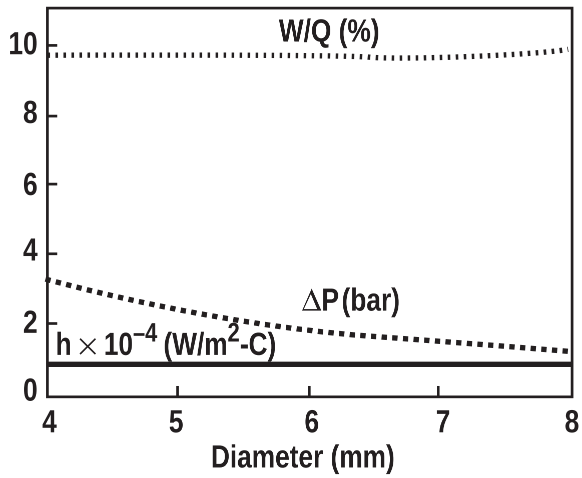

Fig. 3. Performance of a smooth vanadium tube 1 m long and 1.5 mm thick cooled by helium at 4 MPa inlet pressure and 20°C inlet temperature.

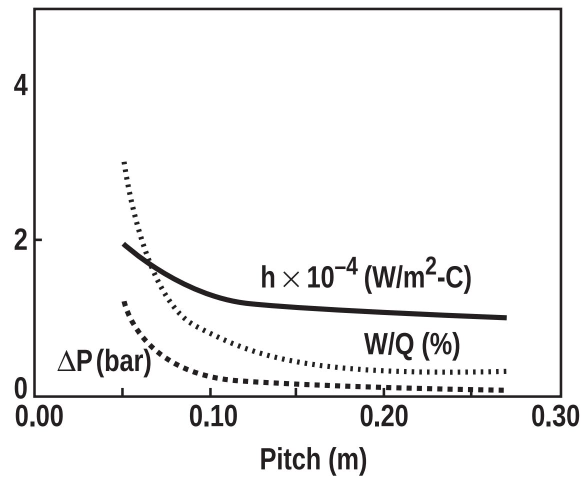

Fig. 4. Effect of pitch on pressure drop, required heat transfer coefficient and pumping power. SRI with 2D roughness with vanadium tube 8 mm diameter. 4 MPa helium pressure and 20°C inlet temperature.

heat transfer coefficient of slightly more than 10,000 W/m^2-C is obtained at a considerably smaller pressure drop compared to the smooth tube. The reason for the smaller pressure drop is that less flow is needed to achieve the required heat transfer coefficient, due to enhancement. Also, application of enhancement on only 25% of the coolant interface does not increase the average friction factor by a large amount. The net result is to reduce the pumping power by more than an order of magnitude. This has been demonstrated in Refs. 2 and 8.

For the same design (vanadium, SRI with 2 D roughness, fin height of 1 mm) for a pitch of 25 cm and a peak heat flux of 10 MW/m^2, the required heat transfer coefficient to keep the peak surface temperature 800°C is about 30000 W/m^2-C. Consequently the flow required, the pressure drop and the pumping power are considerably larger. Thus, a design with vanadium does not seem practical for peak surface heat flux of 10 MW/m^2 at a helium pressure of 4 MPa.

A similar analysis was done for a tungsten heat sink. A tungsten heat sink with a peak heat flux of 10 MW/m^2 seems quite attractive, as summarized Table 2. This is good news because tungsten is also an attractive plasma facing material with a very low erosion rate. A tungsten heat sink/PFC combination could be used, with a higher peak temperature, for a very practical fusion power plant design. This will be studied in the future.

Table 2
Helium Cooled Divertor Designs

	Heat Sink Material	Wall Thickness mm	T_{max} °C	Heat transfer Coefficient required W/m^2-C	Flow kg/m^2	ΔP bar	W/Q %	q_{max} MW/m^2
1	V	1.5	800	10500.0	2.9	0.06	0.33	5
2	V	1.5	800	30500.0	11.2	0.6	14.0	10
3	W	1.5	800	8300.0	2.3	0.04	0.15	5
4	W	1.5	800	17200.0	5.5	0.17	1.87	10
5	Cu	3.0	400	18300.0	4.6	0.17	1.8	5
6	Cu	3.0	400	50000.0	12.5	1.04	25.0	10

Finally, a copper heat sink was analyzed. For copper, the allowable peak temperature was reduced to 400°C and the thickness of the tube was increased to 3 mm. The analysis shows that a 5 MW/m^2 heat flux is possible (2% pumping power) but a 10 MW/m^2 heat flux is difficult, unless higher helium pressure is used. All important parameters are summarized in Table 2.

4. DISCUSSION

Results show that a helium cooled design with a peak heat flux of 5 MW/m^2 is relatively easy. If the divertor consists of modules with an area of 0.5 m^2 (size of FIRE divertor), the manifold size will be 100 mm diameter to keep the flow velocity under 50 m/s (dynamic pressure < 0.1 bar). Designs with a peak heat flux of 10 MW/m^2 are feasible but a higher helium pressure (> 6 MPa) is recommended to keep the manifold sizes small and pumping power less than 1%. Helium cooling of future fusion machines is both highly desirable and practical.

5. CONCLUSIONS

1. A helium cooled divertor design for a steady-state fusion machine is feasible, with a pumping power less 1% of the power removed, at a helium pressure of about 4 MPa for a peak heat flux of 5 MW/m^2.
2. 10 W/m^2 heat flux may be an upper limit with helium cooling. For this heat flux level higher helium pressures may be required.
3. The required flow rate and the pumping power can be minimized by a combination of enhancement techniques and high pressure.

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