THERMAL HYDRAULIC ANALYSIS OF FIRE DIVERTOR

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ABSTRACT

The Fusion Ignition Research Experiment (FIRE) is being designed as a next step in the U.S. magnetic fusion program. The FIRE tokamak has a major radius of 2 m, a minor radius of 0.525 m, and liquid nitrogen cooled copper coils. The aim is to produce a pulse length of 20 s with a plasma current of 6.6 MA and with alpha dominated heating.

The outer divertor and baffle of FIRE are water cooled. The worst thermal condition for the outer divertor and baffle is the baseline D-T operating mode (10 T, 6.6 MA, 20 s) with a plasma exhaust power of 67 MW and a peak heat flux of 20 MW/m^2. A swirl tape (ST) heat transfer enhancement method is used in the outer divertor cooling channels to increase the heat transfer coefficient and the critical heat flux (CHF). The plasma-facing surface consists of tungsten brush.

The finite element (FE) analysis shows that for an inlet water temperature of 30°C, inlet pressure of 1.5 MPa and a flow velocity of 10 m/s, the incident critical heat flux is greater than 30 MW/m^2. The peak copper temperature is 490°C, peak tungsten temperature is 1560°C, and the pressure drop is less than 0.5 MPa. All these results fulfill the design requirements.

I. INTRODUCTION

The Fusion Ignition Research Experiment (FIRE) is being designed for high power density and advanced physics operating modes.[1] The FIRE has a double-null divertor configuration. The baffle and outer divertor are actively water cooled. The inner divertor has low heat flux and is cooled by conduction to the copper shell inside the vessel wall. Figure 1 shows the cross section of the FIRE with location of inner and outer divertor and baffle.

II. DIVERTOR AND BAFFLE GEOMETRY

The divertor and baffle design of the FIRE is based on technologies developed for ITER.[2] There are 32 modules each of the divertor and baffle (16 upper and 16 lower). A module is divided into 24 copper (Cu-Cr-Zr) plates across the front surface. The copper plates include tungsten-brush armor as a plasma-facing component (PFC) and coolant channels on both divertor and baffle. The tungsten rods are 3 mm in diameter arranged on a triangular pitch of 3.1 mm. The rods of the brush have a conical tip over 1 mm length on the heat sink side. The tungsten rods are joined to the copper with HIP-bonding process.[2] A 5 mm thickness of the PFC gives adequate lifetime under the expected disruption conditions. The use of tungsten brush reduces the stresses in the PFC. This is

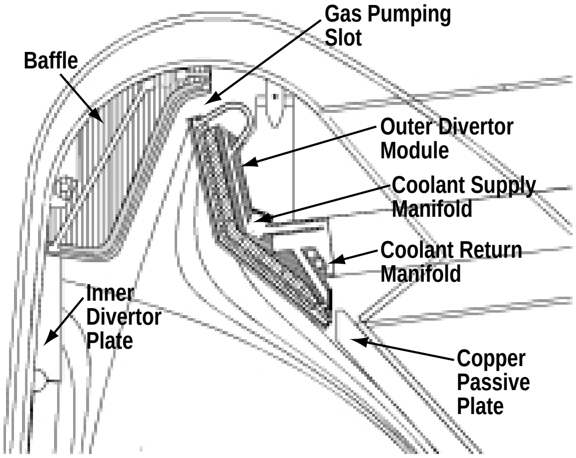

Fig. 1. Cross Section Through FIRE divertor and baffle.

one of the designs for the ITER divertor PFC in the highest heat flux region. This PFC has been successfully fabricated and tested for ITER and found suitable for heat fluxes upto 25 MW/m^2.[2] The divertor module is 0.67 m in the toroidal direction and 0.55 m in the poloidal direction and baffle module is 0.63 in toroidal and 0.50 in poloidal direction. The flow direction is chosen to be poloidal so that the power input to each flow channel is equal.[3] The divertor has a total of 48, 8 mm ID cooling channels for each module. The baffle has 24 cooling channels of 10 mm diameter.

III. POWER FLOWS

The FIRE tokamak is planned to be operated in four modes: 1) base line D-T (20s), 2) an advanced physics D-D (215 s), 3) a long burn D-T mode (31 s), and 4) a high field operation D-T (12 T, 8 MA, 12 s). The heat loads on the outer divertor and baffle are highest during the base line D-T operation with power flows as shown in Table I.

Table I. The power flows during baseline D-T mode

	Outer Divertor	Baffle
Total Power (MW)	34.3	10.7
Peak Power/module (MW)	2.32	0.58
Peak Heat Flux (MW/m^2)	20.0	6.00
Nuclear heating in Tungsten (W/cm^3)	42	34
Nuclear heating in Cu (W/cm^3)	16	13

IV. THERMAL HYDRAULIC ANALYSIS

The thermal design criteria for divertor and baffle are:

Water Inlet Temperature = 30°C
Heat Loads = as shown in Table I.
Maximum Tungsten Temperature = 1800°C
Maximum Copper Temperature = 500°C
Minimize inlet pressure, flow rate and pumping power

In order to remove an incident heat flux of 20 MW/m^2, a very large flow velocity (> 20 m/s) is required if smooth channels are used. The flow velocity and flow rate required to cool the outer divertor can be reduced by using a heat transfer enhancement in the flow channels. A review of enhancement methods[3] shows that a swirl tube (ST) is the best available method. The ST is easy to fabricate and has a large reliable database. Following correlation proposed by Baxi[4] for swirl tube was used for CHF calculations.

$$CHF_{ST} = 0.23\ f_o G H_{fg}\ (1 + 0.00216 pr^{1.8} Re^{0.5} Ja)$$
$$(1 + 0.87/Y^{04}) \quad ,$$

where

$f_o = 8Re^{-0.6}\ (DH/0.00127)^{0.32}$
pr = ratio of coolant pressure to critical pressure
G = mass flux, kg/m^2 s
Hfg = latent heat of water, kJ/kg
Ja = Jakob number
= $(-X)(\rho_L/\rho_G)$
X = quality
Y = twist ratio
ρ_L and ρ_G = density of liquid and vapor at saturation temperature

This correlation does not involve an empirical factor, which depends on the tape thickness and twist ratio, like CEA CHF correlation.[5] This correlation shows excellent agreement with data obtained for ITER (Fig. 2). Recently it was compared with round robin experiments conducted at CEA[6] and SNLA[7] and agreed within 3% with the experimental CHF for flow conditions very similar to one used in FIRE design. The CHF numbers calculated in this paper are higher than ITER calculations due to lower inlet water (30°C for FIRE and 100°C for ITER) temperatures. However, we did use CEA correlation from Ref. 5 for heat transfer in nucleate boiling region.For a ST with a tape thickness of 1.5 mm and a twist ratio of 2 in the divertor channels of 8 mm diameter, a flow velocity of 10 m/s gives sufficient safety margin on CHF for the divertor. If two adjacent channels are connected in series, the maximum outlet temperature is 95°C and minimum exit pressure is 1.05 MPa, resulting in a minimum subcooling of 87°C.

A two dimensional FE analysis of a divertor cell was performed for these flow conditions. The divertor cell

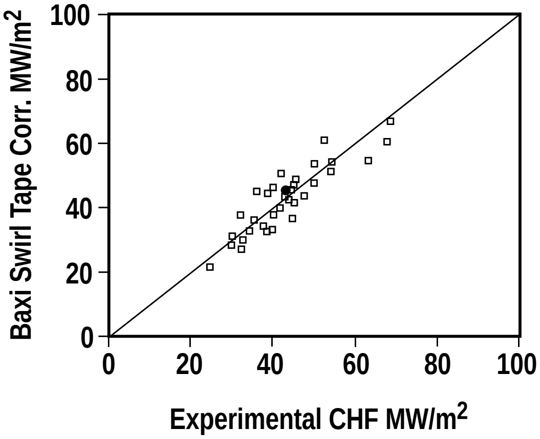

Fig. 2. Comparison of Baxi correlation[4] to CEA 1995 data ❑,[5] CEA 1998 data ■,[6] and SNLA 1999 data●.[7]

consists of a copper mono block 14 mm × 15 mm with the 5 mm tungsten brush as PFC. One mm long conical tip of the tungsten rods is embedded in the copper heat sink by high isostatic pressure (HIP) process. An effective thermal conductance of the tungsten copper interphase was determined by a 3-D finite element analysis with COSMOS code.[8] Figure 3 shows the result. During the analysis, a perfect contact between the conical tip of tungsten rod and copper was assumed. This will have to be verified by experiments. The heat transfer coefficient in the coolant channel is calculated as a function of wall temperature over forced convection, nucleate boiling and post CHF region by the method described in Ref. 3. The pressure drop is calculated by Lopina-Bergles correlation.[9]

In the following discussion and Table I and II, incident heat flux (IHF) is defined as heat flux incident on the surface of the plasma facing component. The wall heat flux (WHF) is a resultant heat flux inside the coolant channel, and is a function of geometry and heat transfer coefficients (as a function of local wall temperatures). Figure 4 shows the temperature distribution at the end of 20 s for the divertor subjected to an incident heat flux of 20 MW/m^2 and nuclear heating as shown in Table I. The peak surface temperature is 1585°C and the maximum copper temperature is 488°C. Based on the flow velocity of 10 m/s, the flow per module is 9 ℓ/s. Figure 5 shows the transient of the peak surface temperature. A steady state is reached in 6 s. The peak temperatures will be lower by 25 to 50°C when axial distribution of heat flux is available and is modeled in the 3D thermal analysis. Similar analysis was performed for the baffle. Due to lower peak heat flux of 6 MW/m^2, smooth channels can be used in this region. Use of heat transfer enhancement is not required in the baffle region. The additional fabrication cost is not justified by very small savings in total flow rate and pumping power. The required flow velocity in baffle channels is 3 m/s. For two channels connected in series, flow per module is 3.5 ℓ/s, the coolant temperature rise is 43.3°C and the pressure drop is16.8 kPa. The results of the thermal analyses are summarized in Table II.

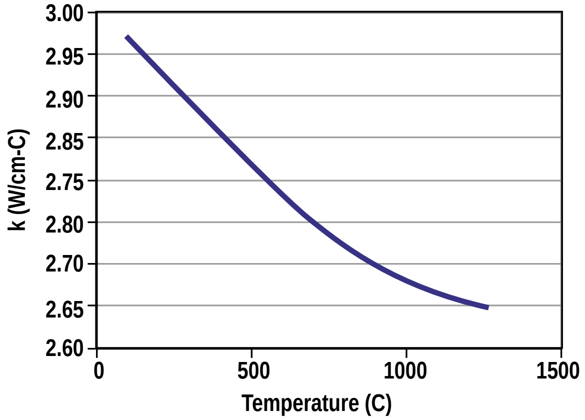

Fig. 3. Effective thermal conductivity of tungsten copper interphase.

Table II. Results of Thermal Hydraulic Analysis

	Outer Divertor	Baffle
Peak Heat Flux(MW/m^2)	20	6
Channel Diameter (mm)	8	10
Pitch (mm)	14	21
Number per Module	48	30
Number in Series	2	2
Enhancement	ST, t=1.5 mm Y= 2	no
Maximum PFC Temperature (°C)	1585	738
Maximum Copper Temperature (°C)	488	404
Flow Velocity (m/s)	10	3
Flow/Module (ℓ/s)	9	3.5
Exit coolant Temperature (°C)	95	73.3
Exit Pressure(MPa)	1.06	1.48
Exit Subcooling (°C)	87	120
Wall CHF (MW/m^2)	45.	12.1
Maximum Wall Heat Flux (MW/m^2)	30.6	6.31

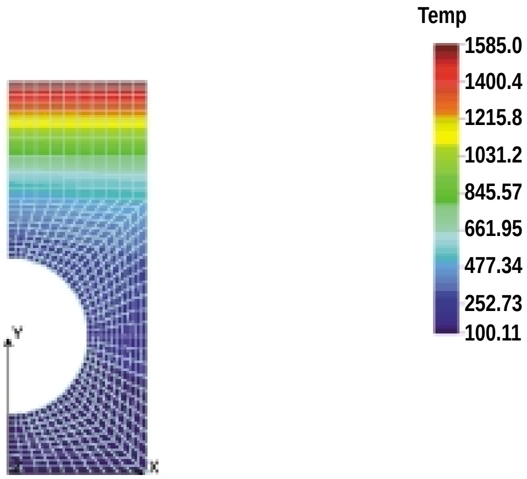

Fig. 4. Temperature (°C) distribution in divertor at the end of 20 s pulse with 20 MW/m^2 heat flux and heat generation shown in Table I.

Due to a number of parallel paths, a possibility of two phase flow instability exits. In this design there will be no two phase flow and channel pressure drops are inherently high, hence this situation will not occur. However, prototypical experiments will be conducted to insure a stable flow.

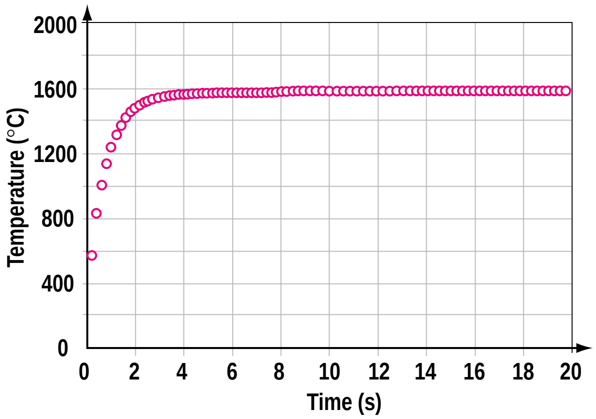

Fig. 5. Variation of Peak Temperature (°C) in Divertor.

V. CRITICAL HEAT FLUX

The FE analysis described above indicated that the peak wall heat flux (heat flux on coolant channel wall) in the divertor is 30.55 MW/m^2. The wall critical heat flux under these flow conditions, calculated by Baxi correlation[3] is 45 MW/m^2. Hence the safety margin on CHF in the divertor region is about 1.5. Similar calculations in the baffle region show a safety margin of 1.9. The safety factor on CHF of 1.5 is sufficient as discussed in Ref. 10. ITER uses similar factor.

VI. CONCLUSIONS

A satisfactory thermal hydraulic design of the FIRE divertor and baffle can be achieved with existing technology. At an inlet of 30°C, 1.5 MPa and a flow velocity of 10 m/s in a swirl tube, water cooling provides a safety margin of 1.5 on the CHF to remove 20 MW/m^2 of peak heat flux on the divertor surface. The total flow rate required for the outer divertor is 288 ℓ/s and for the baffle is 112 ℓ/s. The peak PFC temperature is 1585°C and peak copper temperature is 488°C.

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