Journal of the Korean Nuclear Society
Volume 29, Number 4, pp. 348~359, August 1997

〈Technical Note〉

Coolant Options and Critical Heat Flux Issues in Fusion Reactor Divertor Design

Won-Pil Baek and Soon Heung Chang
Korea Advanced Institute of Science and Technology
373-1 Kusong-dong, Yusong-gu, Taejon 305-701, Korea

(Received March 9, 1996)

Abstract

This paper reviews cooling aspects of the divertor system in Tokamak fusion devices with primary emphasis on the critical heat flux (CHF) issues for water-cooled designs. General characteristics of four (4) coolant options for divertor cooling - gases, water, liquid metal, and organic liquid - are discussed first, focusing on the comparison of advantages and disadvantages of those options. Then results of recent studies on the high-heat-flux CHF of water at subcooled high-velocity conditions are reviewed to provide a general idea on the feasibility of the water-cooled divertor concept for future Tokamak fusion reactors. Water is assessed to be the most viable and practical coolant option for divertors of future experimental Tokamaks.

1. Introduction

The main functions of the divertor system in a D-T Tokamak fusion reactor are (i) the exhaust of helium ash, (ii) impurity control, and (iii) the removal of the heat transported by particles to the plasma edge. Plasma particles reaching the scrape-off layer either from the main plasma or from the first wall move along the magnetic field lines until they strike the divertor target plate where they are neutralized and are then extracted by the vacuum pumping system. The concept of a single-null poloidal divertor is shown schematically in Fig. 1[1].

The particles striking the divertor target are at very high energy and intensity, so two basic engineering problems are brought in divertor design. First, the high-energy particle beams cause the erosion of the target material by sputtering (*material problem*). Sec-

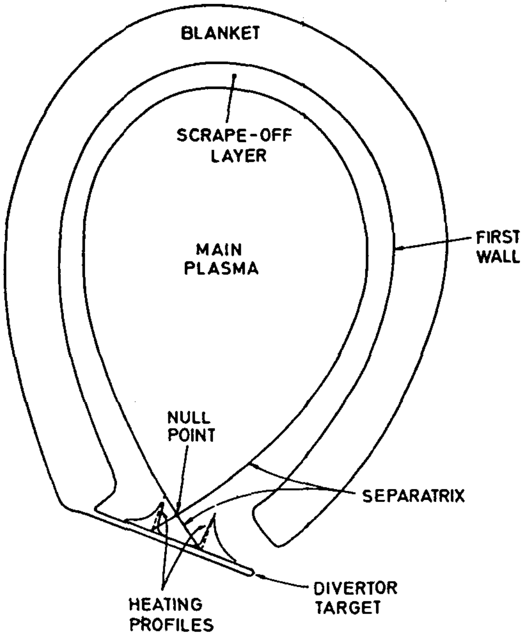
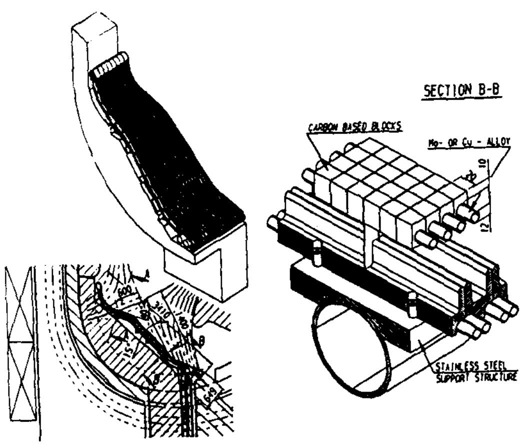
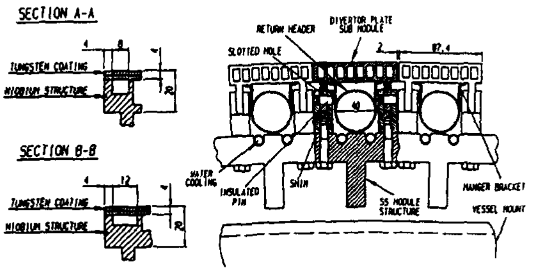


Fig. 1. Schematic Cross-sectional View of a Single-Null Poloidal Divertor[1]



(a) Carbon Monoblock Design for Physics Phase



(b) Tungsten Plate Design for Technology Phase

Fig. 2. Diverter Design Concepts for the ITER[6]

ond, the peak heat flux can be of order 10 MW/m^2, which is higher than that encountered in water-cooled fission reactors by an order of magnitude (*cooling* problem). A combination of materials of high erosion-resistant, high temperature-resistant, high irradiation-resistant, and excellent heat transfer characteristics is required together with a novel cooling system design. At present, the divertor system represents one of the most difficult tasks in design of future Tokamaks such as International Thermonuclear Experimental Reactor (ITER)[2]. Some of divertor plate design concepts for ITER are illustrated in Fig. 2.

It is found that four kinds of coolants used presently or in the past for nuclear fission reactors can also be considered for cooling of Tokamak divertor systems: water, gases, liquid metals and organic liquids. As in the case for fission reactors, there is no absolute choice for the divertor coolant; instead, the coolant material should be selected by considering the overall design and operating characteristics of individual reactors. General requirements for the divertor coolant and characteristics of each coolant option are reviewed in Section 2.

Among the coolant options, water is very attractive in many aspects: good heat transfer properties, easy and safe handling, abundance, economics, etc. Therefore it is used as the coolant for about 90%(light water for 85% and heavy water for 5%) of fission reactors. It has also been adopted as the divertor coolant for many experimental Tokamaks. One of the critical problems related to water cooling is the existence of the *critical heat flux* (CHF), above which the cooling capability is drastically degraded. Although the CHF is a thermal-hydraulic phenomenon that has been investigated extensively with the development of water-cooled fission reactors, the conditions imposed on the divertor cooling system is unique due to its very high peak heat fluxes and nonuniform heat flux distributions. It requires very high water velocity and sometimes heat transfer enhancement devices to remove the unusually high heat fluxes of the divertor plate. During the last 10 years, there have been significant contributions on the high-heat-flux (HHF) CHF for water flow relevant to fusion reactors by several workers. Their achievements and the state-of-the-art knowledge on the high-heat-flux CHF related to fusion applications are summarized in Section 3. As the objective of this paper is to provide an overview of the CHF issues relevant to divertor cooling system design, detailed description of the specific phenomenon or modeling aspects are not included.

2. Assessment of Coolant Options for Divertor Systems

2.1. General Aspects

Desirable characteristics of a coolant for either fission or fusion reactor components include (a) chemical compatibility with structural materials, (b) good heat transfer properties, (c) low pumping power and low density, (d) acceptable coolant pressure in terms of reactor safety and structural material costs, (e) stability under intense irradiation and high temperature, (f) abundance and low costs, (g) high operating temperature for high power conversion efficiency, (h) low melting point and high boiling point for liquid coolants, (i) low induced radioactivity, and (j) easy and safe handling characteristics[3,4]. Sufficient operating experience is also highly desirable.

Four coolant materials are used in existing commercial fission reactors: (a) light water (H_2O) for pressurized water reactors (PWRs) and boiling water reactors (BWRs), (b) heavy water (D_2O) for pressurized heavy-water reactors (PHWRs), (c) carbon dioxide (CO_2) gas for British-type gas cooled reactors (GCRs), and (d) liquid sodium (Na) for liquid-metal fast breeder reactors (LMFBRs). In addition, helium (He) gas has been used for experimental or prototype high-temperature gas-cooled reactors (HTGRs). Organic liquids and other liquid metal coolants were also investigated but have not attracted much attention. Major characteristics of coolant materials are discussed well in books by Ma[3], Marshall[4] and Gupta[5].

There also exist several coolant options for divertors. It is difficult to predict at present what will eventually prevail as the fusion reactor coolant because it also depends on the progress of other technologies related to fusion reactor design and analysis. For instance, the peak heat flux on the ITER divertor plate is assessed to be less than 10 MW/m^2 at the present engineering design activity (EDA), while it was considered as 15-30 MW/m^2 during the conceptual design activity (CDA)[6]. For the heat fluxes of 15-30 MW/m^2, high-velocity subcooled flow boiling of water would be the only practical method for reliable cooling. For heat fluxes significantly lower than 10 MW/m^2, however, other coolant options could be effective, although water is still the best one from the viewpoint of cooling capability.

Boyd et al.[7] assessed three HHF heat removal techniques for fusion applications : (a) subcooled flow boiling of water, (b) high-velocity helium gas convection, and (c) liquid lithium cooling. They concluded that subcooled flow boiling of water would be the most efficient heat removal technique, and several aspects of related thermal-hydraulics, in particular the HHF CHF, should be further investigated. Thompson & Worraker[1] conducted some engineering studies for the divertor target plate. Considering four limits related to cooling (i.e., surface temperature limit, coolant velocity limit, pressure drop limit, and pumping power limit), they suggested two cooling options: (a) cooling by helium at 400 bar with $T_{inlet}=325$℃ and $T_{outlet}=375$℃ in tubes of diameter 9 mm, and (b) cooling by supercritical water at 350 bar with $T_{inlet}=320$℃ and $T_{outlet}=380$℃ in tubes of diameter 2.7mm. Recently Merola & Matera[6] surveyed coolant options for a monolithic CFC divertor that was proposed by themselves. They excluded water from viable coolant options and advocated helium gas, 40% High Boiler(HB-40) organic liquid and some liquid metals.

2.2. Comparison of Coolant Materials

Table 1 summarizes some thermophysical properties of important coolant materials. It should be noted that the conditions used for property evaluation are different according to materials. In addition, Table 2 compares relative advantages and disadvantages of four coolant options. General characteristics of coolant options are discussed in the following paragraphs.

Water has excellent heat transfer characteristics

Table 1. Some Physical and Thermal Properties of Coolant Materials

	Water	Gas		Liquid Metal					Organic
Coolant Materials	H_2O	He	CO_2	Na	Li	Pb-Bi	Ga	Hg	HB-40
T_{melt}(1 atm), ℃	0	-	-	98	179	125	30	−39	
T_{boil} (1 atm), ℃	100	-	-	883	1,317	1,670	1,983	357	
Density, kg/m^3	990	5.11	58.6	903	500	10,425	5,990	13,230	947
Specific heat, J/kg·K	4,173	5,195	1,084	1,330	4,190	147	400	137	2,114
Viscosity, 10^{-4} N·s/m^2	5.44	0.268	0.23	4.57	6.0	21.9	12.0	11.4	16.8
Ther. cond., W/m·K	0.646	0.214	0.033	81.6	38.1	12.2	35.0	9.7	0.120
Prandtl No.	3.515	0.655	0.76	0.0074	0.065	0.0262	0.0137	0.0161	29.6
Elec. resist., $\mu\Omega$·m	-	-	-	0.0042	-	1.17	0.28	0.941	-
Induced radioactivity	^{3}T, ^{16}N	None	^{3}C, ^{16}N	^{24}Na	^{8}Li	^{209}Pb, ^{210}Bi	-	-	-

Note : Properties are evaluated at the following conditions: 3.5 MPa & 50℃ for water; 5 MPa & 200℃ for helium and carbon-dioxide; 0.1 MPa & 200℃ for sodium, lithium, and gallium; 0.1 MPa & 250℃ for lead bismuth; 0.1 MPa & 250℃ for mercury, and 2 MPa and 200℃ for HB-40.

Table 2. Comparison of Coolant Options Applicable to Divertor Cooling

Characteristics	Water	Helium Gas	Liquid Metal	Organic Liquid
Heat removal capability	Best (<~30 MW/m^2)	Reasonable (<~5 MW/m^2)	Good (<~10 MW/m^2)	Good (<~10 MW/m^2)
Operating pressure	Medium to high	High	Atmospheric	Medium
Available temperature	Low	High	Highest	Medium
Required pumping power	Small	High	Medium to high	High
Thermal & radiational stability	Good	Best	Good	Reasonable at low temperature
Induced radioactivity	Low	None	Low	Low
Compatibility with structural materials	Good	Best	Reasonable	Good
Easy & safe handling	Easy	Easy	Difficult	Reasonable
Well-known properties	Good	Good	Reasonable	Reasonable
Operating experiences	Extensive	Reasonable	Reasonable	Least
Abundance & economics	Excellent	Good	Reasonable	Reasonable
Magnetohydrodynamic effects	No	No	Yes	No

due to its favorable properties such as high specific heat, moderate density, low viscosity, etc. The difference between the surface temperature and the coolant saturation temperature can be maintained small due to high heat transfer coefficient. High specific heat together with high heat transfer coefficient result in reasonable values of pressure drop and required pumping power that are considerably smaller than those for gases or liquid metals. There is no effect of the magnetic field on the pressure drop; instead, electric fields produced by the plasma can enhance the boiling heat transfer. Furthermore, there exists extensive operating experience which is beyond comparison with other coolant options. The existence of the CHF condition, however, brings an important design concern. Relatively low operating temperature of water can be another major disadvantage for commercial fusion reactors for electricity generation.

Gas coolants are not subject to magnetohydrodynamic forces and CHF problems. In particular, the water can be another major disadvantage for commercial fusion reactors for electricity generation.

Gas coolants are not subject to magnetohydrodynamic forces and CHF problems. In particular, the helium (He) gas is excellent in the aspects of chemical inertness, high operating temperature, no induced radioactivity, easy tritium extraction, mild leakage problem, etc. However, low heat transfer properties and the high pumping power requirement are major disadvantages of helium. The operating pressure should be high and the peak heat flux should be lowered to several MW/m^2 to make helium cooling attractive.

There are many liquid-metal coolant options: sodium (Na), lithium (Li), potassium (K), sodium-potassium (Na-K), bismuth (Bi), lead (Pb), lead-bismuth (Pb-Bi), tin (Sn), lead-lithium (Pb-Li), galium (Ga), mercury (Hg), etc. They generally have good heat transfer characteristics primarily owing to high thermal conductivity. But they are subject to magnetohydrodynamic forces, resulting in high pumping power requirement. Lithium or lead-lithium can be used for both breeder and coolant; however, poor points (> 200℃). Mercury has too low boiling temperature and toxicity. This leads to the conclusion that gallium, sodium, and lead-bismuth can be possible liquid-metal coolants. If the liquid lithium or lead-lithium are used for the breeder blanket, they can also be seriously considered as the divertor coolant.

The feasibility of organic liquids as divertor coolant was discussed in detail by Gierszewski and Hollies[8]. Organic liquids show relatively good characteristics as a coolant material; however, decomposition and flammability at high temperature can be problematic.

There are several other coolant options and cooling methodologies such as helium-solid suspension cooling[9]. However, it can be concluded as follows :

(a) Water in single-phase forced convection or subcooled boling conditions shows the best cooling capability with many other favorable characteristics; so it can serve as a reliable coolant of experimental fusion reactors for which high coolant temperature for efficient power conversion is not a primary concern. It would be the only coolant that could remove heat fluxes far above 10 MW/m^2.

(b) Helium is an excellent coolant in the aspects of high operating temperature, chemical and radiological inertness, easy cleanup and tritium extraction, etc. It would be attractive for fusion power reactors if the heat flux level can be lowered to several MW/m^2.

3. CHF of Water for Divertor-Relevant Conditions

3.1. General Discussion

The CHF condition is characterized by a sharp reduction of the local heat transfer coefficient which results from the replacement of liquid by vapor adjacent to the heat transfer surface[10]. The term CHF is used to indicate the heat flux on a heated surface at which the CHF condition occurs; however, it somtimes means the CHF phenomenon itself. If the heat flux on a certain heat transfer surface exceeds the CHF, the surface temperature rises sharply due to the sharp decrease in the local heat transfer coefficient. This often leads to melting of the surface in cases of high heat flux conditions. The concept of the CHF is shown in Fig. 3 based on a flow boiling curve. Figure 4 represents typical flow boiling CHF mechanisms. The CHF mechanisms that are expected in water-cooled divertors are (a) local overheating following bubble growth at a nucleation site (for highly subcooled conditions) and (b) near-wall bubble crowding and vapor blanketing (for high vel-

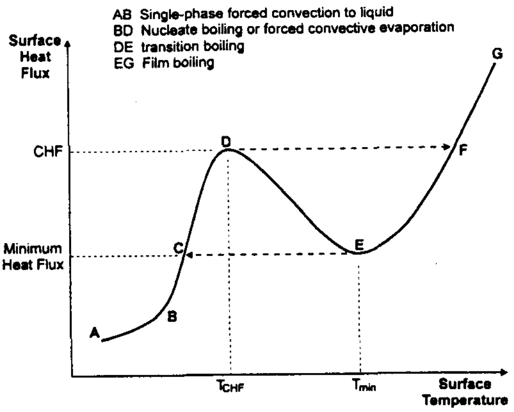
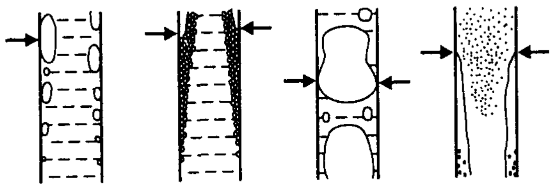


Fig. 3. Flow Boiling Curve and the CHF Condition



(a) Local overheating following bubble growth at a nucleation site

(b) Near-wall bubble crowding and vapor blanketing

(c) dryout of liquid film Surrounding a slug flow bubble

(d) Liquid film dryout from annular flow

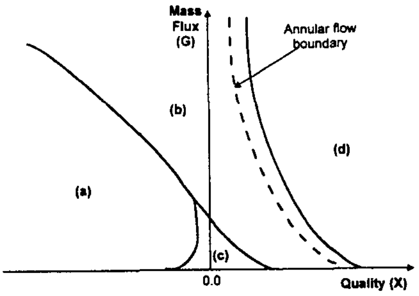


Fig. 4. Physical Mechanisms of the CHF

ocity conditions).

Since the CHF represents the limit on heat transfer capability of liquid coolants, it has been extensively investigated over the last 40 years with the development of water-cooled fission reactors. However, the CHF problem related to divertor cooling is unique at least in two aspects: (a) very high peak heat fluxes (2-60 MW/m^2) and (b) non-uniform heat flux distributions(one-sided heating and high peak-to-average heat flux ratio).

One of reliable CHF prediction methods over a wide range is the look-up table approach that was developed by USSR Academy of Sciences[11] and improved by Groeneveld et al.[12] Both tables present the CHF for a uniformly-heated 8 mm-ID vertical tube at various values of local conditions (pressures, mass flux of 7,500 kg/m^2·s, and local quality of -0.50. As the CHF can be further increased by increasing the mass flux and/or by decreasing the diameter, one can expect that substantially higher heat flux can be removed through water subcooled boiling. In addition, the CHF can be further increased by introducing various CHF enhancement techniques.

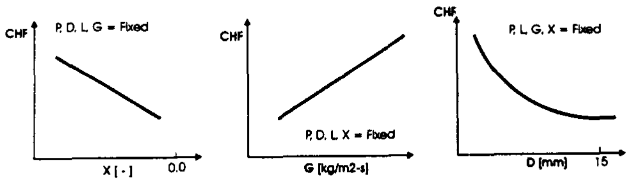
There were limited number of available literature on the HHF CHF when Boyd[13,14] published a dition, the CHF can be further increased by introducing various CHF enhancement techniques.

There were limited number of available literature on the HHF CHF until Boyd[13,14] published a comprehensive reviews on this subject relevant to fusion components cooling. Since then, there have been an increasing effort to investigate the CHF phenomenon both experimentally and theoretically, and findings of subsequent investigations are well summarized in the review papers of Inasaka & Nariai[15] and Celata[16]. It is found that the highest CHF value ever measured is 227.9 MW/m^2 at very high flow, highly subcooled conditions in a very narrow (0.4mm I.D.) tube. This highest heat flux would not be practical due to other design constraints such as excessive pressure drop and manufacturing difficulty; however, it demonstrates the effectiveness of subcooled boiling of water in HHF component cooling.

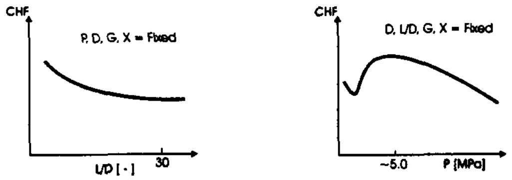
The following sections summarize the parametric trends, enhancement techniques tested, and some prediction correlations for the HHF CHF.

3.2. Important Parametric Trends

Basically there are five major parameters affecting the CHF in uniformly heated vertical round tubes:



(a) Local Quality (b) Mass Flux (c) Tube Diameter



(d) Heated Length (e) Pressure

Fig. 5. Parametric Trends of Subcooled-Boiling Water Flow CHF

(a) pressure (P), (b) mass flux (G), (c) inlet subcooling (Δh_i) or exit quality (X), (d) tube inside diameter (D), and (e) tube heated length (L_h). Some definition of terms are shown in Nomenclature. Other flow channel geometries and orientations also affect the CHF magnitude. The parametric effects of the CHF are schematically shown in Fig. 5 and discussed below. Discussions are primarily based on the review of HHF CHF data by Celata[16]. It should be noted that parametric trends are discussed based on fixed exit conditions instead of fixed inlet conditions.

3.2.1. Influence of Exit Quality

The CHF is a decreasing function of the exit (or local) quality, showing almost linear relationship in highly subcooled conditions. Low exit quality can be achieved by lowering the inlet temperature, i.e., by increasing the inlet subcooling.

3.2.2. Influence of Mass Flux

The CHF is an increasing function of the mass flux (or fluid velocity) in the subcooled region.

3.2.3. Influence of Pressure

Groeneveld et al. table[12] and the data analysis by the present authors[17,18] suggest that the CHF decreases sharply in the very low pressure region, then increases until 3-7 MPa, and then slowly decreases again.

3.2.4. Influence of Channel Diameter

The CHF generally increases as the channel diameter decreases at constant exit conditions, showing large effects in small diameters and high mass fluxes. This is the reason that extremely high CHFs were measured in some tests with tubes of diameter less than 1 mm. However, the effect of diameter becomes rather small for diameters of the order 1 cm, which would be more practical for divertor cooling channels.

3.2.5. Influence of Channel Length

For small L_h/D, the CHF is generally a decreasing function of L_h/D or the heated length. However, the length effect becomes negligible for larger L_h/D, say $>30\sim40$.

3.2.6. Influence of Channel Orientation

The flow orientation (horizontal, vertical, or inclined) does not have significant effect on the HHF CHF under high-velocity conditions. Therefore, most data measured for vertical orientation can be applied to divertor design with horizontal flow paths.

3.2.7. Influence of Non-uniform Heating

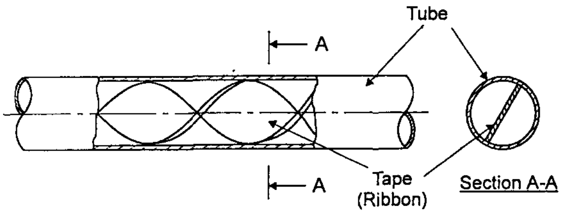
The effect of non-uniform heating has not been analyzed satisfactorily. However, it is expected that nonuniformity in heat flux distribution would not significantly affect the CHF if actual local flow conditions are considered, since the subcooled boiling CHF at high velocities are basically a local phenomenon.

3.2.8. Other Influences

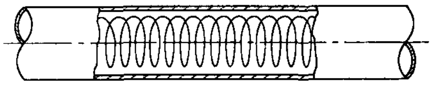
Some investigators have questioned the effects of wall material or dissolved gas content in water. Most studies reveal negligible effects of those factors.

3.3. CHF Enhancement Techniques

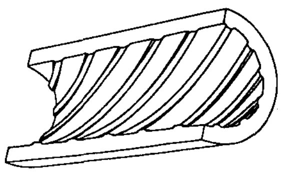
Very high heat fluxes imposed on the divertor plate can be removed with subcooled water flow in straight smooth tubes. However, small diameter channels and/or high velocity conditions required for effective heat removal would bring severe engineering problems as heat duty increases. Passive techniques for enhancing the heat transfer and CHF would alleviate this situation and facilitate practical cooling loop design. Some of the CHF enhancement techniques considered for subcooled flow boiling is illustrated in Fig. 6 and discussed in the following paragraphs.



(a) Twisted Tape Inside Tube



(b) Helically Coiled Wire Inside Tube



(c) Grooved (Ribbed) Tube

(d) Hypervapotron Technique

Fig. 6. Examples of CHF Enhancement Devices

3.3.1. Twisted Tapes Inside Circular Tubes

Twisted tape inserts inside circular tubes increase the heat transfer coefficient and the CHF by inducing swirl flow in the coolant. Disagreement in the degree of CHF enhancement is found among investigators; however, it could increase the CHF up to three times of that for smooth tubes at certain conditions with an increase of the pressure drop by several to several ten times.

3.3.2. Helically Coiled Wires Inside Circular Tubes

Helically coiled wires have been tested as turbulence promoters to enhance the heat transfer and the CHF. The degree of CHF enhancement by helical coil inserts is generally reported to be smaller than that by the twisted tape. However, some recents works report very favorable results.

3.3.3. Grooved Tubes

This concept has been used to increase the CHF for steam power boilers. The height of the internal groove (or fin) is about 1 mm, so that the increase in heat transfer area is negligible. The CHF increase (up to 200%) is mainly caused by the swirl flow induced by the helical grove. As the heat flux applied at the diverter plate is highly non-uniform, grooved tubes may be installed only at the peak-heat-flux region.

3.3.4. Hypervapotron

A channel for the hypervapotron technique is characterized by the presence of fins of high thermal conductivity material, placed perpendicular to the flow of subcooled water[19]. Steam formation, rapid condensation of the steam and quenching of the heated wall are repeated in spaces between adjacent fins and the heated wall, thereby increase the heat transfer and the CHF. This technique is known to be suitable for the removal of high heat fluxes (up tp about 30 MW/m^2) when high values of fluid velocities or subcooling are not practical.

3.3.5. CHF Prediction Methods

More than 500 CHF correlations and models are available in the literature; however, only a limited number of them are applicable to the HHF CHF relevant to divertor design. Recently the assessment of correlations for the subcooled water CHF at high heat fluxes have been conducted by Yin et al.[20], Celata et al.[21] and Inasaka & Nariai[22].

For smooth tubes, the following Tong-68 correlation[23] is widely used as a basis for further improvements :

$$\frac{q_c}{h_{fg}} = C_{Tong} \frac{G^{0.4} \mu^{0.6}}{D^{0.6}} \tag{1}$$

where $C_{Tong} = 1.76 - 7.433X - 12.222X^2$ (2)
Inasaka & Nariai[24] modified the expression for C as follows :

$$\frac{C_{Inasaka}}{C_{Tong}} = 1 - \frac{52.3 + 80X - 50X^2}{60.5 + (P/10^5)^{1.4}} \tag{3}$$

On the other hand, Celeta et al.[21] modified the

$$\frac{q_c}{h_{fg}} = C_{Celata} \left(\frac{G\mu}{D} \right)^{0.5} \tag{4}$$

where

$$C_{Celata} = (0.216 + 0.00474P)\,\Psi \tag{5}$$

$$\Psi = \begin{cases} 1 & \text{if } X < -0.1 \\ 0.825 + 0.986X & \text{if } -0.1 < X < 0 \\ 1/(2 + 30X) & \text{if } X > 0 \end{cases} \tag{4}$$

Both modified Tong-68 correlations are reported to show reasonable prediction capability with root-mean-square (RMS) errors of about 20%[21, 22]. Several other correlations show similar prediction capability; however, they are not reproduced here.

Among the various mechanistic models of Weisman & Ileslamlou[25], Chang & Lee[26], Lee & Mudawwar[27], Katto[28], Celata et al. [29], etc., Celata et al. model is known to show the most promising prediction capability with an r.m.s. error of about 17%[30].

For tubes with CHF enhancement devices, the present prediction correlations such as that of Inasaka & Nariai[16] still require further refinement.

3.5. Further Discussion

Survey of CHF studies for subcooled flow of water indicates that water can effectively remove the heat imposed on the divertor plate. Understanding of the parametric trends and development of prediction methods have been progressed to the level that design of practical divertor cooling system is feasible.

However, much more experimental and theoretical work is necessary to find optimum design parameters. In particular, the CHF enhancement techniques should be studied more systematically to provide more friendly designs of the divertor cooling system.

It should be noted that the divertor cooling system cannot be designed only by considering normal operating conditions. Transient and accident conditions, e.g., loss-of-flow accident (LOFA) or loss-of-coolant accident (LOCA), should be considered in design. Probably the minimum value of the CHF ratio (the ratio of the predicted CHF to the actual local heat flux on the heated surface) in cooling channels should be around 3 during normal operation, in order to allow expected power and flow transients without occurrence of the CHF. An appropriate value of the minimum required CHF ratio can be established through transient and accident analyses. The coolant flow during those transients and accidents will be highly time-dependent; so transient effects on the CHF should also be investigated.

4. Conclusions

The coolant options of the fusion reactor divertors and the CHF characteristics of subcooled water flow under high-heat-flux conditions have so far been discussed. Important findings can be summarized as below.

(a) The cooling requirements for the divertor plate are much severe than those for current nuclear fission reactors due to very high peak heat fluxes.

(b) Water at subcooled conditions and helium gas would be two competing coolant options for divertors of future Tokamak reactors.

(c) Water is an excellent coolant in the aspects of heat removal capability and required pumping power, easy & safe handling, abundance & economics, etc. Subcooled boiling of water would be the only cooling method for divertors with peak heat fluxes above 10 MW/m^2, and would be the easest method of cooling for divertors of lower heat fluxes.

(d) High-velocity forced convection or subcooled boiling of water under moderate pressures would be the most viable and practical method of divertor cooling for experimental Tokamaks where power generation is not a primary concern.

(e) The CHF is a parameter of paramount importance in determining the limits of water cooling. Understanding of the high-heat-flux CHF has been greatly progressed during the last 10 years; reasonable prediction methods are now available for smooth tubes.

(f) Further investigation of the CHF is required for more reliable and optimum design of the divertor cooling system. Important topics include more sound understanding of physical mechanisms, improvement of prediction methods, CHF enhancement techniques, and transient effects.

Nomenclature

C	Constant [−]
D	Tube diameter [m]
G	Mass flux (or mass velocity), (Mass flow rate)/(Flow area) [kg/m^2·s]
h	Specific enthalpy [J/kg]
h_f	Specific enthalpy of saturated liquid [J/kg]
h_{fg}	Latent of evaporation, $h_g - h_f$ [J/kg]
h_g	Specific enthalpy of saturated vapor [J/kg]
h_i	Specific enthalpy of fluid at the heated channel inlet [J/kg]
Δh_i	Inlet subcooling, $h_f - h_i$ [J/kg]
L_h	Length of the heated channel [m]
P	Pressure [Pa = N/m^2]

q_c	Critical heat flux [W/m^2]
X	Quality, $(h-h_f)/h_{fg}$ [$-$]
μ	Dynamic viscosity [N·s/m^2]

References

1. V.K. Thompson and W.J. Worraker, W.J., Divertor target engineering for fusion reactors, *Fusion Eng. Des.* **13**, 187-199 (1990)
2. P.H. Rebut, D. Boucher, D.J. Gambier, B.E. Keen and M.L. Watkins, The ITER challenge, *Fusion Eng. Des.* **22**, 7-18 (1993)
3. B.M. Ma, *Nuclear Reactor Materials and Applications*, pp. 53-54 and pp.361-371, Van Nostrand Reinhold Co., New York (1983)
4. W. Marshall (ed.), *Nuclear Power Technology. Vol. 1 Reactor Technology*, Clarendon Press, Oxford (1983)
5. C.K. Gupta, *Materials in Nuclear Energy Applications*, CRC Press, Boca Raton, Florida (1989)
6. M. Merola and R. Matera, Survey of coolant options of a monolithic CFC divertor, *Fusion Eng. Des.* **24**, 257-273 (1994)
7. R.D. Boyd, C.P.C. Wong, and Y.S. Cha, Thermal-hydraulic assessment of high-heat-flux removal techniques for fusion applications, *Nucl. Eng. Des.* **88**, 103-110 (1985)
8. P. Gierszewski and R.E. Hollies, Organic coolants and their applications to fusion reactors, *Nucl. Eng. Des. -Fusion* **4**, 223-236 (1987)
9. A. Shimizu, Some aspects of gas-solid suspension flows in relation to cooling of the divertor and blanket, *Fusion Eng. Des.* **25**, 239-247 (1994)
10. J.G. *Collier, Convective Boiling and Condensation* (2nd Ed.), McGraw-Hill (1981)
11. USSR Academy of Sciences, Tabular data for calculating burnout when boiling water in uniformly heated round tubes, Teploenergtika 23, 90-92 (1976)
12. D.C. Groeneveld, D.C., S.C. Cheng, and T. Doan, 1986 AECL-UO CHF look-up table, *Heat Transfer Eng.* **7**, 46-62 (1986)
13. R.D. Boyd, Subcooled flow boiling critical heat flux (CHF) and its application to fusion energy components. Part I. A review of fundamentals of CHF and related data base, *Fusion Tech.* **7**, 7-30 (1985)
14. R.D. Boyd, Subcooled flow boiling critical heat flux (CHF) and its application to fusion energy components. Part II. A review of microconvective, experimental, and correlational aspects, *Fusion Tech.* **7**, 31-52 (1985)
15. F. Inasaka and H. Nariai, Critical heat flux of subcooled flow boiling with water for high heat flux application, *Proc. High Heat Flux Engineering II* (12-13 July 1993, San Diego, California)
16. G.P. Celata, Recent achievements in the thermal hydraulics of high heat flux components in fusion reactors, *Exp. Thermal Fluid Sci.* **7**, 263-278 (1993)
17. S.H. Chang, W.P. Baek, and J.W. Park, Classification of CHF patterns using entropy minimax principle, *Int. Comm. Heat Mass Transfer* **18**, 185-193 (1991)
18. S.K. Moon, W.P. Baek, and S.H. Chang, Parametric trends analysis of CHF based on artificial neural network, *Nucl. Eng. Des.* **163**, 29-49 (1996)
19. G. Cattadori, G.P. Gaspari, G.P Celata, M. Cumo, A. Mariani, G. Zummo, G., Hypervaporton technique in subcooled flow boiling CHF, *Exp. Thermal Fluid Sci.* **7**, 230-240 (1993)
20. S.T. Yin, A. Cardella and A.H. Abdelmessih, Assessment of a heat transfer correlations package for water cooled plasma facing components in fusion reactors, *Proc. NURETH-5*, Vol. 4, pp. 929-938, Salt Lake City (1992)
21. G.P. Celata, M. Cumo and A. Mariani, Assessment of correlations and models for the prediction of CHF in water subcooled flow boiling, *Int. J. Heat Mass Transfer* **37**, 237-255 (1994)
22. F. Inasaka and H. Nariai, Evaluation of subcooled critical heat flux correlations for tubes with and without internal twisted tapes, *Proc. NURETH-5*,

Vol. 4, pp.919-928, Salt Lake City (1992)

23. L.S. Tong, Boundary layer analysis of the flow boiling crisis, *Int. J. Heat Mass Transfer* **11**, 1208-1211 (1968)
24. F. Inasaka and H. Nariai, Critical heat flux and flow characteristics of subcooled flow boiling in narrow tubes, *JSME Int. Journal* **30**, 1595-1600 (1987)
25. J. Weisman and S. Ileslamlou, A phenomenological model for predicting the critical heat flux under highly subcooled conditions, *Fusion Tech.* **13**, 654-659 (1988)
26. S.H. Chang and K.W. Lee, A critical heat flux model based on mass, energy, and momentum balance for upflow boiling at low qualities, *Nulc. Eng. Des.* **113**, 35-50 (1989)
27. C.H. Lee and Mudawwar, A mechanistic critical heat flux model for subcooled flow boiling based on local bulk flow conditions, *Int. J. Multiphase Flow* **14**, 711-728 (1988)
28. Y. Katto, A prediction model of subcooled water flow boiling CHF for pressure in the range 0.1-20 MPa, *Int. J. Heat Mass Transfer* **35**, 1115-1123 (1992)
29. G.P. Celata et al., Rationalization of existing mechanistic models for the prediction of water subcooled flow boiling critical hear flux, *Int. J. Heat Mass Transfer* **37** (Suppl. 1), 347-360 (1994)
30. Y. Katto, Critical heat flux, *Int. J. Multiphase Flow* **20** (suppl.), 53-90 (1994)