CRITICAL HEAT FLUX ENHANCEMENT

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Received November 22, 2006

In this paper, works related to enhancement of the CHF are reviewed in terms of fundamental mechanisms and practical applications. Studies on CHF enhancement in forced convection are divided into two categories, CHF enhancement of internal flow in tubes and enhancement of CHF in the nuclear fuel bundle. Methods of enhancing the CHF of internal flows in tubes include enhancement of the swirl flow using twisted tapes, a helical coil, and a grooved surface; promotion of flow mixing using a hypervapotron; altering the characteristics of the heated surface using porous coatings and nano-fluids; and changing the surface tension of the fluid using additives such as surfactants. In the fuel bundle, mixing vanes or wire wrapped rods can be employed to enhance the CHF by changing the flow distributions. These methods can be applied to practical heat exchange systems such as nuclear reactors, fossil boilers, fusion reactors, etc.

KEYWORDS : CHF Enhancement, Swirl Flow, Porous Coating, Surfactant, Nano-fluid, Mixing Vane, Wire Wraps

1. INTRODUCTION

Critical heat flux (CHF) is the heat flux at which a boiling crisis occurs accompanied by a sudden increase of the heat transfer surface or deterioration of the heat transfer rate. The CHF imposes a limit in designing and operating boiling heat transfer equipment in power industries such as nuclear, fusion, and fossil power plants. Thus, an increase in the critical heat flux can increase the safety margins and allows for more economical design and operation at higher heat fluxes. As the capacity of nuclear power plants or fossil boilers increases, a higher heat load per unit heat transfer area is required. In fusion reactors, the maximum heat flux may be higher than 10 MW/m^2 and special heat transfer measures are necessary. The most effective heat transfer mechanism is nucleate boiling, the upper boundary of which is dictated by the CHF. Therefore, efforts have been exerted to expand the regime of nucleate boiling. In this regard, enhancement of the CHF is an important topic in the area of heat transfer research and a considerable body of related work has been reported in the literature.

Studies on CHF enhancement in forced convection can be divided into two categories, enhancement of the internal flow in tubes and enhancement of the CHF in nuclear fuel bundles. The main focus in fossil boiler and steam generator design has been CHF enhancement of the internal flow. Recently, CHF enhancement for effective cooling of high heat flux fusion equipment such as divertors has been attracting greater interest.

Research on CHF enhancement in natural convection is mainly concentrated on the design of severe accident mitigation devices and strategies, such as in-vessel retention through external reactor vessel cooling. For practical applications such as nuclear reactors, fossil boilers, and fusion reactors, fundamental mechanisms and practical applications of the CHF have been studied. In the present paper, methods to enhance the CHF are introduced with a focus on fundamental mechanisms and practical applications.

2. CHF ENHANCEMENT IN AN INTERNAL FLOW

2.1 CHF Enhancement by Enhancing the Swirl Flow

When the flow in a tube is directed by twisted tape, a helical coil or a grooved surface (rifled tube), a swirl flow can be generated. By the centrifugal force generated by the swirling motion of the fluid, liquid is forced to flow on the tube surface and vapor is forced to flow along center line of the tube. Consequently, local velocity of the flow is increased compared to that in a smooth tube under the same mass flux. Therefore, the swirl motion of the flow can contribute to enhancement of the CHF. Several methods to this end have been developed commencing in the 1950s [1]. Among these are insertion of twisted tape, insertion of a helical coil, and grooving the tube surface.

Swirl flow generation by the insertion of twisted tape or twisted ribbon has been widely studied. The inserted twisted tape acts as a flow obstacle and increases the pressure loss. In order to apply the same mass flux, the pumping power should be increased. However, even at the same pumping power, the CHF obtained with twisted tape may be higher than that without tape having an optimized design. Notably, if the heat flux is concentrated at a certain point of the tube, the swirl tape can be placed at that point.

Gambill et al. [1,2] were the first to study the effect of flow swirling on heat transfer and its effect on the CHF. They obtained high CHFs, 118 MW/m^2 for water and 28 MW/m^2 for ethylene glycol. From the mid-1980s a new approach to swirl flow boiling was introduced in connection with the problem of cooling the plasma facing components (PFC) of fusion reactors. Divertors can be subjected to extremely high energy fluxes, around 10-20 MW/m^2.

With the exception of the study of Gambill et al. [1,2], most early studies investigated CHF enhancement under saturated flow conditions (see Table 1). Later, CHF experiments under a subcooled boiling region were performed [3,4]. CHF experiments for one-sided(?) heating were also performed to investigate the effect of a one-sided(?) heat load in a PFS such as a divertor in fusion reactors [5].

Schlosser et al. [6,7] adapted the Tong-75 correlation [8] to fit their one-sided heat flux CHF database for smooth tubes, swirl tape, and hypervapotrons [6,7]. The correlation is as follows:

$$CHF_w = 0.23 f G H_{fg} \left(1 + 0.00216 \left(\frac{P}{P_c}\right)^{1.8} \mathrm{Re}^{0.5} Ja\right) C_f \qquad (1)$$

where $\mathrm{Re} = \frac{G d_h}{\mu_f}$, $Ja = \frac{\rho_f}{\rho_g} \frac{C_p (T_{sat} - T)}{H_{fg}}$, $f = 8\,\mathrm{Re}^{-0.6} \left(\frac{d_h}{d_0}\right)^{0.32}$

where CHF_w is the CHF at the tube wall (W/m^2); f is friction factor; G is the coolant mass flux (kg/m^{2}s); T is the local coolant temperature (°C); P is the local coolant pressure (MPa); T_{sat} is the saturation temperature (°C); H_{fg} is the latent heat of vaporisation of water at T_{sat} (J/kg); P_c is the critical pressure, 22.1MPa; Re is Reynolds number; d_h is the hydraulic diameter (m); μ_f is the water viscosity (kg/m s); Ja is Jakob's(?) number; ρ_f is the water density (kg/m^3); ρ_g is the vapor density (kg/m^3); c_p is the water specific heat (J/kg-K); d_0 is a reference diameter 12.7E-3 m; and C_f is a factor to account for the configuration.

The exact value of C_f is dependent on the channel configuration and dimensions. From previous experimental data, 1.2 is appropriate for a smooth channel and 1.67 for a swirl tape tube with a twist ratio of 2 and swirl tape thickness of 0.8 mm.

Swirl flow can be promoted by the insertion of helical wires. In early stage of helical wire inserted research, helical wires were used as turbulence promoters to enhance heat transfer in a single-phase flow (air, water, water glycerol solution, oil) both in laminar and in turbulent flows [12-16]. Only a few works related to the enhancement of the CHF in flow boiling can be found in the literature. Experimental CHF results on the uniform circumferential heating of a helical wire inserted tube shows very promising CHF performance (up to a 50% increase of the CHF), and in some cases the CHF surpasses that of a swirl tape inserted tube [17,18].

It has been widely reported many the literature that a

Table 1. Experimental Work on CHF Enhancement with Twisted Tape

Source	L [m]	D [mm]	y	P [kPa]	G [kg/m^{2}s]	X
Gambill et al. [2]	0.0381-0.442	3.45-10.25	4.2-24	172-5020	4500-47500	Subcooled-0.17
Viskanta [9]	0.457	8.0	2.5, 5.0	13800	670-2700	0.01-0.53
Moeck et al. [10]	1.016	11.43	5.55, 34.5	7000	390-1150	0.74-0.95
Matzer et al. [11]	4.88	10.16	15.0	6900	1260-4600	0.33-0.88
Araki et al. [3]	0.5	7.0	2.0, 2.5	< 1100	4300-12900	< 0.0
Nariai et al. [4]	0.1	6.0	> 2.6	100-1500	6000-17000	< 0.0
Boscary et al. [5]	0.085-0.105	10-18	2	1000-3600	5000-16000	< 0.0

rifled tube yields significant improvement in heat transfer and CHF [19-29]. A rifled tube is a tube whose inner surface is machined like that of a nut. It can be fabricated on the basis of a simple mechanical drawing. The nut-like (grooved or rifled) surface can work as an enlarged heat transfer area and a swirl promoter, thereby enhancing heat transfer and the CHF. The improvement in the CHF is attributed to centrifugal fluid flow near the surface arising from the swirl flow. The centrifugal flow forces the water to the tube wall, retards re-entrainment of the liquid, and causes drift in the radial direction, which carries the vapor to the center region. Steam blanketing and film dryout at CHF conditions are thus prevented until substantially higher steam qualities are reached. The strength of the swirl flow can be quantified by the ratio of centrifugal acceleration to gravity:

$$\frac{a_r}{g} = \frac{V_r^{\ 2}}{Rg} = \frac{V_a^{\ 2}}{Rg\tan^2\phi} \tag{2}$$

where a_r is the centrifugal acceleration, V_r is the radial velocity on the wall, R is the inside radius of the tube, V_a is the axial velocity, and ϕ is the angle between the center line of the tube and the rifle or groove on the inner tube wall. The relationship between the acceleration ratio and the rifle angle is displayed in Fig. 1.

Major applications of rifled tubes include coal fired boilers and fusion divertors. Experimental works for boiler applications are conducted at high pressure and high quality (~22 MPa, x>1). The CHF in the spiral internally rifled tubes can be enhanced by a factor of 1.3–1.6 as compared to a smooth tube [19,20,26,29]. However, the enhancement ratio depends upon the various flow conditions and geometries.

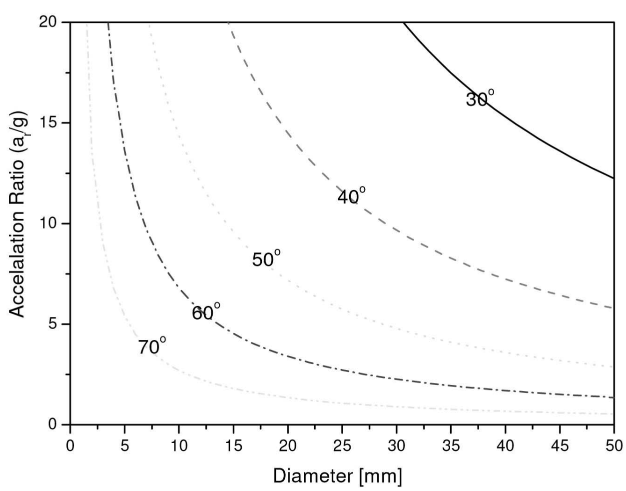

Fig. 1. Centrifugal Acceleration Ratio and Rifle Angle

Iwabuchi et al. [30] studied a four-head rifled tube with an average inner diameter of 17 mm. They found that enhancement of the CHF disappeared at pressure exceeding 20.6 MPa. Cheng et al. [26] conducted a similar study and found that the enhancement effect is apparent from 10 MPa to 19 MPa. However, there was no obvious enhancement at 21 MPa. The ratio of liquid water density to vapor density was reduced and approached 1 as the pressure approached a critical pressure (~22 MPa). With a low (~1) density ratio, the swirl flow cannot lend strong centrifugal force to the liquid water and the effect of the swirl flow on the CHF is reduced. Works for fusion divertor applications are conducted at low pressure and low quality (~ 1 MPa, x<0) [31,32].

2.2 CHF Enhancement by Promoting Flow Mixing

CHF can be enhanced by increasing flow mixing. One interesting method to increase flow mixing is the use of a hypervapotron [33]. A hHypervapotron is a heat transfer surface with fins vertical to the flow direction. The shape of the fins can be sharp rectangular, rounded rectangular, or saw-tooth [33,34]. Celata [35] assessed the effect of the hypervapotron on the thermal hydraulics of high heat flux components and noted that it can increase the CHF up to 30 MW/m^2 even under moderate mass flux and inlet subcooling.

Janeschitz et al. [36] reviewed the design of the ITER divertor and noted that, for an equivalent flow and pressure drop, the hypervapotron has a higher CHF limit than the swirl tube. The hydraulic parameters used in the tests were 4 MPa inlet pressure and 150°C inlet temperature and a flow velocity of 12 m/s [36]. However, the performance of the swirl tube and hypervapotron strongly depends on the flow conditions. The method of CHF enhancement should be selected according to the specific flow conditions or purpose.

2.3 CHF Enhancement by Application of a Porous Coating

Many works have investigated the application of surface coatings for CHF enhancement. Porous coatings offer a heat transfer enhancement technique that has proved to be of great interest to numerous researchers. The role of a porous coated surface with respect to boiling enhancement is to increase the number of small scale cavities on a surface. Coated layer has uniform pore size in the micrometer range and high particle surface area (high surface to volume ratio). Each void/pore is interconnected and assists the fluid flow towards the heated surface. The CHF enhancement is due to capillary assistance to the liquid flow towards the phase-change interface. Coated layer reduces the liquid vapor counter flow resistance and hinders the development of localized dryout conditions. Capillary pumping in porous media generates the required liquid draw, and establishes a fluid flow artery [37, 38]. C.N. Ammerman and S M You [39] also observed that the mechanism of enhancement involves an increase in the number of nucleation sites and bubble departure frequency and the coating provides a means through which boiling dominates convection.

However, the effect of the porous coating on critical heat flux has not yet sufficiently been investigated under the boiling flow condition. Most research has been conducted with pool boiling. O'Connor and You [40] noted a 109% increase in the CHF over a plane surface in saturated FC-72. Chang and You [41] observed 100% enhancement of the CHF using micro-porous layer coatings made of copper particles (D=1–50 μm) and aluminum particles (D=1–20 μm). Liter and Kaviany [38] achieved three times increased CHF data using modulated porous-layer coatings. Dizon et al. [42] and Yang et al. [43] reported a 100% increase in the CHF on a downward facing curved surface through transient quenching experiments. Pool boiling on thin, uniform porous coatings was examined experimentally by Hwang et al. using different copper particles (D=40-80 μm) with coating thickness varying between 3 and 5 particle diameters [44]. The results show that the critical heat flux (CHF) is about 1.8 times higher than the plane surface. They postulated that for a 2-fold increase in the CHF, the wavelength in the Zuber CHF model is nearly one-fourth of that for a plain surface, and or the area of the vapor channels increases by $2^{2/3}$ compared to a plain surface.

The effect of surface coatings under flow boiling conditions still needs to be explored. D. Schroeder-Richter [45] conducted flow boiling experiments with plain and porous tubes at atmospheric pressure and determined there was some enhancement of heat transfer under specific conditions. Youchison et al. [46] made a porous-coated mock-up consisting of two IO-mm-ID channels covered with a porous coating made from sintered 100-150 μm OFHC (oxygen- free high-conductivity) copper pellets to an approximate depth of 300 to 1000 μm. The local CHF was detected at 21.3 MW/m^2 for the hypervapotron and 24.5 MW/m^2 for the porous coated mock-up when subjected to a flat heat flux profile using water under 4 MPa. Recently, Sarwar et al. [47] measured the flow boiling CHF under low mass flux (100-300 kg/m^2sec) and atmospheric pressure. The maximum increase in CHF was about 25% for micro-porous Al_2O_3 (D=10-50 μm). They suggested enhanced wettability, i.e., the ability to attract and hold water on the surface, as a cause of the increase in the CHF with microporous coated surfaces.

2.4 CHF Enhancement by Nano-fluids

Recently, the application of nano-fluids was introduced as a method to enhance the CHF. I. C. Bang et al [48] studied the boiling heat transfer characteristics and CHF trends of nano-fluids suspended in water using different volume concentrations of alumina nano-particles. They also measured the surface roughness of the heated surface to investigate the cause of CHF enhancement in nano-fluids.

Table 2 shows the experimental results on the CHF on a horizontal and vertical plate with variation of the concentration of nano-particles.

In this table, the CHF value does not related to the concentration of the nano-fluid, just related to the existence of nano-particle in the water. This means that the heated wall was coated by nano-particles. The surface coating by nano-particles changes the nucleation site density. The roughness of the coated surface is determined by the roughness of the smooth plate and the size and concentration of the nano-

Table 2. CHF Enhancement in a Nano-fluid [48]

	Prediction (pure water)	Pure water	0.5% NF	1% NF	2% NF	4% F
Horizontal [MW/m^2]	1.22	1.74	2.30	2.64	2.57	2.4
Vertical [MW/m^2]	0.88	1.2	1.36	1.36	1.36	1.36

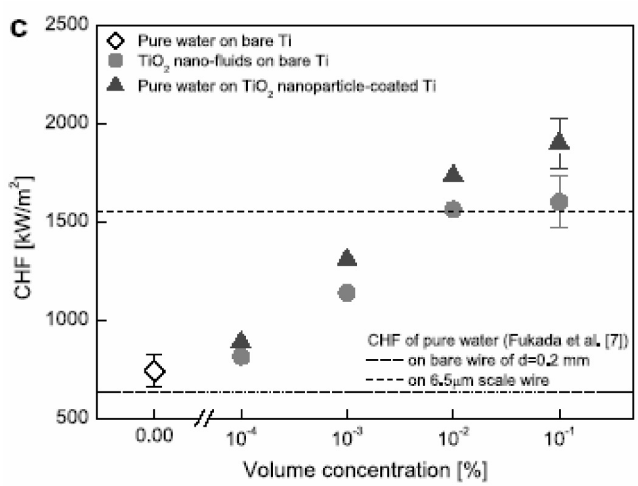

Fig. 2. CHF in Nano-particle Coating and Nano-fluid [50]

particles. This affects the CHF value and boiling heat transfer coefficient.

S. M. You et al. [49] and H. Kim et al. [50] obtained similar results. The results showed that water based nano-fluids significantly enhanced the CHF compared to pure water. In order to investigate the role of a nano-particle surface coating on CHF enhancement of nano-fluids, pool boiling CHF of pure water was measured using a nano-particle coated heater prepared by pool boiling of nano-fluids on a bare heater. It was found that pool boiling of pure water on the nano-particle coated heater yielded CHF enhancement of the nano-fluids (Fig. 2).

2.5 CHF Enhancement by Additives

CHF enhancement has also been achieved through the use of additives such as surfactants or mixture fluids, which serve to decrease the surface tension. By decreasing the surface tension of the fluid, the contact angle for flow boiling is also decreased. Consequently, bubbles with smaller diameter depart from the heated wall in a shorter time period. Boiling heat transfer thus becomes vigorous and it is expected that the CHF will also be enhanced.

T. Inoue et al. [51] studied this phenomenon and explained how an increase of the heat flux simultaneously decreased the effect of the surfactant effect. At low heat flux, enhancement of the heat transfer is larger due to the many surfactant molecules near the heated wall where the void fraction is low. However, at high heat flux, the enhancement is negligible because the surfactant molecules cannot access the heated wall due to an abundance of bubbles (Fig. 3). Therefore, it was concluded that the surfactant effect is negligible under the CHF condition.

In the T. Inoue et al.'s study, CHF experiment was performed with varying mass fraction of mixture and concentration of surfactant. Conclusively, the mass fraction affected the CHF whereas the concentration did not (Fig. 4).

W. Wu et al. [52] experimentally investigated the relation between the surface tension and the CHF in relation to the application of surfactant solutions. They found that the CHF increased as the surface tension decreased and that an increase of the surfactant concentration decreased the CHF (Fig. 5).

Celeta et al. [53] measured the CHF values with a R12/R114 mixture under DNB and LFD conditions. They concluded that the inlet mass fraction affected the CHF linearly in the DNB condition but the CHF was not related

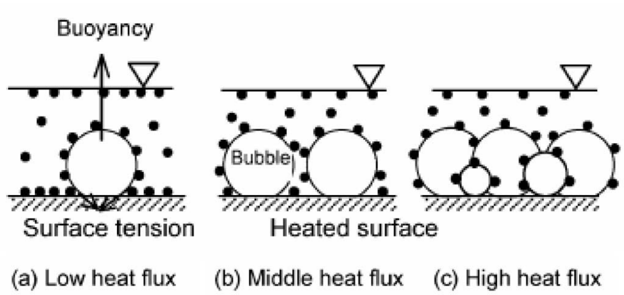

Fig. 3. Model of Distribution of Surfactant Molecules Near a Heated Surface [51]

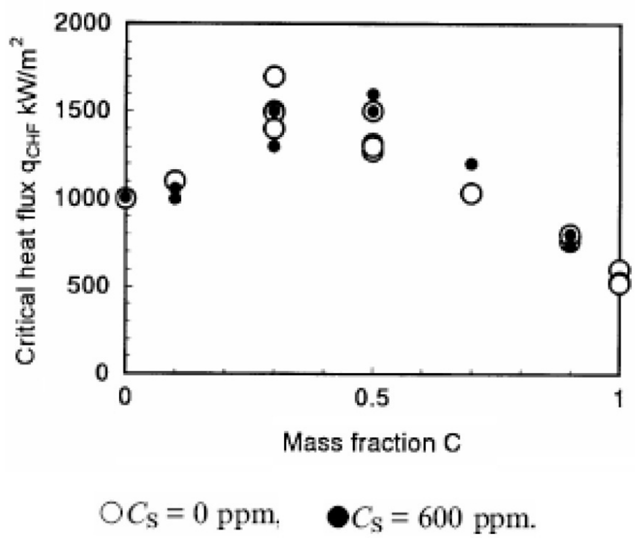

Fig. 4. Effect of Mass Fraction and Surfactant on Critical Heat Flux [51]

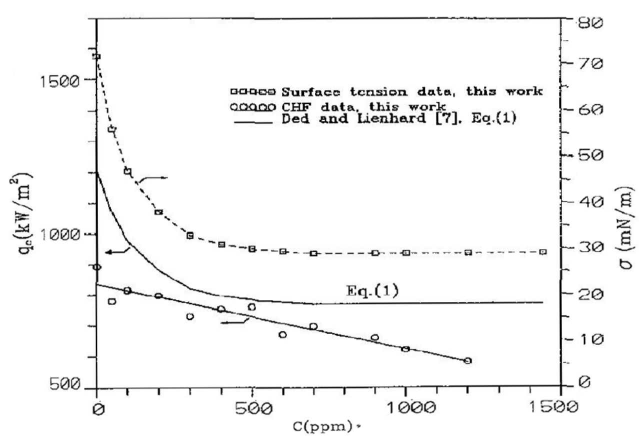

Fig. 5. Variation of Critical Heat Flux (Experimental and predicted) and Surface Tension (25°C) with SLS Concentration [52]

to the inlet mass fraction in the LFD condition. Jeong et al. [54] reported CHF enhancement of a few percent by adding trisodium phosphate (TSP, Na_3PO_4) in a 2-D real scale CHF test for in-vessel retention. They used 0.5% TSP solution and experiments were conducted under low mass flux conditions (0~150 kg/m^2sec).

The surface tension of a fluid has an impact on the formation of droplets and on wetting of solid surfaces. As the surface tension is decreased, a thinner fluid film can be sprayed before collapsing into droplets and larger wettability can be obtained [55].

Frost and Kippenhan [56] attributed the increased CHF to the inhibition of vapor bubble coalescence over the boiling surface by the Marangoni effect. This effect is a result of slow migration of surfactant molecules from the bulk to the adsorption layer at the extended vapor/liquid interface during bubble coalescence. It is generally believed that a small amount of surfactant can increase boiling heat transfer. The extent of enhancement has been found to be dependent on additive concentrations, additive type and chemistry, wall heat flux, and the heater geometry, as recently documented by Wasekar and Manglik [57]. Although many researchers have conducted experiments to determine the boiling enhancement mechanisms caused by addition of surfactants to water, the effects of surfactant on boiling heat transfer remain unclear.

Hetsroni et al. [58,59] found that the heat transfer coefficient depends both on the surface tension and the kinematic viscosity; an increase of the heat transfer coefficient at low concentration is attributed to decreased surface tension, while for high concentration, an increase in kinematic viscosity decreased the heat transfer coefficient. On the other hand, numerous studies have reported that decreasing the surface tension by adding additives has a significant impact on the boiling heat transfer coefficient.

3. CHF ENHANCEMENT IN FUEL ASSEMBLY

3.1 Introduction

Nuclear fuel assemblies are placed vertically in pressurized water reactors (PWR), boiling water reactors (BWR), and liquid metal cooled fast breeder reactors (LMFBR). In a CANDU reactor, the fuel assembly is placed horizontally. The flow path of the coolant is parallel with the axis of the fuel assembly. With regard to safety assessments, the CHF is one of the most important thermal-hydraulic parameters limiting the available power, and its size directly affects the safety and economy of the nuclear power plant. Hence, enhancement of the fuel bundle CHF is an important research topic.

To maintain the spacing between fuel rods and to prevent flow-induced vibration, spacing devices have to be used. The spacing device can be a grid (PWR and BWR), wire wrap (LMFBR) or wart (CANDU). The effect of the spacing device on the CHF has been extensively studied. Generally, spacing devices promote turbulent mixing and channel mixing. The CHF is increased by promoted mixing. However, the effect depends on the design of the spacing devices and operating conditions.

3.2 CHF Enhancement Using Mixing Vanes

Various CHF promoters can be used to increase the CHF. Generally, CHF promoters are attached to spacing devices. In PWRs, mixing vanes are generally used for extension of the CHF limit. A mixing vane promotes turbulent flow, cross flow, and/or swirl flow, which can increase the CHF considerably [60-62]. The geometries of mixing vanes are various and some are complicated. However, the fundamental mechanism of the CHF enhancement by application of a mixing vane can be summarized as follows [60-62]:

Table 3. Effects of Mixing Vane on CHF

Flow Regime	Mechanism	CHF
General	Increase of enthalpy mixing	Increase
Low quality (subcooled, bubbly)	Prevention of bubble crowding	Increase
	Centrifugal acceleration	Increase
High quality (annular)	Enhanced deposition of liquid droplets	Increase
	Liquid film breaking	Decrease

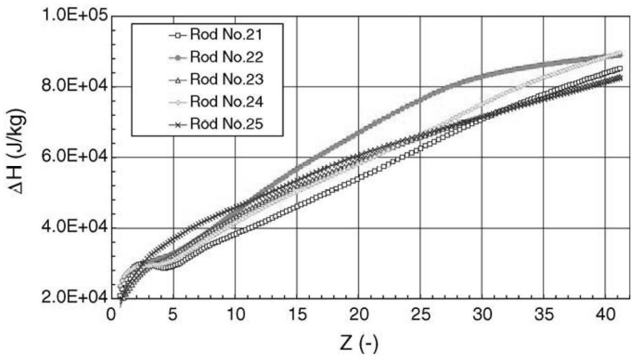

Fig. 6. Average Enthalpy Increments in the First Fluid Layer Adjacent to each Rod [67]

Table 4. Water DNB Test Condition and Results [67]

Water DNB test condition and result				
Coolant condition			Test result	
Pout (MPa)	G (kg/m2s)	X (-)	Elevation of first DNB (m)	Rod No. of first DNB
10.3	3.453	0.048	2.87	22

increase of the effective liquid flow rate by breaking the liquid film on the cold wall

- increase of flow mixing between sub-channels
- reduction of enthalpy difference between sub-channels
- supply of liquid droplets to the heated wall by swirl with annular flow
- breaking large vapor clots or vapor blankets

The effects of the mixing vane are summarized in Table 3.

Recently, numerous studies have been conducted in efforts to attain detailed understanding of the effects of mixing vane on the CHF. These studies can be categorized into two groups, CHF experiments using various flow obstacles or mixing vanes [60,62-64] and investigations of the effects of mixing vanes on the CHF by he experimental or numerical investigation of single- or two-phase flow structures downstream of mixing vanes [65-67].

De Crey [60] and Shin et al. [62] performed a CHF experiment in a rod bundle with mixing vanes. They focused on the effect of cross and swirl flows, and concluded that the two factors are the most important in terms of CHF enhancement. De Crey [60] found that the cross flow generated by a mixing vane reduced the enthalpy difference between subchannels. He also noted that the DNB occurred at random azimuthal locations.

However, the cross flow may induce rod vibration, and hence the flow could negatively affect the integrity of the nuclear fuel rod [68]. However, by inducing relatively low FIV (Flow Induced Vibration), the swirl flow can enhance the CHF as much as the cross flow. Shin et al. [62] performed CHF experiments with various angles of mixing vane that could effectively generate a swirl flow and suggested the optimum mixing vane angle. The swirl flow only effectively enhances the CHF in a subchannel. However, in the case of a rod bundle geometry with multi-subchannels, the cross flow should be considered together. That is, it is necessary to determine the optimum states. This is an important point in the development of mixing vanes for PWR nuclear fuel assemblies.

H. Anglart [66] numerically analyzed the effect of spacers on the void fraction distribution in a rod bundle with simple spacers. Their results showed that the void fraction around the spacer was increased and the void fraction around the heater wall was decreased. It was expected that the CHF value would be increased if there exists a relation between the void fraction and critical heat flux.

K. Ikeda [67] performed a numerical analysis of a single phase flow in a rod bundle with a mixing vane. They compared the local enthalpy predicted via a numerical analysis with the locations at which the CHF occurred. It was found that the CHF occurred at the rod with maximum local enthalpy (Fig. 6 and Table 4).

3.3 CHF Enhancement Using Wire Wraps

The effect of wire wraps on a 7-rod fuel bundle CHF was investigated by Cheng and Muller [69]. The CHF enhancement was mainly dependent on the local vapor qualities and subsequently on the flow regimes. At low vapor quality with a bubbly flow, the wire wrapped bundle resulted in a higher CHF compared to that obtained for a gridded bundle. However, at high vapor quality with an annular flow, the wire wraps caused a reduction in the CHF relative to that attained with application of grid spacers.

4. CONCLUSIONS

The CHF is a fundamental physical phenomena that involves mass and heat transfer and interfacial multi-phase interactions. It is a critical parameter with respect to practical applications such as nuclear and fossil power plants, especially insofar as it can limit the plant performance.

Recent progress in CHF enhancement using passive measures was reviewed in this paper. A considerable body of work on CHF enhancement and the mechanisms underlying the enhancement has been reported in the literature to date. In the future, more comprehensive experimental and theoretical study is needed for better understanding of the physical phenomena, the CHF, and, consequently, better output from the power industry.

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