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THERMAL HYDRAULICS OF WATER COOLED DIVERTORS

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DISCLAIMER

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ABSTRACT

Divertors of several new machines, such as JT-60SU, FIRE, SST-1, ITER-RC and KSTAR, are water-cooled. This paper examines critical thermal hydraulic issues associated with design of such divertors.

The flow direction of coolant in the divertor can be either toroidal or poloidal. A quantitative evaluation shows that the poloidal flow direction is preferred, because the flow rate and pumping power are about an order of magnitude smaller compared to the toroidal flow direction. Use of heat transfer enhancement technique leads to a lower water pressure requirement, lower flow rate, lower pressure drop, lower pumping power and lower flow velocity. A review of techniques to increase the heat transfer coefficient and critical heat flux, such as hypervapotron, swirl tube, wire insert, etc., was performed. It is concluded that swirl tube is the best available method due to a large amount of data and ease of fabrication.

The standard critical heat flux (CHF) correlations calculate the CHF value at the surface of the coolant channel, whereas divertor physics studies specify the value of the heat flux incident on the divertor surface. Hence, a finite element thermal analysis of typical divertor geometry was performed. Such an analysis requires computation of heat transfer coefficients over a number of heat transfer regimes such as forced convection, incipient boiling, nucleate boiling and post critical heat flux regime. The analysis shows that the ratio of incident heat flux to coolant channel heat flux varies between 1.4 to 1.5 and depends on the heat flux magnitude. The temperatures predicted by the analysis compare very favorably with experimental measurements. The method presented in this paper also correctly predicts incident critical heat flux for a uniform as well as an axially peaked heat flux profile. A typical axial distribution of heat flux results in about a 20% higher incident critical heat flux compared to a uniform heat flux. Recommended correlations and procedures for water-cooled divertor thermal analyses are presented. The expected peak heat flux of 20 MW/m^2 in tokamak divertors can be accommodated with a flow velocity of about 10 m/s and coolant pressure at an outlet pressure of 1 MPa.

1. INTRODUCTION

The peak heat flux in divertor tokamaks occurs on the divertor surface and is about 10 to 20 MW/m^2. The critical engineering issues for the divertor design are: 1) thermal hydraulic design, 2) stresses due to disruptions, 3) thermal stresses and 4) plasma facing components (PFC) design. The General Atomics (GA) divertor team has been associated with design of several water-cooled machines such as DIII–D, TPX, ITER, KSTAR, FIRE, and JT60-U. An optimized thermal hydraulic design results in not only a safe operation of the tokamak but also minimizes the PFC temperatures, cooling flow and pumping power requirements, while extending life.

2. ANALYSIS PROCEDURE

Figure 1 shows the typical arrangement of a water-cooled divertor and the terminology used in thermal analysis. In order to remove the peak incident heat flux of 10 to 20 MW/m^2, without high plasma facing material temperature, a water flow at a velocity of about 10 m/s (forced convection), at a minimum pressure of 1 MPa and at a maximum temperature about 100°C less than the saturation temperature (subcooled) is utilized in the flow channels. Local boiling on the coolant channel is allowed to achieve high heat transfer coefficient without the bulk temperature of the coolant exceeding the saturation temperature (subcooled boiling).

Thermal analysis consists of 1) using proper correlations to compute the heat transfer coefficient as a function of local coolant wall and coolant temperature over the range expected, 2) accounting for material property variation with temperature, and 3) modeling the axial variation of heat flux and coolant temperature. All this needs to be modeled in a finite element model in a code such as ANSYS [1].

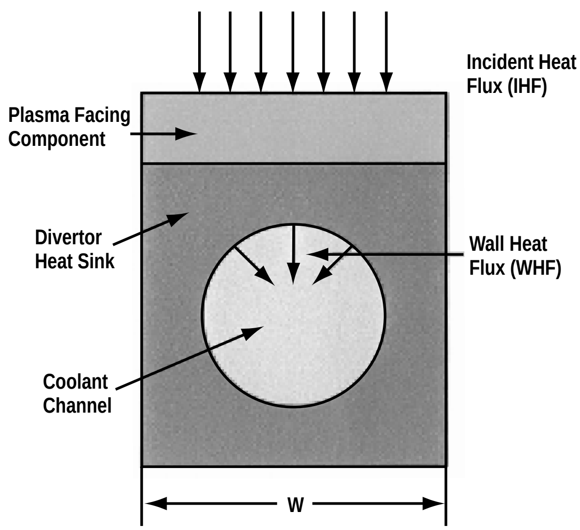

Fig. 1. Divertor heat sink and terminology.

A. Heat transfer coefficients

The surface temperature of the coolant channel varies in value from temperature of cooling water, to a temperature slightly higher than saturation temperature. In order to properly predict the temperature distribution in the divertor assembly, heat transfer from the coolant channel over six different regimes must be calculated, namely, 1) forced convection heat transfer, 2) onset of nucleate boiling, 3) nucleate boiling, 4) transition between nucleate boiling and forced convection, 5) critical heat flux (CHF) and, 6) post critical heat flux region. References 2 and 3 give the recommended correlations to use for the first five of these regimes. For the post CHF region, procedure [4] should be followed. The procedure consists of assuming the value of heat flux to be constant at the CHF value.

Figure 2 shows a typical plot of heat transfer coefficient as a function of coolant channel wall temperature covering these six regimes.

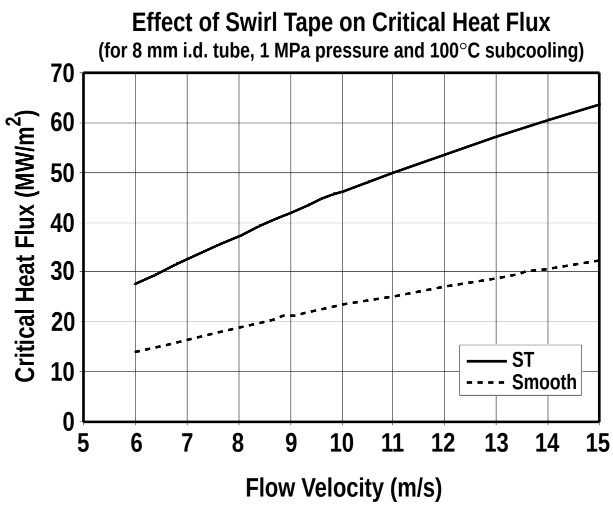

Fig. 2. Variation of heat transfer coefficient over six regimes. 1) forced convection, 2) onset of nucleate boiling, 3) nucleate boiling, 4) transition between nucleate boiling and forced convection, 5) CHF and, 6) post CHF.

B. Critical heat flux

The heat transfer coefficient increases with wall temperature as seen from Fig. 2. Critical heat flux condition is characterized by a sharp reduction in local heat transfer coefficient and resulting in an increase in the heat sink temperature, if the heat flux is increased beyond this value. Hence it is good practice not only not to exceed wall heat flux beyond CHF but also to use a safety factor of at least 1.5 on the CHF value. For heat sinks made from high conductivity material, with one sided heating, the heat sink can survive beyond a local condition of CHF because the heat sink is still capable of removing the incident heat flux by heat conduction to surfaces which have not yet reached the CHF condition [4]. Figure 3 shows a typical relation between incident heat flux and peak wall heat flux.

C. Heat transfer enhancement

The divertors are designed with a safety margin of 1.5 on the CHF to avoid runaway PFC temperatures. The ratio of incident heat flux to the wall heat flux is about 1.5. For an incident

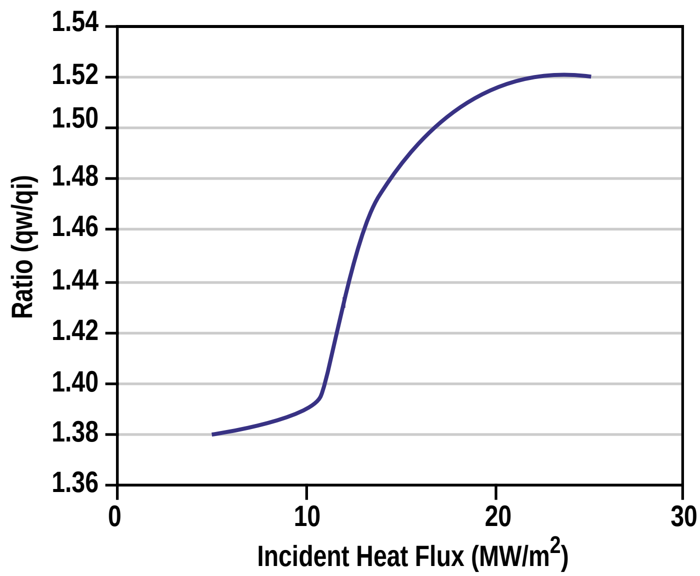

Fig. 3. Ratio of incident heat flux to wall heat flux as a function of incident heat flux.

heat flux of 20 MW/m^2, the wall CHF must be greater than 45 MW/m^2 (20×1.5×1.5). This value of CHF is difficult to achieve at a moderate flow velocity in a smooth channel (Fig. 4). There are several methods to increase the CHF at a given velocity. The most proven amongst them are: 1) swirl tape (ST) insert [2,3], 2) hypervapotron [3], 3) wire insert [5] and, 4) porous coating [6].

All these methods increase the CHF at a given velocity by about a factor of two but also increase the pressure drop by a factor of 4 at a given velocity compared to smooth tube. But since pumping power is proportional to the third power of flow rate, the net result of using an enhancement method is a reduced flow rate and icreased pumping power. Reference 3 compares the performance of swirl tape and hypervapotron from a system consideration for ITER parameters and concludes that ST is slightly superior. Wire insert is an old technique, recently retested by SNLA with promising results on CHF but rather large increase in pressure drop [5]. Porous coating to increase the CHF has been developed and tested in Russia [6]. However, the possibility of erosion and corrosion of the porous coating has kept this method from wide acceptance. Review of all existing methods and experiments indicates that ST is the best method to use for enhancement of CHF in water-cooled divertors. If it is desirable to have rectangular coolant channel, for ease of brazing PFC to the coolant channel, hypervapotron is preferred as a heat transfer enhancement method. GA has developed CHF correlations for ST and hypervapotrons [3] which show an excellent (±10%) agreement with experimental results.

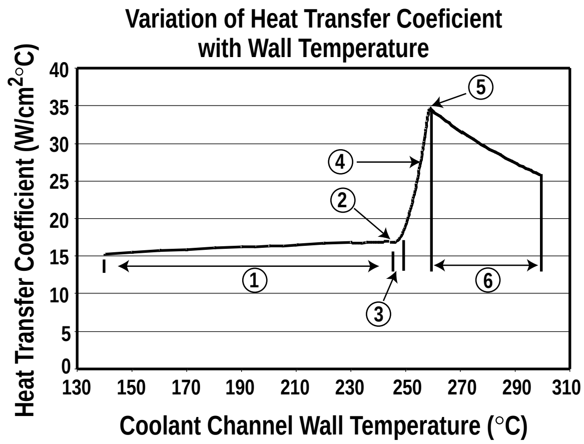

Fig. 4. Effect of enhancement method on critical heat flux.

D. Flow direction

The heat flux distribution on the surface of the divertor is toroidally uniform but is highly peaked in the poloidal direction with a peak to average of up to 9. The radial location of the peak heat flux is not fixed due to different plasma configurations to which the tokamak may be subjected. Hence, if the flow is in toroidal direction, each coolant channel must be designed to accommodate the peak heat flux over the entire length. This results in a higher outlet temperature and need for higher flow velocity to achieve the necessary thermal performance. If the flow is poloidal in direction the coolant temperature rise in each coolant channel is based on the average heat flux. Although, these arguments are obvious, in some cases mechanical design may prefer toroidal flow arrangement to poloidal flow.

In connection with JT-60SU divertor design, GA performed a systematic study of relative merits of these two flow arrangements. The peak to average heat flux in this study was 9 to 1. The conclusion was that the poloidal flow arrangement would require 15% flow and 25% pumping power relative to toroidal flow direction.

3. RECOMMENDED METHOD OF ANALYSIS

1. Use heat transfer correlation package from Ref. 2 or 3 and include post CHF region.
2. Use CHF correlations from Ref. 3.
3. Use any of the verified FE codes and include variation of thermal properties.
4. Use 3-D model and incorporate axial variation of heat flux and coolant temperature.

Calculated maximum wall flux should be less than 67% of the calculated CHF. Finally the test of analysis lies in comparison to experiments. Methods described in this paper were used to analyze a copper mockup fabricated for ITER and tested by Sandia National Laboratory. The analysis predicted the CHF values to within 5% and temperatures of the mockup to within 10% of the measured results.

4. CONCLUSION

Procedure described in this paper can predict the CHF and divertor temperatures with a high degree of accuracy.

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