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THERMAL-HYDRAULIC LIMITATIONS ON WATER-COOLED FUSION REACTOR COMPONENTS[1]

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THERMAL-HYDRAULIC LIMITATIONS ON WATER-COOLED FUSION REACTOR COMPONENTS[1]

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ABSTRACT

An assessment of the cooling requirements for fusion reactor components, such as the first wall and limiter/divertor, was carried out using pressurized water as the coolant. In order to establish the coolant operating conditions, a survey of the literature on departure from nucleate boiling, critical heat flux, asymmetrical heating and heat transfer augmentation techniques was carried out. The experimental data and the empirical correlations indicate that thermal protection for the fusion reactor components based on conventional design concepts can be provided with an adequate margin of safety without resorting to either high coolant velocities, excessive coolant pressures, or heat transfer augmentation techniques. If, however, the future designs require unconventional shapes or heat transfer enhancement techniques, experimental verification would be necessary since no data on heat transfer augmentation techniques exist for complex geometries, especially under asymmetrically heated conditions. Since the data presented herein are concerned primarily with thermal protection of the reactor components, the final design should consider other factors such as thermal stresses, temperature limits, and fatigue.

NOMENCLATURE

D	equivalent diameter of fluid channel
G	mass flux
h	heat transfer coefficient
L	equivalent heated length
P	pressure
ΔP_b	pressure drop through bends
ΔP	total pressure drop
q	surface heat flux
T_w	wall temperature
T_B	bulk fluid temperature
T_{NV}	bulk fluid temperature at the net vapor detachment point
T_{ONB}	bulk fluid temperature at onset of nucleate boiling
T_{SAT}	saturation temperature
ΔT_{sub}	degree of sub-cooling
V	average fluid velocity
W	pumping power
y	diameters/180 deg twist

INTRODUCTION

A critical parameter in fusion reactors is the upper bound of the surface heat flux on the first walls, limiter, or divertor. Determination of the heat flux limits would allow the designer to accommodate the uncertainties in calculations (from plasma engineering) of surface heat fluxes, as well as provide some flexibility in determining the heat loads among various components, such as the first wall and the limiter/ divertor.

The purpose of this scoping study is to establish an upper bound on the surface heat flux for a limiter from a thermal hydraulic viewpoint which includes considerations of pressure drop, critical heat flux, etc. It should be noted that other factors, such as temperature limits on the protective coatings and structural materials, thermal stress, fatigue, etc., will also limit the surface heat flux and should be included in the overall design evaluation.

[1] Work supported by the U. S. Department of Energy, Office of Fusion Energy.

The geometry selected for this analysis is a double-edge limiter shown in Fig. 1, which is similar to the design adapted for FED/INTOR [1]. This design is considered to have a thermal hydraulic response that is typical of other impurity control systems. The linear length (L) that is exposed to surface heat flux is assumed to be one meter. The coolant channel cross-section is 8 mm × 4 mm which corresponds to a hydraulic diameter (D) of 5.33 mm. Table I summarizes the design and operating parameters used in this study.

Table I
Range of Parameters Employed

Pressure (P)	3.45 and 6.89 MPa (500 & 1000 psia)
Velocity (V)	2.5-15.0 m/s
Length (L)	1.0 m
Equivalent diameter (D)	5.33 mm

PRESSURE DROP AND PUMPING POWER

In contrast to conventional heat transfer components, the limiter consists of many narrow passages with widely varying surface heat fluxes. In addition, the flow passages are both convergent and divergent between the inlet and the outlet headers, and the surface heat flux is imposed on only one side of the flow channels. It is assumed that the coolant passage from the supply manifold to return manifold includes three relatively straight sections and six 90-deg bends (see Fig. 1). The straight sections have a total length of approximately 2.5 m. For the velocities (V) used in this study, the flow is turbulent and the coolant channels are assumed to be made of smooth pipes. The pressure drop through bends (ΔP_b) depends on the ratio of the radius of curvature of the bend and the pipe diameter. It is assumed that each bend has an average equivalent length to diameter ratio (L/D) of 20. Using the method described in Ref. 2, calculations were carried out for single-phase pressure drop and pumping power (W) for the limiter. The results show that the pressure drop and the pumping power losses were acceptable when the coolant velocities are of the order of 7-8 m/s. As expected, the pressure drop and the pumping power increase rapidly for larger velocities.

CRITICAL HEAT FLUX

The critical heat flux (CHF) referred to here corresponds to the departure from nucleate boiling (DNB) in the subcooled or low-quality region at relatively high heat fluxes. If the applied heat flux exceeds the CHF, a sharp rise in the coolant channel wall temperature could occur leading to failure of coolant channel. Thus, CHF provides a practical upper limit for the imposed heat flux in a system.

Table II is a list of six CHF correlations employed in the present evaluation. The relevant parameter ranges for these correlations are also

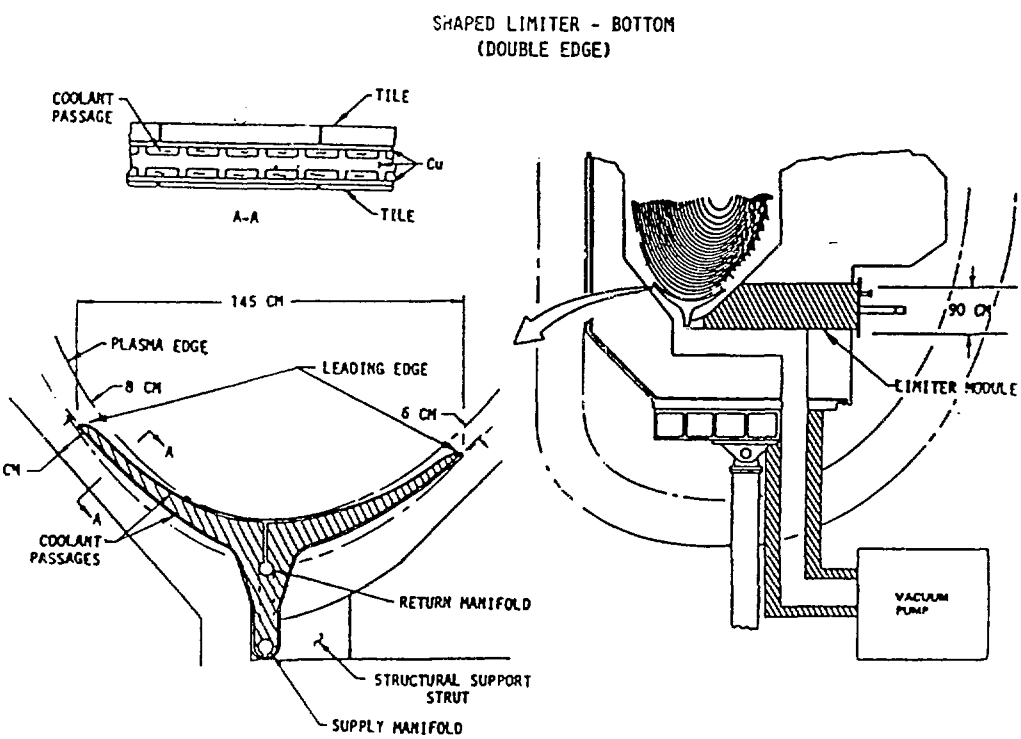

FIG. 1 Geometry and dimensions of double-edged bottom limiter

listed in Table II. The Bowring [3] and Katto [4] correlations are among the recommendations of a recent evaluation by Boyd, et al. [5]. Groeneveld and Snoek [6] recently provided the CHF table look-up technique based on 10,000 experimental data. The Jens and Lottes [7], Westinghouse APD [8], and Bernath [9] correlations are some of the earlier correlations chosen here for comparison. All the correlations are developed for uniformly (axially and circumferentially) heated vertical tubes. Most of the correlations are based on the local parameters such as the quality or subcooling CHF always occurs at the pipe exit for uniformly heated test sections.

Figure 2 shows the results of the various CHF correlations versus velocity (or mass flux) for a system pressure of 3.44 MPa (500 psia), an axial heated length of one meter, a pipe diameter of 5.33 mm, and an inlet water temperature of 60°C. Each correlation is represented by a solid line if it is within the parameter range listed in Table II. The dashed lines in Fig. 2 represent extrapolations outside the range of parameters listed in Table II. Several interesting observations can be made by examining the results shown in Fig. 2:

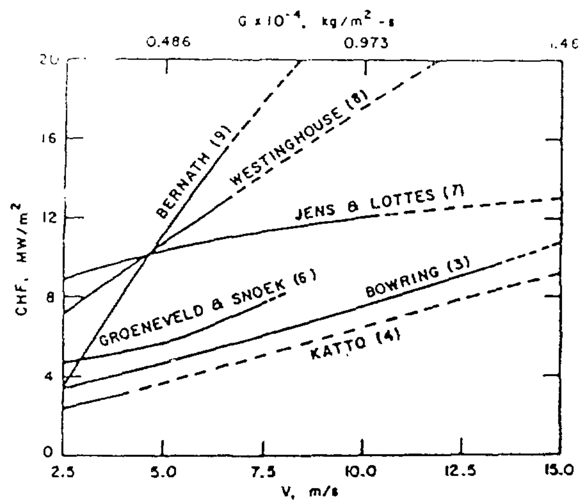

Fig. 2 CHF versus velocity from various correlations for a limiter with a heated length of 1 m, a channel diameter of 5.33 mm, and an average system pressure of 3.44 MPa.

1. The results of various CHF correlations appear to differ significantly from each other. The magnitude of difference among some correlations can be very large (a factor of 2 to 3).

2. It appears that all of the correlations evaluated here are developed for velocities less than 10 m/s (except the Bowring correlation) and for heat fluxes less than 12.6 MW/m² (except the Bernath correlation). This indicates that there is a lack of data and reliable CHF correlations for high velocity and high heat flux applications.

3. The recently published correlations (Bowring, Katto, and Groeneveld and Snoek [3-6]) appear to give CHF values much lower than the earlier correlations (Jens and Lottes, Westinghouse, and Bernath).

The wide difference in CHF values among various correlations is an accurate description of the current state-of-the-art and shows a lack of understanding of the basic mechanism for CHF. For the present evaluation, the more recently published CHF correlations (Bowring, Katto, and Groeneveld and Snoek) will be adopted for the following two reasons: (1) the recently published CHF correlations give conservative results compared to the earlier correlations; and (2) the more recently published CHF correlations are probably based on better and more extensive data base (for example, the Groeneveld and Snoek correlation is based on 10,000 experimental data).

Figure 3 shows the CHF versus velocity plot at a pressure of 6.89 MPa (1000 psia) by using the Bowring, the Katto, and the Groeneveld and Snoek correlations. Again, it must be noted that the reliability of these correlations decreases as the velocity is increased beyond 10 m/s.

From the results shown in Figs. 2 and 3, it can be observed that the CHF is approximately 8 MW/m² for a velocity of 10 m/s and a pressure of 3.44 MPa, and 10 MW/m² for a velocity of 10 m/s and a pressure of 6.89 MPa. For the design of a limiter or other components, the applied heat flux must be lower than the CHF at the operating conditions. This is discussed further in the next section.

Table II Parameter Ranges for Various CHF Correlations

Pressure	Mass Flux		Axial Length	Diameter	CHF	
Correlation	P (MPa)	G (kg/m²-s)	L (m)	D (mm)	MW/m²	Ref./y
Bowring	0.20-19.3	136-18,600	0.15-3.7	2.0-45	(?)	3/1972
Katto	3.0-19.9	750-4,000	0.08-6.3	8	7.95	4/1981
Groeneveld & Snoek	0.20-15.0	0-7,500	---	8	0.16-11.2	6/1983
Jens & Lottes	3.45-13.8	1,302-10,170	0.076-0.625	3.63-5.75	up to 12.6	7/1951
Westinghouse APD	5.51-18.9	271-10,848	L/D = 21-365	2.54-13.7	1.2-12.6	8/1963
Bernath	0.10-20.6	V = 1.82-12.8 m/s	L/D = 58	2.06-19.0	0.2-18.1	9/1960

$$\text{DNBR} = \frac{\text{DNB heat flux predicted by applicable correlations}}{\text{Reactor local heat flux}}$$

and a typical PWR design criterion is that DNBR ≥ 1.3 at the maximum overpower conditions. Pending further evaluation of the safety margin for fusion applications, we will adapt the PWR safety criterion. Hence, the CHF limit for the current design becomes <4.5 MW/m². This leads to a minimum velocity of 5 m/s based Bowring correlation.

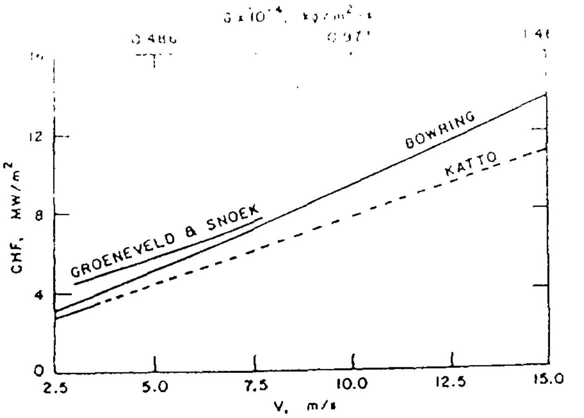

Fig. 3 CHF versus velocity from various correlations for a limiter with a heated length of 1 m, a channel diameter of 5.33 mm, and an average system pressure of 6.89 MPa.

OTHER CONSIDERATIONS

In addition to the pressure drop and CHF limitations, there are other thermal hydraulic constraints which may limit the coolant velocity or pressure of the limiter or the first wall system. Among these constraints are flow-induced vibrations, cavitation, erosion, two-phase flow instability, etc.

A preliminary estimate of the flow-induced vibrations for the relatively thick structure, as shown in Figure 1, shows that large amplitude vibrations are not likely to occur for velocities up to 10 m/s. However, for velocities beyond 10 m/s, tests should be conducted to determine the impact of flow-induced vibrations on such a system.

In a moderately pressurized system (3.45 MPa), there is sufficient margin of safety for cavitation even at relatively high velocities (>10 m/s). Erosion is not likely to be a problem for a water velocity of 10 m/s, especially for a component lifetime of two years (such as a limiter). Two-phase flow instability is system-dependent and should be examined if subcooled boiling occurs in the coolant channels of the limiter/divertor or the first wall.

EXAMPLE

As an example, we shall consider a limiter exposed to a peak heat flux of 3.5 MW/m², to determine the minimum coolant velocity and the heat transfer coefficient (h) for this design.

As mentioned previously, the applied heat flux should be lower than the critical heat flux to provide some margin of safety. For pressurized water reactors (PWR), this safety margin is expressed in terms of the DNB ratio [10]

Figure 4 shows the variations of temperatures along the coolant channel for a velocity of 5 m/s which is the minimum velocity required to satisfy the CHF criterion. It is seen that the onset of nucleate boiling occurs at an axial distance of ~0.62 m from the inlet. From this point on, partial nucleate boiling exists in the channel. Fully-developed boiling does not exist anywhere in the heated channel since the bulk fluid temperature is always below that of net vapor detachment. This design is acceptable, provided that nucleate boiling can be tolerated in the limiter. To calculate the wall temperature accurately, two heat transfer coefficients should be used: one corresponding to the single-phase region and the other corresponding to the partial nucleate boiling region.

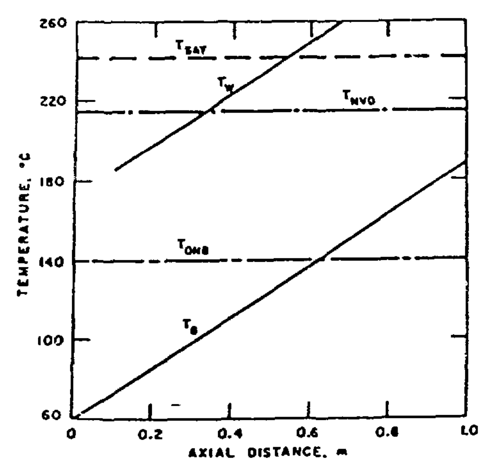

Fig. 4 Variations of bulk fluid temperature and the wall temperature along the coolant channel of a limiter with a peak heat flux of 3.5 MW/m² and an average velocity of 5 m/s.

The alternate design would be to increase the velocity and operate the entire limiter in the single-phase regime. Figure 5 shows the various temperature-versus-axial distance plots for a velocity of 7.5 m/s. In this case, the bulk liquid temperature is always below the temperature at which the onset of nucleate boiling occurs, and the wall temperature is always below the saturation temperature. Thus, the flow is single-phase and only one heat transfer coefficient is needed. The total pressure drop for the limiter is approximately 0.48 MPa (70 psi). The above pressure drop is acceptable and thus this design may be preferable since it eliminates partial nucleate boiling in the channel. Further increases in velocity will (1) increase the heat transfer coefficient and the DNB ratio, (2) reduce the bulk fluid and wall temperatures, and (3) increase the pressure drop and pumping power.

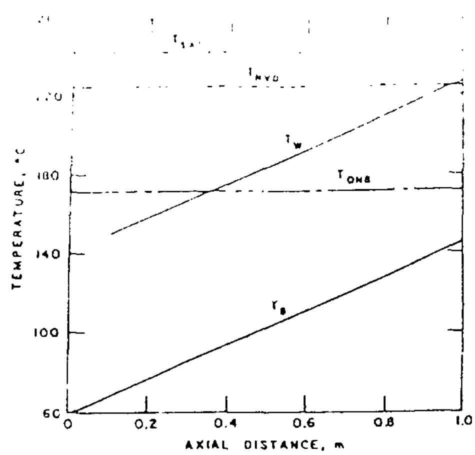

Fig. 5 Variations of bulk fluid temperature and the wall temperature along the coolant channel of a limiter with a peak heat flux of 3.5 MW/m^2 and an average velocity of 7.5 m/s.

Table III summarizes the results of the thermal hydraulic parameters for a limiter with a peak heat flux of 3.5 MW/m^2, a uniformly heated length of 1 m, a channel diameter of 5.33 mm, and an average system pressure of 3.44 MPa.

It should be noted that in the example shown in Table III, the peak heat flux of 3.5 MW/m^2 was assumed to be applied uniformly along the coolant channels. This is a conservative assumption since the heat flux decreases linearly from the center of the limiter (where the peak heat flux occurs) towards either leading edge.

If the applied heat flux is increased, the velocity will have to be increased correspondingly to satisfy the CHF requirement until other constraints (such as pressure drop or flow-induced vibrations) become the limiting factors. The CHF can be further increased by varying the system pressure or by shortening the heated length through design changes. If none of these are feasible, heat transfer enhancement techniques as described in the next section should be considered.

CRITICAL HEAT FLUX FOR ASYMMETRICALLY HEATED SURFACES

A review of the literature was carried out to assess the effect of nonsymmetrical heating on DNB. The experimental data reviewed included both axial and radial flux variations covering a wide spectrum of flux profiles such as hot patches, cosine, chopped cosine, and skewed cosine [11,12]. The experimental parameters also cover a range of L/D ratio, inlet subcooling, inlet pressure, and heat fluxes. The results indicate that the experimentally observed variations in DNB values are so large that no single empirical correlation can be used to represent the data, especially in situations where marked nonuniformities exist. However, these data indicate that the influence of nonuniformities on CHF decrease as the inlet quality increases. Experimental data from an asymmetrically heated tube [13] show that correlations for uniformly heated tubes may be used to predict the DNB behavior of asymmetrically heated tubes. It should be noted that since Ref. 13 covers only a limited range of test parameters, (e.g., heat flux <1 MW/m^2) its validity may be questionable. The results of the literature survey shows that there are not sufficient data for asymmetrically heated surfaces that would be directly applicable to limiter/divertor and first wall designs.

ENHANCEMENT OF HEAT TRANSFER

A survey of the literature on heat transfer enhancement techniques indicate that attempts to improve heat transfer characteristics dates back to the early 1930s [14]. These experiments were confined to simple techniques such as surface roughening, and no attempts have been made for a

Table III
Thermal Hydraulic Parameters for a Limiter
With a Peak Heat Flux of 3.5 MW/m^2, a Heated Length of 1 m,
a Channel Diameter of 5.33 mm, and an Average System Pressure of 3.44 MPa

Velocity (m/s)	ΔP (MPa)	CHF (MW/m^2)	DNBR (a)	Flow Regime	Heat Transfer Coefficient $h \times 10^{-4}$ (W/m^2-C)	Bulk Temp. at Exit (T_B) (°C)	Wall Temp. at Exit (T_W) (°C)
5.0	0.236	4.8	1.37	Single-phase and partial nucleate boiling	3.09	189	302
7.5	0.483	6.2	1.77	Single phase	4.27	146	228
10.0	0.802	7.6	2.17	Single phase	5.38	124	189
12.5	1.160	9.2	2.63	Single phase	6.43	112	166
15.0	1.610	10.9	3.11	Single phase	7.44	103	150

[a]Minimum required DNBR $\geq$ 1.3.

fundamental understanding of the nature of augmentation techniques until the mid-1950s. Since then a large number of augmentation techniques such as surface roughening, surface treatment, chemical additives, mechanical and acoustic vibrations, electrostatic [illegible] turbulence promoters, [illegible] twisted tape and helical tubes, porous surfaces, porous coating, and reentrant cavities have been tried [15-20]. Experiments under nonboiling, boiling, and condensation in free convection and forced convection modes have been conducted to identify the augmentation techniques that are best suited for a given operating system. The experimental results show that the augmentation techniques have widely varying effects on heat transfer coefficients. From a modest improvement of the order of 20% for simple augmentation techniques such as surface roughening to more than a 20-fold increase in heat transfer coefficients for twisted tape inserts have been reported in the literature. Hence, it is desirable to make an assessment whether any of the proven augmentation methods are applicable to the fusion reactor components subjected to intense heat fluxes.

A closer examination of the literature indicates that most of the heat transfer enhancement techniques have been developed for simple shapes such as round tubes and flat surfaces. In addition, these techniques have been developed for the external surfaces using soft materials. Hence, most of the potential heat exchanger surfaces that have been examined may be unsuitable for fusion reactor components such as limiter/divertor and the first wall. However, the results of experiments based on turbulence promoters such as twisted tapes seem to have special interest for fusion reactor components.

The results of Ref. 18 are discussed below from the standpont of components requiring protection from unusually high (e.g., q > 10 MW/m²) heat fluxes.

[illegible] data of [illegible] IV. An examination [illegible] that the [illegible] wide range of operating conditions. The burnout heat fluxes for twisted tape swirl generators are quite high, the lowest burnout heat flux being 8.7 MW/m². This indicates that very high heat fluxes are possible with judicious application of turbulence promoters. At the expected peak heat flux of 4.5 MW/m² for the limiter, the margin of safety can be very high for twisted tapes and can be incorporated into the limiter design. For the design concepts presently under consideration, it may not be feasible to incorporate the twisted tapes. However, there is no reason why alternate designs cannot be pursued that will make it possible to use swirl generators to augment heat transfer. Incorporation of turbulence promoters into the complex geometry will require further evaluation in terms of stresses, inlet and outlet ducting, inlet pressure, and coolant velocity requirements.

SUMMARY AND CONCLUSIONS

The three CHF correlations [3,4,6] employed here also included the effects of heated length (L), channel diameter (D), and inlet subcooling which are not shown in Figs. 2 and 3. The users can choose any of these correlations to optimize their design.

Table IV
Ranges of Test Conditions at Burnout

Variable	Swirl Flow (40 Tests)
D, mm (in.)	3.45-10.2 (0.136-0.402)
Inlet pressure, MPa (psia)	0.1-3.75 (15-545)
y, diameters/180-deg twist	2.08-12.03
L, heated length, mm (in.)	37-411 (1.45-16.2)
L/D	6.6-88.2
Tube material	Al, Cu, "A" nickel
Velocity, m/s (fps)	4.5-47.5 (14.7-156.0[a])
Inlet temperature, °C (°F)	27-77 (48-138)
Outlet temperature, °C (°F)	51-194 (91-350)
ΔP (overall), MPa (psi)	0.02-3.0 (3.0-432)
Subcooling (Δt_{sub}), °C (°F)	17 wt % quality,144 (260) subcooling
Critical heat flux, MW/m² (Btu/hr·ft²)	8.7-117.8 (2.77×10^6 - 37.35×10^6)

[a]Which corresponds to a range of exit resultant velocity of 5.1-59.5 m/s (16.6 - 195.3 fps).

The Bowring and Katto correlations are straightforward to use since the CHF is expressed explicitly in terms of all the parameters. The table look-up method reported by Groeneveld and Snoek requires some iteration. For a set of given pressure, mass flux, and equilibrium quality one can look up the table provided by Groeneveld and [illegible] and determine the CHF. If this CHF divided by DNBR is greater than the applied heat flux, the chosen parameters for the design are acceptable. Otherwise one or more of the system parameters (pressure, flow rate, heated length, etc.) has to be changed to increase the CHF until it meets the design requirement. Again it must be cautioned that one should not extrapolate the results beyond the parameter ranges listed in Table III.

The data presented in Table IV are limited to pressures less than 3.8 MPa (545 psia). These pressures fall within the expected lmiter design pressure. Since the operating pressure for the first wall is of the order of 14 MPa (2000 psia); the data presented in Table IV may not be directly applicable to first wall design.

As mentioned previously, most of the data used to develop CHF correlation are from tests of uniformly heated, both axially and circumferentially, tubes. For fusion components such as the limiter or divertor, the surface heat flux is nonsymmetric circumferentially and nonuniform axially, and the coolant channel may not be circular. The coolant channels are exposed to the surface heat flux on one side only.

Regarding the effect of nonuniformity, axial heat flux along the coolant channel, it is recommended that the peak heat flux be used as the requirement for CHF. This would give a conservative estimate with a safety margin for CHF. The above requirement could be relaxed by examining the specific heat flux distribution for a given design together with the DNBR requirement described previously.

The following conclusions may be made:

1. The limiting factor for the water-cooled fusion reactor components is the critical heat flux (CHF). The design must provide adequate margin of safety so that the expected peak heat flux never approaches the CHF.

2. The predicted CHF based on a number of empirical correlations vary over a wide range (by a factor of 2 to 3). For this study the most conservative correlations were chosen to determine the operating parameters.

3. For a moderately pressurized system (3.45 to 6.89 MPa), the upper bound of CHF is of the order of 10 MW/m^2 for an average velocity of 10 m/s over a heated length of 1 m. For velocities greater than 10 m/s and heat fluxes greater than 12 MW/m^2, there are not sufficient data. The upper bound of CHF can be increased somewhat by increasing the system pressure and coolant velocity, and by decreasing the heated length.

4. The CHF can be increased significantly without increasing either the systems pressure or the coolant velocity by using heat transfer enhancement techniques (e.g., swirl generators). For peak heat fluxes greater than 10 MW/m^2, heat transfer enhancement techniques would be needed in order to provide an adequate margin of safety.

5. A numerical example for a peak heat flux of 3.5 MW/m^2 shows that the required CHF (with a margin of safety of 1.3) can be met in a 1 m long channel when the coolant inlet velocity is 7.5 m/s at a coolant pressure of 3.45 MPa. Hence, cooling of the limiter with an adequate margin of safety does not seem to be a problem for the limiter operating conditions considered herein.

Finally, it is considered to be convenient and useful to assess the CHF limit for water-cooled systems. The following statements and classifications are the opinions of the authors since a certain amount of judgment is involved, and is applicable for a system with a pressure below 6.90 MPa (1000 psia) and a heated length of 1 m.

a. $q \leq 10\ MW/m^2$

Adequate cooling can be achieved based on existing technology for simple shapes. For complex geometries, experimental verification would be necessary.

b. $10\ MW/m^2 \leq q \leq 20\ MW/m^2$

Adequate cooling can be achieved only with heat transfer enhancement techniques. However, the necessary high coolant velocities and the resultant large pressure drops may be the design limiting factors.

It should be pointed out that for complex geometries such as the fusion reactor first wall and limiter/divertor, application of heat transfer enhancement techniques may not be feasible. Hence, one cannot rely on enhancement techniques when the heat fluxes exceed 10 MW/m^2. If one were to use heat transfer enhancement techniques for such critical parts, the results must be verified with prototype components under simulated operating conditions.

c. $q \geq 20\ MW/m^2$

Difficult to provide adequate cooling with a reasonable margin of safety.

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