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UNDERSTANDING, PREDICTING, AND ENHANCING CRITICAL HEAT FLUX

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KEY WORDS

Critical heat flux, CHF database, CHF mechanism, CHF enhancement, CHF prediction

ABSTRACT

This paper presents an overview of major issues, recent achievements, and future needs for critical heat flux (CHF) research focusing on nuclear reactor applications. Covered areas are: (a) understanding of physical mechanisms, (b) prediction methods for simple and complex geometries, and (c) enhancement of CHF. Significant advances have been made during the last 15 years, in particular, in the areas of theoretical modeling. However, considering the significance of the phenomena and insufficient modeling capability, extensive R&D activities are still required in several areas, including clear identification of physical mechanisms for low-quality and pool-boiling CHF, extension of CHF data bases for new applicable ranges and transient conditions, improvement of prediction methods focusing on theoretical models, development and application of CHF enhancement techniques, etc.

1. INTRODUCTION

The critical heat flux (CHF) condition is characterized by a sharp reduction of the local heat transfer coefficient that results from the replacement of liquid by vapor adjacent to the heat transfer surface (Collier & Thome, 1994). The occurrence of CHF is accompanied by an inordinate increase in the surface temperature for heat-flux-controlled systems, and an inordinate decrease in the heat transfer rate for temperature-controlled systems. The CHF condition is generally more important in the heat-flux-controlled systems such as nuclear reactors since the temperature increase can threaten the physical integrity of the heated surface.

The CHF is a very interesting and important phenomenon from both fundamental and practical points of view. From the fundamental point of view, CHF accompanies tremendous changes in heat transfer, pressure drop and flow regime. Heat transfer is maximized at the CHF point and is drastically degraded after the CHF point. For flow boiling in a confined geometry, the flow regime changes at the point of CHF as shown in Fig. 1. If the CHF occurred under bubbly flow condition, the flow regime is changed into inverted annular flow due to the formation of stable vapor film on the heated surface. In the similar way, the slug flow is changed into inverted slug flow and the annular flow into dispersed flow.

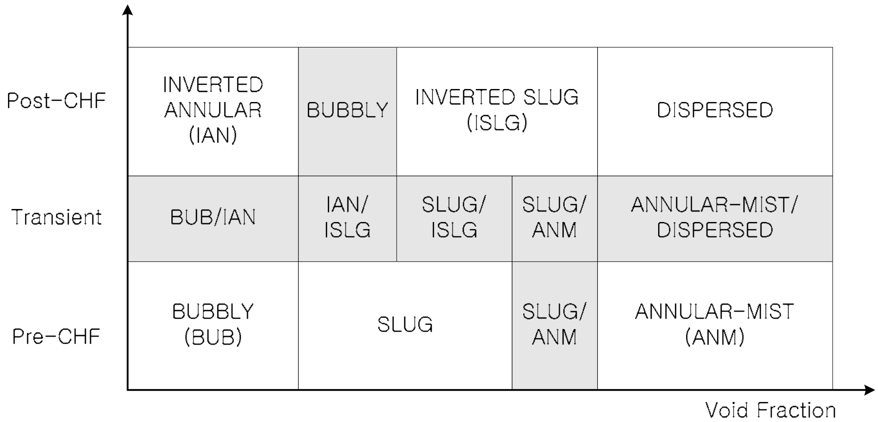


Fig. 1 Flow Regime Changes at the CHF

From the practical point of view, there are many application areas involving the CHF, including nuclear power plants, fusion applications, fossil power plants, the electronics cooling, steam generators, etc, as illustrated in Fig. 2. In those application areas, the CHF affects significantly on the integrity, safety, and/or economic competitiveness of systems and components.

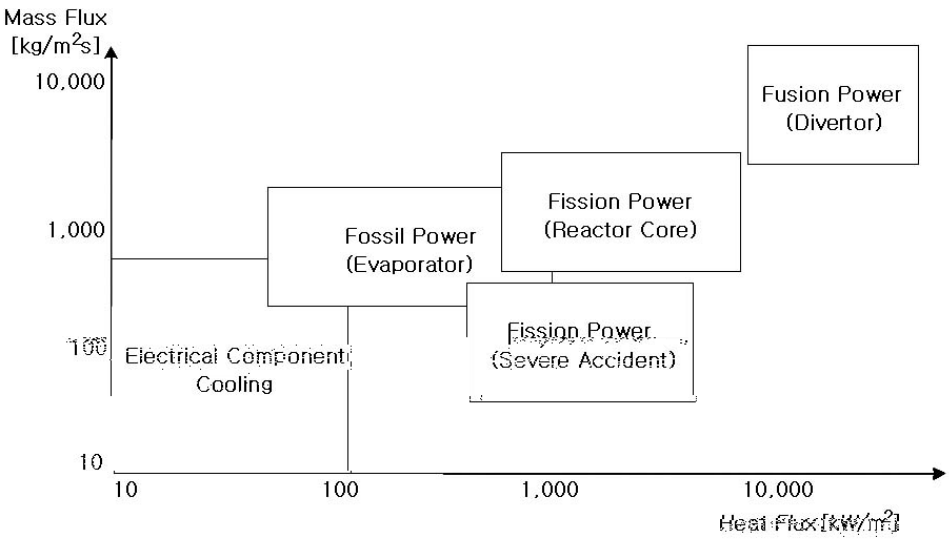


Fig. 2 The Application Areas of the CHF

The occurrence of CHF can deteriorate the integrity of fuel rods of water-cooled nuclear reactors that contain radioactive fission products. Therefore, the water-cooled reactor cores are designed to preclude (i.e., to assure the very low probability of) the occurrence of CHF during normal operation and anticipated operational transients. For accident conditions of the lower likelihood, it is impossible to preclude the occurrence of CHF; instead, safety analysis is performed with assuming the damage of fuel rods that are assessed to experience the CHF. For the postulated loss-of-coolant accident (LOCA), the safety criteria are given to other parameters such as the peak cladding temperature (PCT). It should be noted that the PCT is significantly affected by the CHF phenomenon.

The CHF phenomenon has been extensively investigated over the last four decades mainly with the development of water-cooled nuclear reactors. Recently, the cooling requirement of high-heat-flux components of fusion reactors has also stimulated the research in this area. The ultimate objectives of the CHF research for nuclear applications would be (a) to accurately predict the CHF for given conditions, and/or (b) to enhance the CHF for given operating conditions. An accurate prediction of the CHF requires the understanding of physical mechanisms and parametric trends as well as sufficient experimental data bases. The efforts to enhance CHF have mainly been related to the improvement of nuclear fuel performance.

R&D efforts have been focused on: (a) understanding of fundamental characteristics such as physical mechanisms, parametric trends, etc., (b) development of reliable prediction models, and (c) development and implementation of CHF enhancement techniques. Now many aspects of the phenomenon are well understood and several reliable prediction models (mainly empirical) are available for wide parameter ranges of conventional interests. However, the CHF is still the subject of active research and its application is continuously expanding to new areas.

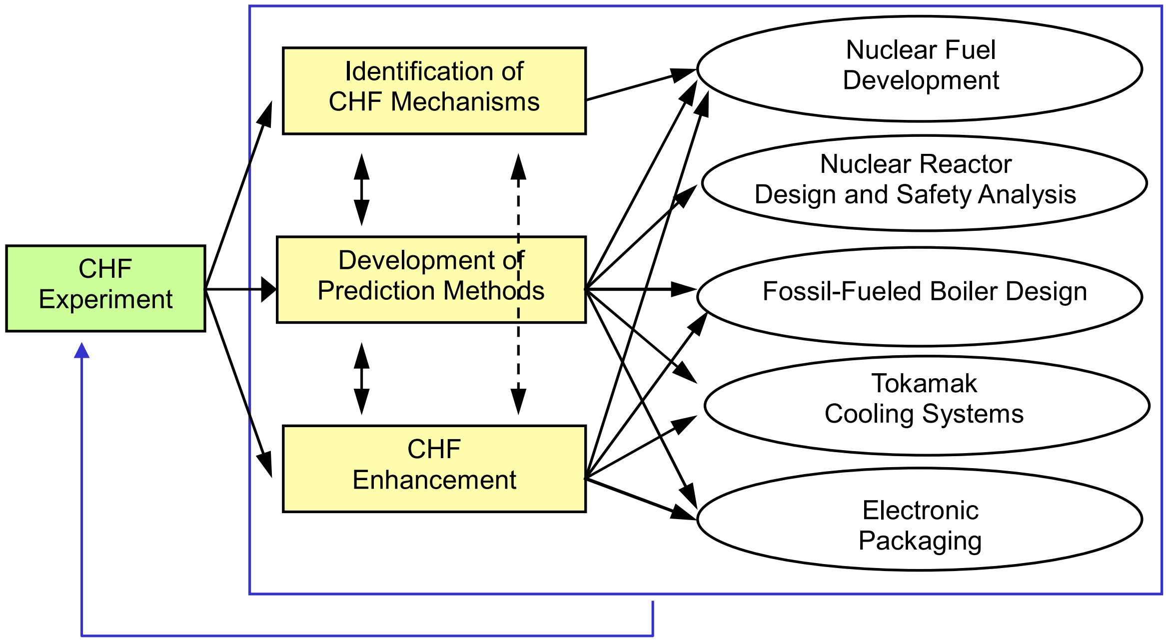


Fig. 3 CHF Research and Major Applications

There have been excellent reviews on CHF in books and journals (Collier & Thome, 1994; Hewitt, 1982; Bergles, 1977, 1979; Theofanous, 1980; Katto, 1985, 1994; Chang & Baek, 1997). This paper presents the state-of-the-art review on the major issues and significant achievements in CHF research during the last 15 years focusing on the nuclear reactor applications. Considering the space limitation, an overall review will be given with introducing key references instead of describing individual works in detail. Directions for future research are also suggested based on the result of the state-of-the-art analysis.

2. UNDERSTANDING OF PHENOMENA

Understanding of the phenomenon forms the basis for the reliable prediction and enhancement of CHF. While the parametric trends of CHF are widely understood for wide range of geometrical and

2.2 Flow-Boiling CHF

Two major categories of CHF mechanisms exist for flow boiling: (a) departure from nucleate boiling (DNB) at subcooled or low-quality conditions and (b) liquid film dryout (LFD) at high-quality conditions. The physical mechanism of the LFD is relatively well understood and reliable theoretical models are also available. On the other hand, the detailed aspects of the DNB mechanisms have not been clearly understood. Several different mechanisms, which seem to be dependent on flow and geometrical conditions, have been proposed based on visual observations and theoretical investigations.

During the last decade, important experimental studies on DNB mechanisms have been conducted by several workers (Galloway & Mudawar, 1993a; Gersey & Mudawar, 1995; Celata et al. 1995; Chang et al., 2002; Zhang et al., 2002). They have significantly increased the visualization data and enhanced the understanding on DNB mechanisms even though they are still insufficient and sometimes contradictory,

Among DNB mechanisms proposed so far, the following 3 models are being considered to be the most promising:

(a) bubble crowding model

(b)

It is believed that several different CHF mechanisms govern the phenomena according to the geometrical and flow conditions, in particular for CHF at low qualities. Sufficient understanding of CHF phenomena would result in a generalized *CHF regime map* encompassing pool and flow boiling by introducing suitable non-dimensional parameters.

3. PREDICTION OF CHF

CHF prediction methodology can be categorized as the analytical (or theoretical) methods and the empirical methods. Analytical models are developed by considering specific physical mechanisms leading to the CHF as discussed in the previous section. Empirical methods are mainly based on the experimental data bases and known parametric trends of the data. The general aspects of CHF prediction were discussed in an IAEA report (IAEA, 2001).

3.1 Analytical Methods

(a) Pool Boiling

Analytical CHF prediction models are also called as the theoretical models or mechanistic models. As there is no conclusive evidence of governing CHF mechanisms, there are several analytical models even for the same geometrical and operating conditions. Analytical models proposed by the early 1990's were critically reviewed by Weisman (1992).

For pool boiling, Zuber's hydrodynamic instability model has been the most widely accepted with the extension by many other researchers including Lienhard and his co-workers (Lienhard & Dhir, 1973). Lack of visual evidence and poor prediction for some cases evoked the efforts to develop other models; the liquid macrolayer dryout model by Haramura & Katto (1983) would be the most important model. This model was further elaborated by Katto (1992) and Celata et al.(1994). Please refer to Sadasivan et al. (1995) for valuable discussion on pool-boiling CHF models.

Several other analytical models have been proposed during the last 15 years. Among them, the models by Kolev (1995), Ha & No (1998), Theofanous et al.(2002b), Kandlikar & Steinke (2002) deserve further investigation in parallel with more experimental work.

(b) Flow Boiling

Theoretical modeling for the flow-boiling CHF has been continuously progressed by several investigators, as reviewed by Weisman (1992). The modeling for the LFD was relatively well established by the early 1980s (Whalley, 1987) and continuous improvements are being made to existing models. Now some thermal-hydraulic codes use analytical models instead of the empirical correlations for CHF at high-quality conditions.

A significant progress has been made to the theoretical DNB models during the last 15 years. Among various types of models that have been proposed, the bubble coalescence model (Weisman & Pei, 1983; Chang & Lee; 1989) and the liquid sublayer dryout model (Lee & Mudawar, 1988; Lin et al. 1989; Katto, 1992; Celata et al. 1994) have been showing the most promising results. Several authors have attempted to assess those theoretical DNB models and reported different results according to the parameter ranges of the experimental data bases. In overall, Weisman & Pei (1983) model shows good prediction for the high pressure region relevant to PWR conditions, while the Celata et al. (1994) model or Katto (1992) model for low-pressure, high-flow conditions relevant to fusion applications. In the critical review by Bricard & Shouyri (1995), the Katto model and the modified Lin model are reported to show better predictions than the Weisman & Pei model even for

PWR-relevant conditions. It is also reported that some modification to the Lee & Modawar model shows reasonable prediction of the CHF at low-pressure and low-flow conditions (Ho et al., 1993).

The interfacial lift-off model by Mudawar and his co-workers (Galloway & Mudawar; 1993b) have been reported to represent the CHF for various conditions including inclined surfaces (Zhang et al. 2002). The operating parameter ranges they tested are still very limited. Recently Chun et al. proposed a DNB model considering the depletion of the liquid layer under the flowing bubbly layer, resulting in very promising prediction capability.

Table 1. Typical Flow Boiling CHF Models

Condition	Model	Developers	CHF Mechanism	Major Parameters	CHF Expression
Bubbly flow - low quality & subcooled condition	Bubble crowding model	• Weisman & Pei (1983) • Chang & Lee (1989) • Kwon & Chang (1999)	Critical bubble packing in the bubble boundary layer	- Critical void fraction - Momentum or turbulent transport btwn core & bubbly layer	$CHF = G' h_{fg} (x_2 - x_1) \frac{h_f - h_{ld}}{h_l - h_{ld}}$
	Liquid sublayer dryout under a vapor blanket	• Lee & Mudawar (1988) • Katto (1992) • Celata et al. (1994)	Complete evaporation of the liquid film beneath a vapor blanket	- Liquid sublayer thickness - Vapor blanket length - Vapor blanket velocity	$CHF = \frac{\rho_f \delta h_{fg}}{L_B} U_B$
	Liquid sublayer dryout under a bubbly layer	• Chun & Chang (1999)	Complete evaporation of superheated liquid layer	- Effective evaporation length	$CHF = \frac{\dot{m}_D i_{fg}}{\pi D L_{evap}}$
Annular flow - high quality condition	Liquid film dryout	• Whalley et al. (1978) • Levy et al. (1981) • Katto (1984)	Depletion of liquid film on the heated wall	- Evaporation - Deposition - Entrainment	$\frac{dG_{fF}}{dz} = \frac{4}{D} \left(D_d - E - \frac{q}{h_{fg}} \right)$

3.2 Empirical Prediction Methods

Empirical prediction methods have been developed with the continuous expansion of experimental data bases and applicable systems of interests. Three categories of empirical methods are being used: (a) *empirical correlations*, (b) *look-up table methods*, and (c) *artificial neural network* and other information processing techniques.

The CHF in uniformly-heated vertical round tubes has its own applications and also forms the basis for investigation of the flow boiling CHF in other geometries. It has been extensively investigated all over the world, resulting in over 30,000 experimental data for wide operating conditions. A reliable prediction of the CHF in this geometry is crucial because it represents the basic parametric trends and can be used to predict the CHF in other geometries with incorporation of appropriate correction factors.

Traditionally empirical correlations are mainly used in CHF prediction but the prediction accuracy is deteriorated when any single correlation is applied to a wide parameter range. While the efforts to develop more reliable empirical correlations are also being exerted, new approaches such as table look-up methods and artificial neural network applications are being applied, sometimes showing very promising results.

Table look-up method was originally developed by Russian investigators, see Doroschchuk et al. (1975). Groeneveld et al. (1986) extended the look-up table method of CHF prediction and their 1986 table was widely adopted in many best-estimate thermal hydraulic analysis codes for safety analysis of nuclear reactors such as RELAP5/MOD3, CATHARE, CATHENA, etc., due to its wide applicable range, accuracy, and simplicity in use. Their new table (1995 table) (Groeneveld et al. 1996) is based on 22,946 data from the combined AECL-IPPE data base. The table provides CHF values for 8 mm tubes at discrete values of pressure, mass flux, and critical quality, based on the local conditions hypothesis and assuming a simple relationship for the diameter effect. Due to its advantages in accuracy and simple application, the look-up table method is expected to be widely used in the future, with continuous improvements.

In addition to the conventional methods, the artificial neural network (ANN) technique has been applied to the CHF database (Moon et al., 1996). The trained ANN shows the least prediction error among the available prediction methods when it is used within the range of experimental data base. Though it does not provide a simple analytical expression, the ANN would be a very useful tool for prediction and parametric trends analysis of CHF and other thermal-hydraulic phenomena (Mazzola, 1997; Su, 2003).

A reliable and extensive set of experimental database is crucial for any empirical CHF predictions. Recently, Hall & Mudawar (2000a,b) published the compilation and assessment of world CHF data including their PU-BTPFL CHF database for water flow in uniformly heated tubes. The CHF database was compiled from the world literature dating back to 1949 and represented the largest CHF database ever assembled, with 32,544 data points from over 100 sources in the following range of conditions: Pressure 70~21800 kPa; mass flux 10~134000 kg/m^{2}s, outlet qualities -2.25~1.00; diameter 0.00025~ 0.0447 m; length to diameter ratios 1.7~2484.

It should be noted that a issue of *Nuclear Engineering Design* (1996) provided very useful discussions on the implications of CHF prediction errors and the CHF margin. Inasaka & Nariai (1996) presented a clear definition of the "direct substitution method (DSM) " and the "heat balance method(HBM)" for local-condition-based correlations and explained the reason for the smaller prediction error of the HBM.

3.3 Future Research Directions

Main focus should be given to the further improvement of theoretical models in parallel with the establishment of a CHF regime map. Existing models of reasonable accuracy should be carefully examined with experimental evidences and further supporting experiment can be performed if necessary. Several different physical mechanisms would exist according to geometrical and thermal-hydraulic conditions; however, unification of the fundamental CHF models focusing on the disappearance of stable liquid supply to the heated surface would also be possible as suggested in Kim et al. (2000).

Even though the ultimate goal in CHF prediction method would be theoretical prediction for the whole condition of interests, empirical approaches will keep their values in practical applications. Empirical correlations developed from prototypic conditions are useful in design and analysis of nuclear reactors; but most of them belong to the realm of proprietary information. Some efforts would be needed to identify suitable correlating parameters, which can represent the actual local conditions and upstream effects instead of thermal-hydraulic equilibrium parameters, for unusual conditions including low-pressure and low-velocity conditions.

The look-up table method can be improved by more properly incorporating the effects of diameter and heated length. A new variable instead of the thermodynamic equilibrium quality would be necessary to adequately deal with the high-quality CHF and low flow conditions. The artificial neural network technique also deserves further attention. A combination of different approaches (e.g., correlations, tables, and artificial neural networks) has also been tried with providing promising results.

4. ENHANCEMENT OF CHF

A significant enhancement of CHF allows reliable operation of equipment with more margin to the operational limits. Therefore significant efforts have been made to develop enhancement techniques for CHF.

4.1 Pool Boiling CHF

While nuclear boiling heat transfer can be significantly improved by applying various surface conditions, it was apparent that the pool-boiling CHF is not significantly increased by normal surface treatment. As this finding is consistent with the hydrodynamic instability model or macrolayer dryout model, the efforts to improve CHF by surface treatment were not active until the early 1990's. Instead, the enhancement by other methods such as ultrasonic or electromagnetic excitation has been tried.

However, several new data sets related to electronics cooling indicated significant variations of CHF according to surface conditions. Theofanous et al. (2002 a,b) also found significant variation of CHF with surface conditions even for water coolant. Rainey et al. (2003) also found that CHF enhance with micro-porous, square pin-finned surface. Modulated (periodically non-uniform thickness) porous-layer coatings are experimentally shown to enhance the pool-boiling critical heat flux nearly three times over that of a plain surface. It is proposed that the modulation separates the liquid and vapor phases and thus reducing the liquid-vapor counter-flow resistance adjacent to the surface (Liter et al., 2001). The surface condition can affect the microscopic behavior of fluid on the heated surface. The other possibility it can also change the macroscopic parameters such as the effective liquid macrolayer thickness.

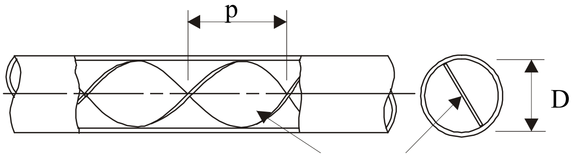
Typical approaches considered to enhance the pool-boiling CHF include:

- oxidation or selective fouling of the heater surface to increase the wettability or the stability of the liquid layer
- vibration of heaters to promote the departure of bubbles from the heater surface
- coating or extended heater surface to increase the heat transfer area and/or the effective liquid layer thickness
- heater rotation to promote bubble departure from and liquid deposition onto the heater surface
- fluid vibration to promote bubble departure and liquid supply
- application of electric fields to promote bubble departure from the surface by dielectrophoretic force and to increase liquid renewal

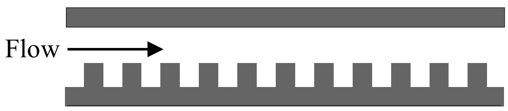
The understanding on the enhancement mechanisms and experimental data bases are still very limited.

4.2 Flow Boiling CHF for Simple Geometry

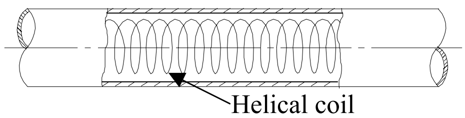
Several methods of CHF enhancement have been investigated and applied to remove high heat fluxes while maintaining reasonable pumping power requirements. Usual approaches are twisted tape inserts in round tubes (Inasaka & Nariai, 1993, 1998; Kabata et al., 1996), hypervapotron technique for rectangular channels (Cattadori et al., 1993; Falter & Thompson, 1996), helically coiled wire inserted in round tubes (Celata et al., 1993; Kabata et al., 1996), grooved (ribbed or rifled) tubes (Cheng & Xia, 2002; Ravigururajan & Bergles, 1996) etc., as illustrated in Fig. 7. They can increase the subcooled boiling CHF up to over 100%, but the degree of enhancement is highly dependent on flow conditions. In the ITER design, among the several candidates for CHF enhancement, the swirl tape inserted round tube has taken priority up to now (Janeschitz et al., 1998, 2002). Pioro et al. (2002) showed that the presence of flow obstacles generally increases the CHF downstream of the obstacle. Guo et al. (2001) developed a semi-theoretical prediction method of CHF enhancement due to flow obstacles inserted in a flow channel. A significant amount of knowledge on CHF enhancement techniques has been accumulated though there are still some disagreements between experimental results and its applicability.



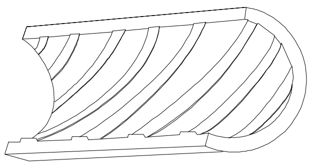
(a) Round tube with a twisted tape insert



(b) Rectangular channel with a hypervapotron



(c) Round tube with a helical coil insert



(d) Ribbed tube

Fig. 7 CHF enhancement techniques for internal flow boiling

The vibration is regarded as an alternative method of heat transfer enhancement; a great deal of experimental investigations have been performed to demonstrate the influence of vibrations/sounds upon the rate of convective heat transfer from heated surfaces to fluid. (Martinelli et al., 1938; Bergles, 1964; Takahashi & Endo, 1990).

For the flow-induced vibration (FIV) effect on two-phase flow structure in vertical tubes, Hibiki and Ishii (1998) reported that the FIV drastically changed the void fraction profiles from “wall peak” to “core peak.” Nariai and Tanaka (1994) also reported that an oscillating heater rod affected local void fraction of subcooled flow around the rod. These indicate the possibility of a significant CHF variation with vibration. Unfortunately, as each of these two important topics (CHF and FIV) has so far been independently discussed, there is little information that deals with the relation between CHF and FIV.

Lee et al. (2002) performed experimental study to find out the relationship between CHF and vibration (see Fig. 7). The CHF generally increases with vibration intensity that is represented by vibration Reynolds number and the CHF enhancement is more dependent on the amplitude than on the frequency. They concluded that CHF enhancement comes from reinforced fluid turbulence induced by vibrations. They also suggested an empirical CHF enhancement correlation based on a heat transfer enhancement correlation.

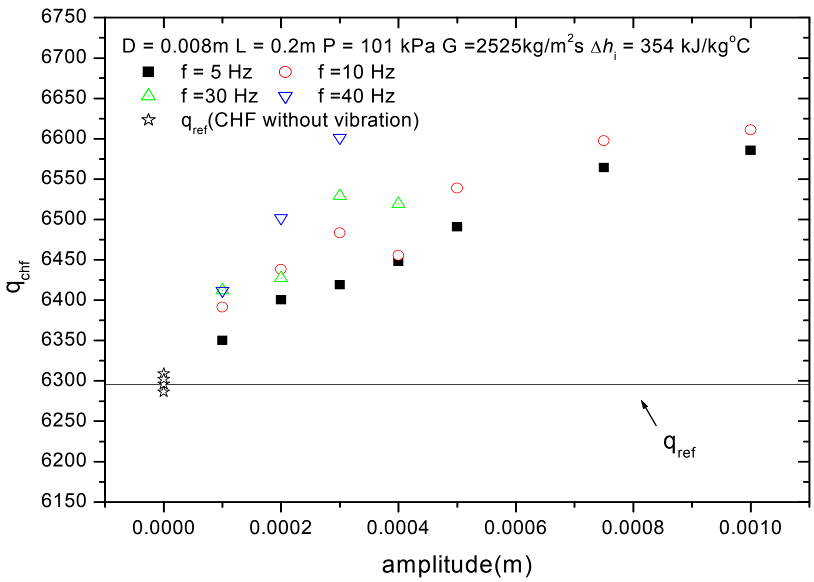


Fig. 8 The Tube Vibration Effect on the CHF

4.3 CHF in Rod Bundles

The CHF phenomenon in rod bundles is different from that in round tubes or annuli due to the cross flow between subchannels, effects of spacing devices and CHF promoters, effects of cold walls, etc. Figure 9 illustrates the effect of CHF promoters (mixing vane) in rod bundles. Accurate prediction and enhancement of the CHF in rod bundles is very important because it limits the allowable core power level. If we enhance the CHF for given conditions or reduce the uncertainties in CHF prediction, we can find more margin in core thermal design that can be used for operational flexibility or power upgrade. The CHF enhancement is one of the most important considerations in new fuel development. An exact understanding of the basic CHF mechanisms in rod bundles would facilitate the implementation of enhancement techniques. Figure 8 illustrates the effect of CHF promoters in rod bundles.

Generally, a role of mixing vane in rod bundle is the enhancement of CHF. De Crecy (1994) investigated the effect of the grid assembly mixing vanes on both the value of the CHF and the azimuthal location of DNB in 5x5 vertical rod bundles. Chung et al. (1996) studied experimentally the effects of spacer grids and mixing vanes on CHF. And they refer to the major mechanism of enhancements as summarized in Table 2.

There are some efforts to prediction of CHF in rod bundles using look-up table or round tube data. Hwang et al. (1993) suggested correction factors applicable to the look-up table for prediction of CHF in rod bundles. Lee (2000) suggested a prediction method in which a set of correction factors is developed to extend the applicability of the CHF table to flow in rod bundles of square array.

Fortini (2002) also predicted the CHF in 5x5 rod bundles using the 1995 CHF table for uniformly heated round tubes with an appropriate diameter correction.

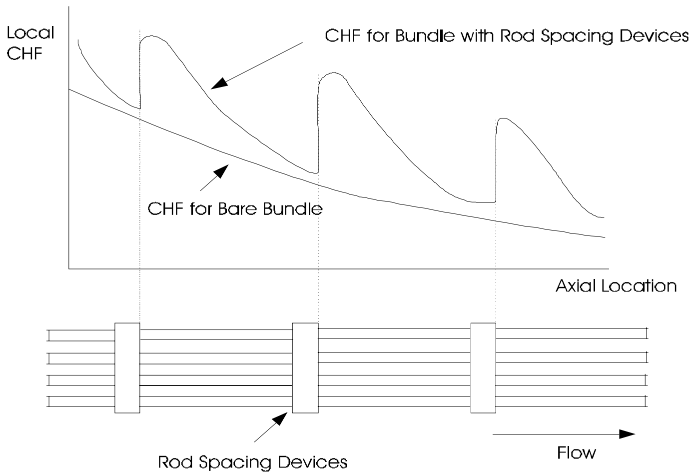


Fig. 8 CHF in rod bundles with CHF promoters

Table 2. CHF Enhancement Mechanisms by Spacers and Mixing Vanes

Flow Conditions	Mechnisms	Effect on CHF
Overall	Enthalpy mixing	Increase
Subcooled & Low Quality	Preventing bubble crowding	Increase
	Centrifugal acceleration	Increase
High Quality	Centrifugal acceleration	Increase
	Perturbation on liquid film	Decrease

4.3 Future Research Directions

For CHF enhancement in pool boiling, it is necessary to further understand the detailed CHF mechanisms and the effect of surface structure on those mechanisms. New experiment and analysis should be done to identify key parameters affecting the CHF.

For flow boiling, the basic approach for CHF enhancement is to achieve the maximum CHF without accompanying excessive pressure drop and without threatening structural integrity due to vibration. It is apparent that the enhancement effect varies with the geometrical and flow conditions; however, the available experimental data are still very limited. Much more experimental work and theoretical investigation are required to understand the involving mechanisms and to quantify the enhancement effects.

5. CONSIDERATIONS FOR PARTICULAR APPLICATIONS

5.1 CHF Related to Severe Accidents

Severe accidents are now explicitly considered in most advanced reactor designs. If core melt occurs in water-cooled reactors, core debris is formed inside the reactor vessel. Two approaches are being considered as the means for retaining the molten corium inside the vessel: (a) injection of emergency coolant into the vessel to directly cool the core debris, and (b) external cooling of the reactor vessel lower head containing the molten corium pool. If those approaches fail, the molten corium is released to the reactor cavity. To prevent the core debris from breaching the containment due to core-concrete interaction, the debris should be cooled on the cavity floor. The CHF phenomenon for core debris bed related to both in-vessel and ex-vessel cooling has long been a subject in nuclear safety. Recently, the CHF on the external surface of the reactor vessel lower head has attracted much attention as it limits the cooling of the lower head containing the molten corium.

The CHF on curved downward surface representing the external surface of a lower vessel head has been tested by several investigators (Cheung & Haddad, 1994; Granovskiy et al., 1995; Theofanous et al., 1996). The CHF for this geometry is quite different from the usual pool-boiling CHF on downward-facing or inclined flat plates. It depends on the dimension, material and surface condition of the lower head, local liquid subcooling, flow channel geometry and induced flow, etc. Generally the CHF increases with the surface slope, i.e., as the location moves from the bottom center to the head-to-cylindrical shell junction. In most integral tests, two regions of different boundary layer characteristics are observed (Cheung et al., 1999):

(a) the central bottom area with large pulsating vapor bubbles, and
(b) the outer area with stable two-phase boundary layer.

There have been some experimental works on the CHF on external surface of the lower head. Theofanous and Syri (1997) suggested a CHF correlation as a function of the angular position (= 0º at the bottom center and 90º at the head-shell junction) as follows:

$$\begin{aligned} q_c &= 500 + 13.3\theta \qquad kW/m^2 \; for\, \theta < 15^o \\ &= 540 + 10.7\theta \qquad kW/m^2 \; for\, 15^o < \theta < 90^o \end{aligned} \tag{3}$$

It is considered that the above correlation is applicable to other cases if the effects of different operating parameters (scaling, subcooling, and induced flow, etc) are properly incorporated. Recently, they have been shown the possibility of CHF enhancement using aged surface and optimized configurations (Theofanous et al., 2002c).

There have been some different characteristics between three dimensional small scale experiments (Cheung et al., 1999) and two dimensional full scale experiments (Theofanous et al., 2002c): (a) the bubble behavior at the bottom of the reactor vessel and (b) subcooling and induced mass flux at the equator of the reactor vessel. It is needed to integrate the difference between two kinds of experimental methods.

There has been a hypothesis that heat removal through the naturally formed narrow gap between the debris crust and the internal surface of the lower head is a feasible mechanism of in-vessel retention of the molten core (Okano et al., 2003; Thomsen, 2002).

5.2 CHF related to Fusion Reactor Cooling

The reliable cooling of high-heat-flux (HHF) components is one of the most important engineering problems in developing advanced Tokamak devices. For example, the heat flux levels over 20 MW/m^2 is expected for the divertor of International Thermonuclear Experimental Test Reactor (ITER) (Ibbott et al., 2001). Among various coolant options, water is primarily considered due to its unique advantages as a coolant: effective heat removal, abundance and low cost, extensive operational experiences, easy handling, etc. (Baek & Chang, 1997). In this context, water is going to be used for divertor cooling in ITER (Janeschitz et al., 1998; Ibbott et al., 2001). In the divertor cooling, the CHF is the most important factor which limits the cooling performance. As the expected heat flux level is about one order higher that that for water-cooled fission reactors, CHF enhancement techniques have been being investigated along with the adoption of high flow velocities. Figure 8 illustrates a typical heat flux distribution of a divertor cooling channel. It is highly non-uniform in both axial and circumferential directions.

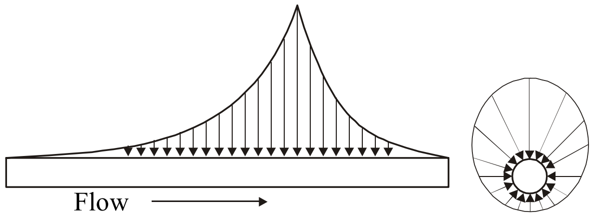


Fig. 9 Typical Heat Flux Distribution for a Divertor Cooling Channel

Significant amount of work has been performed on the CHF relevant to HHF components cooling of Tokamak fusion devices. As the expected maximum heat flux is very high, water flow at high mass fluxes, low-to-intermediate pressures and high subcooling is generally considered. Several approaches to enhance the critical heat flux has been pursued. Available experimental data bases, CHF enhancement techniques, and prediction models are well reviewed by Celata (1993, 1998), Inasaka & Nariai (1996), Hall & Mudawar (1999), Mudawar and Bower (1999), Baxi (2001), etc. An issue of Fusion Technology (1996) provides some status-of-the-art information on the cooling aspects of the HHF components of fusion reactors.

5.3 CHF at Low Pressure, Low Flow Conditions

The interest on the CHF at low pressure and low flow (LPLF) conditions has been continuously increased. While it is important with respect to accident conditions of light water reactors, and normal and transient conditions of several research reactors, available data bases and prediction models are very scarce compared with those for high-pressure, high-flow conditions.

General characteristics of the CHF at LPLF conditions are now understood owing to the recent work by several investigators (Mishima, 1984; Mishima & Nishihara, 1987; Chang et al., 1991; Ruan & Yang, 1993; Kim et al., 2000a). Some models are also available for predicting the LPLF CHF at stable conditions. Kim et al. (2000a) has shown that Shah (1987) correlation reasonably predict the stable LPLF CHF. It is also shown that the liquid film dryout model is promising in the prediction of the LPLF CHF. However, the effects of flow oscillations which usually occur in actual systems at LPLF conditions are not reliably handled in existing prediction models.

It is thought that the thermodynamic equilibrium quality calculated from the inlet conditions and heat input would not be a suitable correlating parameter for low-pressure and low-flow conditions, in particular in transient cases.

5.4 CHF under Transient Conditions

The CHF in actual systems occurs due to transients of flow, power, pressure, or combinations of them, while most of the CHF data are obtained under quasi-steady-state conditions. Therefore the identification of transient effects on the CHF has long been an important subject in CHF research. Important transient conditions are flow transients, power transients, pressure transients, flow and power transients, pressure and flow transients, flow, pressure and power transients, flow oscillating conditions.

The transient CHF has been investigated by many workers. Focus has been given to (a) experimental identification of the effects of change rates of independent variables on the CHF, and (b) derivation of correction factors correlating the transient CHF with the steady-state CHF (Serizawa, 1983; Kataoka et al, 1983; Celata et al., 1987; Iwamura, 1987; Chang et al., 1989; Pasamehmetoglu et al, 1990; Sakurai, 2000; Fukuda et al., 2000). The quasi-steady-state approach in CHF prediction, i.e. direct use of steady-state CHF correlations with local transient conditions, is found to be appropriate for slow transients and conservative for most rapid transients. Several empirical correction factors or theoretical models are available for rapid transients of flow and power. Recently valuable sets of experimental data are reported for CHF under flow oscillating conditions (Ozawa et al., 1993).

6. CONCLUDING REMARKS

Major issues, recent achievements, and future research needs have been discussed for critical heat flux (CHF) phenomena focusing on nuclear reactor applications. Covered areas have been: (a) understanding of physical mechanisms, (b) prediction methods for simple and complex geometries, (c) enhancement of CHF, and (d) specific applications. It is found that significant advances have been made during the last 15 years, in particular, in the areas of theoretical modeling.

However, considering the significance of the phenomena and insufficient modeling capability, extensive R&D activities are still required in several areas, including:

- clear identification of physical mechanisms for low-quality and pool-boiling CHF and development of a CHF regime map
- extension of CHF data bases for new applicable ranges and transient conditions
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