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CRITICAL HEAT FLUX

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Abstract—Studies of the critical heat flux (CHF) carried out during the last decade have been reviewed, with emphasis on the main current of investigation flowing steadily toward a better and "unmysterious" understanding of the CHF phenomenon, together with a survey of a number of fundamental studies on the CHF. In order to attain this objective and, at the same time, provide a clear map of this field, the materials have been classified into four main boiling modes, subdivided into individual important topics and arranged in a proper sequence so as to show the synthetic framework of the CHF phenomenon, not as a mere accumulation of unrelated knowledge but as an organic combination.

Key Words: critical heat flux, pool boiling, external flow boiling, forced internal flow boiling, countercurrent flow boiling

1. INTRODUCTION

The critical heat flux (CHF) is an interesting subject studied by many researchers, and hence a large number of papers have been published to date. However, since space is limited, only studies conducted during the last decade are reviewed herein. The author sees the CHF as a complicated phenomenon with similarities to "boundary lubrication" in tribology, because both phenomena are related to not only the fluid dynamics, but also the nonfluid-dynamic movement of liquid on the solid wall, and because of the important function of the solid wall. In addition, the CHF is associated with various thermal aspects, including the intense evaporation of liquid attached to the heated surface. An exact theory of the CHF has not yet been obtained, but it seems likely that our physical images of this phenomenon have recently begun to converge owing to the results of many research efforts.

During the last decade, a number of review or similar papers on CHF have been published, for example the papers by Lienhard (1988a, b), Straub *et al.* (1990), Dhir (1990), Bar-Cohen (1991) and Auracher (1990, 1992) on pool and external flow boiling; and the papers by Boyd (1985a, b), Sohal (1985), Groeneveld & Snoek (1986), Kalinin *et al.* (1987), Weisman (1991) and Celata (1991) on forced internal flow boiling. In addition, the present author has published several review papers (Katto 1983, 1985, 1986, 1992b). Hence, viewing the literature from a new standpoint, a fresh review of recent CHF studies is presented below.

2. THE CHF IN POOL BOILING

2.1. *Heat Transfer Characteristics in Nucleate Boiling at High Heat Fluxes*

Lienhard (1985) discussed the heat transfer characteristics of nucleate boiling on an inclined heater surface with reference to the effect of gravity, explaining the ineffectiveness of gravity on "heat transfer" in fully developed nucleate boiling [as indicated by the experimental data of Nishikawa *et al.* (1983)] in terms of the establishment of steady-state vapor escape jets on the heater surface, such as those postulated in the hydrodynamic CHF model [see section 2.9.1 and figure 5(a)]. Lienhard (1988b) also viewed boiling from the same standpoint—paying no attention to the existence of a very thin, self-regulating boiling region adjacent to the heater surface, as mentioned by Katto (1992b)—on the basis of the insensitivity of heat transfer not only to gravity but also to many other factors (forced flow of bulk liquid, quite low immersion depth, forced supply of liquid to the heater surface through a thin tube, artificial acceleration etc.). Originally, the concept of "fully developed nucleate boiling", although recently it has also become familiar in the field of pool boiling, was born from the ineffectiveness of forced flow on heat transfer at high heat fluxes (Bergles & Rohsenow 1964; Rohsenow 1985, p. 12.41).

2.2. Observations of Fluid Behavior Near the CHF Condition

Haramura (1989) conducted an experimental study on the boiling of water at high heat flux from a horizontal narrow tube (0.69-mm o.d. and 7.7-mm long), controlled by a computer to maintain a constant temperature. He observed, via high-speed ciné camera, the successive states of the vapor escape configuration near the CHF condition, as shown in figure 1, which showed similar features to those observed in boiling on a disk heater of about 10-mm dia.

With regard to vertical rectangular heaters, Liaw & Dhir (1989) measured void fraction profiles on a large, vertical flat surface (63-mm wide, 103-mm high and with a contact angle of 14°–90°) during nucleate boiling of water at 1 atm by means of a γ-beam traversing parallel to the surface, reporting that the maximum void fraction occurs about 1–1.5 mm away from the heater surface (note that the measurement was restricted to a range of > 0.4 mm away from the heater surface). Meanwhile, Katto & Otokuni (1994) performed visualization experiments of vapor escape behavior in nucleate boiling at high heat flux on a vertical flat heater (10-mm wide and 100-mm high), by means of a simulation method employing air and water. Their study suggests that a vapor mass rises, growing along the vertical heater surface intermittently near the CHF condition.

2.3. The CHF on Vertical and Inclined Surfaces

With regard to boiling on a vertical rectangular surface, Bui & Dhir (1985) experimented on the transition boiling of saturated water on a vertical heater (63-mm wide and 103-mm high) under the conditions of "steady-state", "transient heating" and "transient cooling" (quenching), respectively, showing that the CHF obtained during transient cooling is much lower than that obtained in steady-state tests (see section 2.7.1 for details). Meanwhile, Park & Bergles (1988) conducted experiments on R-113 boiling on thin foil heaters (2.5- to 70-mm wide and 1- to 80-mm high), providing empirical correlations of CHF. Figure 2 shows the locations of the onset of CHF observed by these authors for heaters 5-mm wide and 5- to 80-mm high, which may be useful information in considering the mechanism of CHF for vertical heaters (cf. section 2.2 and figure 6).

Nishio & Chandratilleke (1989) studied experimentally the effect of the surface roughness and inclination on the heat transfer of saturated helium boiling on a disk heater of 20-mm dia, including the CHF point and transition boiling regime. Meanwhile, Ohama & Miyazaki (1986) measured the CHF of slightly subcooled water boiling from a nearly downward-facing disk heater of 29.5-mm dia.

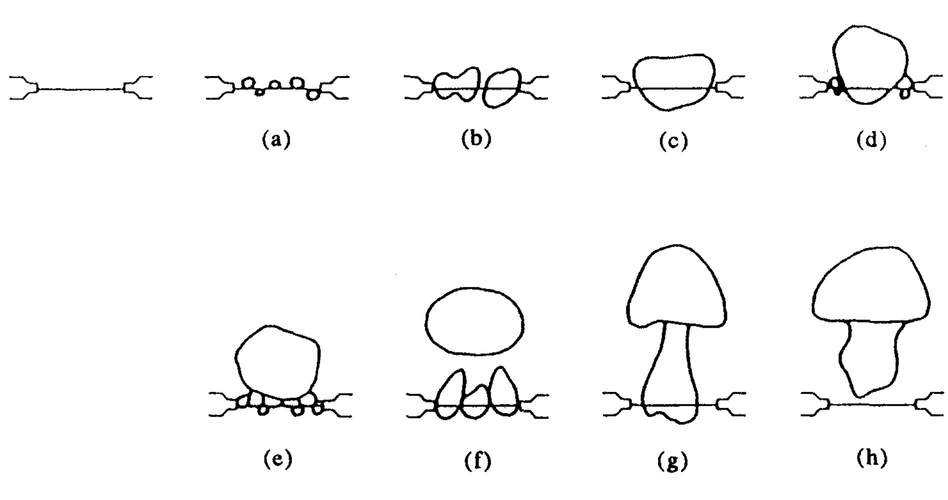


Figure 1. Successive states of the vapor escape configuration near the CHF from a horizontal cylindrical heater of 0.69-mm dia kept at a constant temperature (from Haramura 1989).

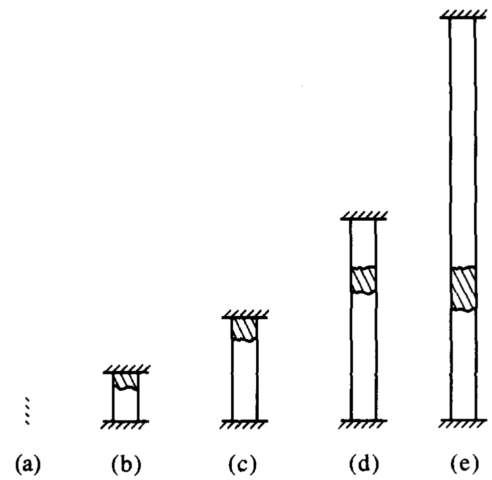


Figure 2. Position of the onset of the CHF: (a) 5 × 5-mm high; (b) 5 × 10-mm high; (c) 5 × 20-mm high; (d) 5 × 40-mm high; (e) 5 × 80-mm high (from Park & Bergles 1988).

The following three studies employed the "quenching method" to measure the boiling curve, including the nucleate and transition boiling regions for inclined surfaces: Dix & Orozco (1990) studied subcooled boiling of R-113 on a spherical surface of 38.4-mm dia, showing that boiling curve, as well as peak heat flux values, change according to the location on the sphere surface (see also section 2.7.2); Guo & El-Genk (1992) measured the CHF for water boiling at 1 atm on an inclined disk heater of 50.8-mm dia; and El-Genk & Guo (1992) then proposed an empirical correlation for the CHF on inclined surfaces.

2.4. *Geometrical Factors Exerting an Influence on the CHF*

Employing the "quenching" method, Egan & Westwater (1985) conducted experiments on boiling on a horizonal disk heater of diameter $D = 6.4$ to 304.8 mm, which closed the open bottom end of a vertical glass tube of the same inside diameter D reserving liquid nitrogen in it, with the purpose of determining the condition obtainable CHF value for a horizontal infinite surface. If $D/\lambda_{Td} > 2.5$, where λ_{Td} is the most dangerous wavelength for Taylor instability, then the measured value of CHF on the disk heater is in agreement with that on an infinite surface.

Elkassabgi & Lienhard (1987) measured the CHF of methanol boiling at 1 atm on a horizontal wire of diameter $D = 0.813$ mm placed in the middle of the two parallel vertical sidewalls (of width W) with an immersion depth H, observing that the CHF decreases as W/D decreases, and that the CHF also decreases with a decrease in H/D if H/D is very small (see also section 2.7.2 for the effect of the clearance between the heater and the side wall). Elkassabgi & Lienhard (1987) explained this variation in the CHF value in terms of the steady-state vapor escape flow, such as that postulated in the hydrodynamic CHF model [see figure 5(a)]. Bockwoldt *et al.* (1992) conducted a similar study for boiling on a horizontal disk heater of 15-mm dia immersed coaxially at the center of a vertical cylindrical pool of slightly subcooled water.

Relating to the cooling problem of microelectronic components, experiments on the CHF in the boiling of dielectric fluorocarbon FC-72 were carried out by Bar-Cohen & McNeil (1992), for horizontal thin heaters, and by Golobic & Bergles (1992), for horizontal, vertically oriented ribbon heater of 15 kinds of materials. These two studies analyzed experimental data, leading to the common conclusion that CHF can be correlated fairly well by the use of a parameter $\delta(\rho c k)^{1/2}$, where δ, ρ, c and k are the thickness, density, specific heat and thermal conductivity of the heater wall, respectively. Meanwhile, Carvalho & Bergles (1992) performed more thorough analyses of data obtained under various conditions, and suggested that, among the various parameters considered, the abovementioned $\delta(\rho c k)^{1/2}$ seems the best to correlate CHF data for different heater materials and thicknesses.

2.5. *The CHF in Very Low Pressure and Microgravity Boiling*

2.5.1. *The CHF in very low pressure boiling*

When the system pressure is reduced noticeably, pool boiling tends to change its features from the ordinary state because of the enormous increase in the specific volume of vapor. This peculiar trend was found by Katto *et al.* (1970) for the CHF of water boiling at $p < 0.2$ atm on a disk heater of 10-mm dia, when observations by high-speed ciné camera disclosed that the fluid behavior on the heater surface near the CHF condition differs from that in ordinary boiling. Subsequently, many experiments of CHF at low pressures were conducted: by Labuntsov (1978), for water and ethanol on a disk heater of 32-mm dia as well as on a horizontal cylindrical heater of 15-mm dia; by Wu *et al.* (1982), for water and methanol on a square surface of 47 × 47 mm; by Sakurai *et al.* (1982), for water on a horizontal wire of 1.2-mm dia and sodium on cylindrical heaters of 7.6- and 10.7-mm dia; by Abuaf & Staub (1983), for R-113 on a horizontal disk heater of 59-mm dia; and by Samokhin & Yagov (1988), for heptane, hexane, acetone, isopropanol and R-113 on a disk heater of 64-mm dia. Recently, Soziev & Khrizolitova (1989) proposed a simple dimensionless equation to predict the CHF q_{cp} at a very low pressure p:

$$q_{cp} = q_{c,k}(1 + p_0/p)^{1/2}. \qquad [1]$$

In [1], $q_{c,k}$ is the CHF value given by the Kutateladze correlation

$$q_{c,k}/\rho_G H_{fG} = 0.16[\sigma g(\rho_L - \rho_G)/\rho_G^2]^{1/4} \qquad [2]$$

and $p_0 = [\sigma g(\rho_L - \rho_G)]^{1/2}$, where ρ_G is the vapor density, H_{fG} is the latent heat of evaporation, σ is the surface tension, g is the gravitational acceleration and ρ_L is the liquid density.

2.5.2. *The CHF in microgravity boiling*

Microgravity boiling is, obviously, a different subject to low pressure boiling. However, consider the situation when gravity is reduced—vapor tends to stay on the heater surface for longer due to the reduction in the buoyancy force; and meanwhile, when pressure is reduced, a similar tendency for vapor appears because of the large volume of vapor generated on the heater surface strongly pushing away the overlying bulk liquid. Therefore, one can expect similar characteristics for these two boiling situations, and this is the reason why the subject of CHF in microgravity boiling is dealt with in this section.

Straub *et al.* (1990) reported the study of the CHF of saturated R-113 boiling on a thin wire of 0.2-mm dia as well as on a flat plate (in horizontal and vertical positions) observed in ballistic flight programs and, also, the study of the CHF of R-12 boiling on thin wires of 0.05- and 0.2-mm dia and on a rectangular plate of 40 × 20 mm observed in parabolic aircraft flights. According to these studies, bubbles as large as 30- to 40-mm dia are observed on the heated flat surface, and the magnitude of the CHF measured in microgravity boiling does not decrease as much as predicted by the ordinary CHF correlation (see [2] where $q_{c,k}$ decreases in proportion to $g^{1/4}$). It is of interest to note that these characteristics of the CHF in microgravity boiling bear a resemblance to those in low pressure boiling.

2.6. *The Problem of the Existence of Two Transition Boiling Curves*

CHF and transition boiling are closely connected, and hence the study of transition boiling is regarded as a part of the study of CHF and vice versa. In particular, the change in the transition boiling curve near the CHF point is nothing but the change in the CHF value.

2.6.1. *Hypothesis of two transition boiling curves*

Sakurai & Shiotsu (1974) conducted experiments on boiling on a horizontal wire (1.3-mm dia and 100-mm long) kept at constant temperature by a computer, obtaining two boiling curves in the transition boiling regime according to the increase/decrease cycle in the wire temperature, with a comparatively slow temperature variation speed: 2 K/s. Then, Witte & Lienhard (1982) reanalyzed the above data, together with the results of the famous experiment of Berenson (1962), to propose the hypothesis that two transition boiling curves exist for a given liquid–heater configuration. They stressed the existence of experimental data to support this hypothesis, and discussed the characteristics of the transition boiling regime on the basis of the concept of an extension of either nucleate boiling or film boiling. Later, in accordance with this hypothesis, comments were presented by Winterton (1983), followed by a reply from Witte & Lienhard (1983).

Ramilison & Lienhard (1987) re-created Berenson's experiment of transition boiling, resulting in the conclusion that the jump between two transition boiling curves was caused by the shift between the advancing and retreating contact angle. Rajab & Winterton (1990) experimented on boiling of saturated water and R-113 at 1 atm on a disk heater of 34-mm dia equipped with a temperature controller of 0.1-s cycle time, testing the two processes of "steady-state heating" and "steady-state cooling". The steady-state heating (or cooling) process here means that the surface was previously at a lower (or higher) temperature, but measurements are made in the steady state. A substantial part of the transition boiling regime was missing in their experiments, suggesting that the temperature control was insufficient to stabilize the surface temperature, but they concluded that the existence of two transition boiling processes was confirmed, because of the result that the abovementioned "steady-state" boiling curves showed a distinct difference between increasing and decreasing temperature.

2.6.2. Steady-state transition boiling in the strict sense

According to Auracher (1990, 1992), it is necessary for the realization of real steady-state boiling in the transition boiling regime to establish the stability of the average surface temperature as well as the temperature uniformity on the surface. Even if a feedback-controlled system for the wall temperature is included, electrically heated boiling systems are apt to cause strong temperature nonuniformity in the heating element. The experiments of Sakurai & Shiotsu (1974) (section 2.6.1) were not exactly in the steady state (a temperature variation of 2 K/s is too fast) with temperature nonuniformity of the heating wire. Auracher (1992) reported the details of his experimental apparatus with a feedback-controlled, electrically heated system carefully designed so as to maintain stable boiling throughout the entire region of transition boiling on a disk heater of 11.3-mm dia; figure 3 shows the boiling curve measured by this apparatus, displaying the agreement between increasing and decreasing temperature. In other words, no hysteresis occurs in transition boiling if steady-state experiments are realized.

Meanwhile, Haramura (1991a) pointed out that a large temperature disturbance is apt to appear on the heater surface even in the so-called steady-state transition boiling, and hence clarification of the condition required to maintain a uniform surface temperature is indispensable in reaching the correct understanding of transition boiling. Haramura carried out a three-dimensional heat conduction analysis for a cylindrical block heated uniformly from the bottom side under a

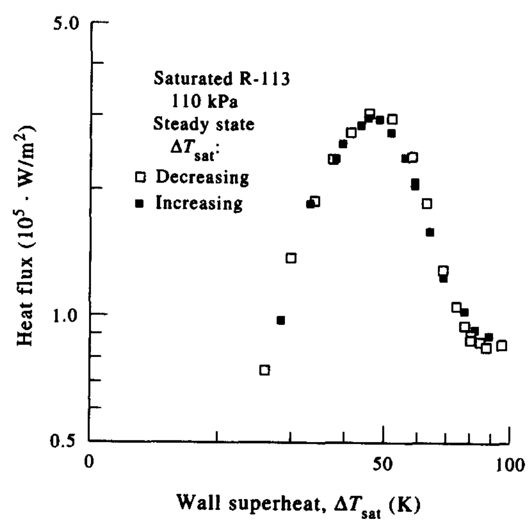


Figure 3. Boiling curve of saturated R-113 measured for a horizontal disk heater of 11.3-mm dia set up in a well-controlled stable boiling system (from Auracher 1992).

disturbed heat transfer condition on the upper boiling surface, leading to the following condition for keeping the surface temperature uniform:

$$-\mathrm{d}q/\mathrm{d}T_w < 3.390(H_0/R_0)(k/R_0), \qquad [3]$$

where $\mathrm{d}q/\mathrm{d}T_w$ is the slope of boiling curve, H_0 is the thickness of the block, R_0 is the radius of the cylindrical block and k is the thermal conductivity of the block material. Meanwhile, Haramura (1991b) carried out experiments on the steady-state transition boiling of R-113 at 1 atm on a disk surface of 63.5-mm dia, equipped with a steam jet nozzle for heating the block and a cooling coil for condensing the steam, specially designed so as to realize the steady-state transition boiling, showing no significant hysteresis between increasing and decreasing temperature.

Shoji *et al.* (1990) experimented on water boiling at 1 atm on a large disk heater of 100-mm dia via the quenching technique. In this case, in spite of a considerably slow temperature variation speed of 5–6 K/min (i.e. 0.083–0.10 K/s), the measured value of the CHF was quite low compared with the ordinary magnitude of the CHF of water at 1 atm, suggesting that steady-state boiling was not attained near the CHF point even in their very slow quenching experiment. Meanwhile, Adiutori (1991) analyzed the literature data regarding the behavior of the heat flowing into and out of the heater surfaces in transition boiling, resulting in the conclusions that: steady-state boiling was not realized in the experiment of Berenson (1962) referred to in section 2.6.1; and that his abovementioned analysis disproves a widely accepted conventional view that the means of condensing vapor as the heat source on the back side of the heater wall can realize stable boiling in the whole region of transition boiling.

2.7. Measurement of the Boiling Curve by the Transient Technique

2.7.1. Characteristics of the CHF measured via the transient technique

Mainly for the purpose of studying the nature of transition boiling influenced by the surface condition, many experiments to date have been performed with the transient technique employing large size heaters (e.g. Bui & Dhir 1985; Roy Chowdhury & Winterton 1985; Liaw & Dhir 1986; Maracy & Winterton 1988; Shoji *et al.* 1990). From the viewpoint of the basic study of CHF, real steady-state transition boiling, such as mentioned in section 2.6.2, is desirable in order to avoid useless confusions of our concept of the CHF phenomenon. However, as many of the studies to date have been performed with the transient technique, it is necessary to know the trend of the CHF measured in these studies. Figure 4 (Liaw & Dhir 1986) shows typical results obtained in this type of study, showing the general characteristics that the CHF in transient cooling (i.e. quenching) is low in magnitude compared with the CHF in transient heating, and that the CHF in transient heating is close to the CHF in steady-state boiling (see section 4.1.1 for the case of internal flow boiling).

2.7.2. Quasi-steady-state boiling curve (supplement: local state of boiling on a sphere)

Westwater and coworkers carried out several experimental studies on the criterion to obtain the quasi-steady-state boiling curve by the quenching method (note that the boiling state, called quasi-steady-state boiling here, is not necessarily the real steady-state boiling). Lin & Westwater (1982) conducted experiments on boiling of liquid nitrogen at 1 atm on disk heaters (50.8-mm dia and 1- to 203-mm thick) made of five different kinds of pure metal. If the condition of $hH_0/k > 0.9$ holds, where h is the heat transfer coefficient at the peak heat flux point of a boiling curve, H_0 is the thickness of the heater and k is the thermal conductivity of the heater material, then the quasi-steady-state boiling curve is obtained by this quenching method. Irving & Westwater (1986) conducted experiments for the boiling of liquid nitrogen at 1 atm on heated spheres (6.35- to 101.6-mm dia) made of five different kinds of pure metal. Significant effects are exerted on the shape of the boiling curve by the clearance between the sphere and the liquid container wall, by the diameter of the sphere and by the kind of metal. In addition to this, there is an azimuthal angle variation of heat flux over the sphere surface; and the highest heat flux value attained at each azimuthal angle varies with the angle and metal. Roughly speaking, the angle which gives a peak heat flux value closer to the ordinary CHF value for horizontal flat plates is in the upper half of the sphere. Westwater *et al.* (1986) summarized the foregoing two studies, indicating the conditions which must be satisfied to obtain the quasi-steady-state boiling curve. Namely, the conditions in the case of a disk heater are: heater

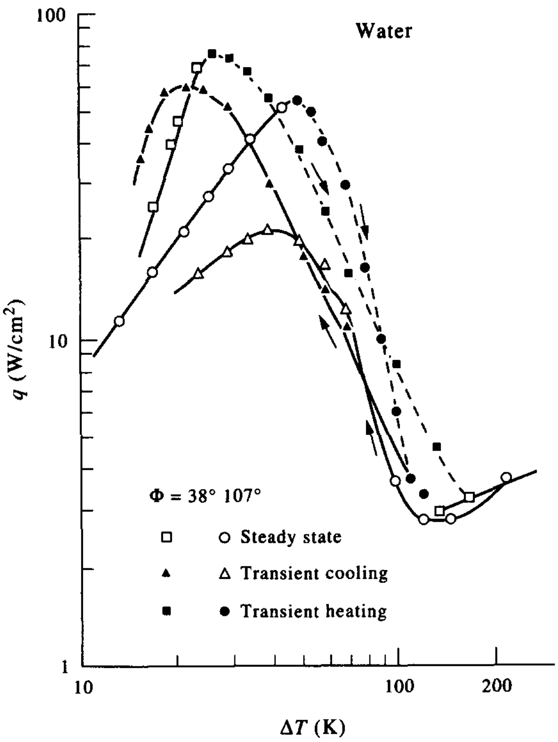


Figure 4. Boiling curve of saturated water on a vertical surface (63-mm wide × 103-mm high) at contact angles of 38° and 107° (from Liaw & Dhir 1986).

diameter $> 7\lambda_{Td}$ (cf. section 2.4 for λ_{Td}); heater thickness $hH_0/k > 0.9$; diameter of the liquid container = heater diameter; and immersion depth ≈ 100 to 150 mm. In the case of a sphere: diameter $> 4.5\lambda_{Td}$; diameter of the liquid container $>(3.5 \times$ sphere diameter); and immersion depth ≈ 100 to 150 mm.

Regarding the complicated problem of the variation of the local heat flux as well as the local temperature over a spherical (or a cylindrical) heater surface of large diameter, Subramanian & Witte (1987) studied the boiling of methanol and water at 1 atm on a hollow sphere of 25.4-mm dia via the quenching method. The sphere was split into nine azimuthal rings for a finite-difference calculation of the local heat flux. According to observations by a high-speed ciné camera, the collapse of film boiling starts from the bottom of the sphere and, thereafter, three regimes of boiling coexist on the sphere surface: i.e. nucleate boiling at the bottom, film boiling at the top and oscillating transition boiling in the middle region.

2.8. *Surface Effects on the CHF*

Liaw & Dhir (1986) conducted experiments on the boiling of saturated water and R-113 at 1 atm on a vertical rectangular surface (63-mm wide and 103-mm high) with various contact angles. They reported experimental results obtained not only in transient modes but also in the steady-state mode, such as those shown in figure 4, from which the conclusion can be derived that the CHF under the "steady-state" condition is certainly higher at a contact angle of 38° (comparatively well-wetted surface) than at a contact angle of 107° (poorly-wetted surface).

Alem Rajabi & Winterton (1988) conducted experiments on the steady-state boiling of methanol on a disk heater of 28-mm dia equipped with a temperature controller. Similarly to the experiment of Rajab & Winterton (1990), cited in section 2.6.1, a greater part of the transition boiling regime near the CHF point could not be realized, but the CHF condition measured as an upper limit of nucleate boiling was uninfluenced by this unstable situation in the transition boiling regime. In this study, the state of the liquid–solid contact was observed at the center of the disk heater surface by means of the electrical impedance between a test probe and the heater surface. The fraction of the wetted area at the CHF condition [determined through a one-point measurement similar to that of Shoji (1992) mentioned in section 2.10.2] was found to be about 0.65; and Alem Rajabi &

Winterton regarded this value as comparable with the magnitude of $1-\pi/16$ ($=0.80$), i.e. the base area fraction of the steady-state vapor escape passage [see figure 5(a)] assumed by Zuber (1959) in his hydrodynamic instability model of CHF.

Wang & Dhir (1993) conducted experiments on saturated water boiling at 1 atm on a vertical rectangular surface (63-mm wide and 103-mm high) via the quenching method with extremely slow temperature variation speeds, <0.2 K/min (i.e. 0.003 K/s), which they regarded as practically steady-state conditions. The CHF value for a well-wetted surface (contact angle of 18°) is tolerably close to the ordinary CHF value of water at 1 atm [cf. Shoji *et al.* (1990) mentioned in section 2.6.2]. A square surface area of 10×10 mm in the lower middle portion of the heater surface was observed, by means of still photographs taken by extinguishing the vapor near the heater surface through the tentative introduction of subcooling, reporting the quantitative relationship between active nucleation site density and heat flux in nucleate boiling for three different contact angles of 18°, 35° and 90°.

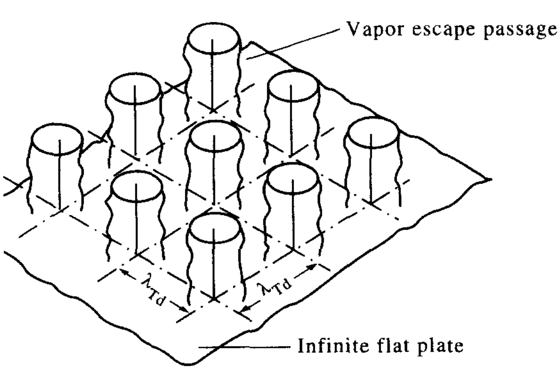
It is added here that a number of studies have been conducted via the "quenching method": for the problem of liquid–solid contact, see the papers by Lee *et al.* (1985), Dhuga & Winterton (1985, 1986) and Shoji *et al.* (1991); and for the effect of roughness and contact angle on heat transfer, see the paper by Roy Chowdhury & Winterton (1985).

2.9. *Models of the CHF and Transition Boiling*

2.9.1. *Primary models of the CHF*

CHF is a very complicated phenomenon, and it is impossible to give an exact model capable of explaining the detailed mechanism of CHF completely. However, there are models which are useful to explain the CHF phenomenon, even though some imperfections are involved, and their role is regarded as similar to that of the famous Bore's atomic model that was very effective prior to the establishment of quantum mechanics. In concrete terms, two such primary models of CHF have been put forward in the last decade: i.e. the hydrodynamic instability model [figure 5(a)] and the macrolayer dryout model [figure 5(b)].

The hydrodynamic model [including the "mechanical energy stability criterion" proposed by Lienhard & Eichhorn (1976)] postulates that the increase in vapor generation from the heater surface causes a limit of the steady-state vapor escape flow, such as shown in figure 5(a), when CHF occurs. Generally, this model notices the stability of the vapor escape flow only, paying no attention to the near-wall fluid behaviors. Meanwhile, the macrolayer dryout model postulates that a liquid sublayer (macrolayer) formed on the heater surface with an initial thickness δ_0 is evaporated away during a hovering period τ_v of the overlying vapor mass (under the balance of simultaneous growth and upward motion), when the CHF appears. This model has a freedom and flexibility which makes it applicable to CHF under various flow configurations.



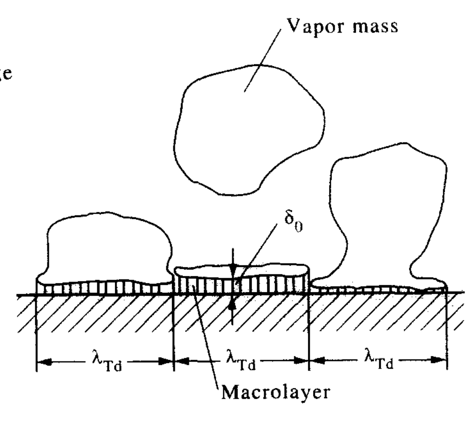


Figure 5. Vapor escape configuration from an infinite horizontal surface: (a) the hydrodynamic instability model; (b) the macrolayer dryout model (see sections 2.4 and 2.10.2 for λ_{Td} and δ_0, respectively).

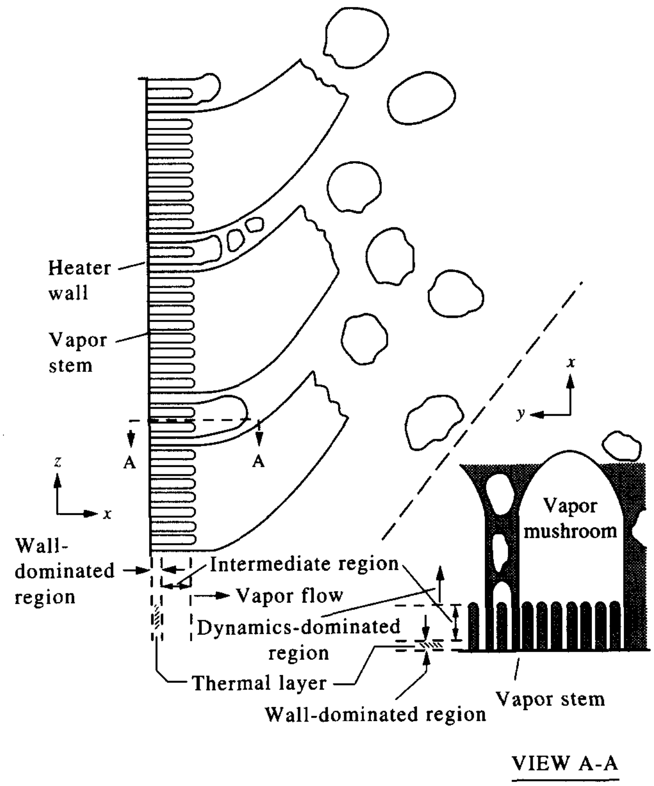


Figure 6. Conceptualization of the boiling process on a vertical surface for a contact angle of 90° (from Liaw & Dhir 1989).

Recently, Bergles (1992) reviewed these two models along with a somewhat classical "bubble packing" model, stating that the steady-state vapor escape flow from the heater surface is not necessarily in agreement with visual observations (also Bergles 1988) and that the hydrodynamic model is experiencing a challenge from the macrolayer dryout model. On the other hand, Lienhard (1985, 1988a) and Dhir (1990, 1992) criticized the Haramura & Katto (1983) model, related to the macrolayer dryout model.

2.9.2. *Steady-state model of the CHF considering surface wettability*

In order to consider the effect of surface wettability on the CHF, Dhir & Liaw (1989) postulated the existence of a thermal boundary layer adjacent to the heater surface throughout the nucleate and transition boiling regimes (see figure 6 for their flow model) and assumed that, depending on the contact angle and surface temperature, the vapor stems standing on the heated surface undergo changes in the shape of interface, the base diameter at the wall D_w and the spacing L. The steady-state heat transmission and evaporation assumed within the thermal boundary layer is then analyzed by connecting the analytical wall void fraction, $\varepsilon_w = (\pi/4)(D_w/L)^2$, with the measured ε_w [by Liaw & Dhir (1989) as mentioned in section 2.2], and a theoretical boiling curve including the CHF point is derived. Then it is insisted that if the CHF value q_{cs} of this model (i.e. the CHF dominated by the vapor generation rate) is higher than the CHF value q_c of the hydrodynamic model (i.e. the CHF dominated by the vapor escape rate), then q_c appears as the CHF and, if $q_{cs} < q_c$, then q_{cs} appears as the CHF. [N.B. This model seems to have two questionable points: (1) it is unable to indicate the steady-state liquid (or vapor) flow passages between the bulk liquid region and the thermal layer at contact angles < (or >) 90°; and (2) there have been no examples of a boiling curve with a flat summit portion restricted by q_c for sufficiently wettable surfaces.]

Meanwhile, with respect to the effect of contact angle and roughness on the CHF, Ramilison *et al.* (1992) analyzed the existing CHF data to derive the following empirical equation:

$$q_{cs}/q_{c,z} = 0.0336(\pi - \beta_r)^{3.0}(r_s)^{0.125}, \qquad [4]$$

where $q_{c,z}$ is the CHF value predicted by the Zuber correlation (the hydrodynamic model), β_r is the retreating contact angle (cf. section 2.5.1) and r_s is the RMS surface roughness.

2.9.3. Modeling of the CHF and transition boiling based on the macrolayer concept, including the effect of surface wettability

Pan and coworkers have conducted a series of analytical studies on transition boiling including CHF based on the macrolayer concept. First, Pan *et al.* (1989) developed a theoretical model of transition boiling based on the repetition of the following sequential processes: (1) transient heat conduction in the bulk liquid brought into contact with the heater surface; (2) boiling incipience on the heater surface; (3) generation of a macrolayer on the heater surface and its evaporation; and (4) blanketing of the heater surface by a vapor mass.

Then, Pan & Lin (1990) extended the above model to take the effect of the surface wettability into consideration by assuming the area fraction of the vapor stems, A_v/A_w, included in the Haramura & Katto (1983) model (see [5] in section 2.10.2), to be a function of the contact angle. Subsequently, based on the earlier theoretical model of Pan *et al.* (1989), Pan & Lin (1991) analyzed the effects of various parameters on transition boiling, such as the cavity size distribution, the thickness of the surface coating, the thermal properties of the heater substrate, the system pressure and the liquid subcooling. In addition, Pan & Ma (1992) reported modeling for transition boiling under "external flow boiling" based on the macrolayer concept.

2.10. Studies Relating to the Macrolayer

2.10.1. Analyses of nucleate boiling heat transfer at high heat flux based on the macrolayer

Analyses of "heat transfer" in nucleate boiling at high heat flux (fully-developed nucleate boiling) have been conducted based on the macrolayer concept. Bhat *et al.* (1983b) attempted an analysis of heat transfer assuming a macrolayer of invariable thickness, leading to the result that heat conduction across the macrolayer occupies the major portion of heat transfer. Chu (1987, 1989) analyzed heat transfer, assuming variation of the macrolayer thickness with time, and stressed that the heat conduction across the macrolayer and the evaporation at the free surface are not enough to account for nucleate boiling heat transfer, and that the evaporation of the "microlayer" (which is not part of the macrolayer) formed at the base area of the vapor stems must be taken into account. Jairajpuri & Saini (1991) proposed a heat transfer model based on the transient one-dimensional heat conduction across a macrolayer changing its thickness on a constant heat flux wall allowing for timewise variation of the wall superheat.

On the other hand, Pan & Lin (1989) developed theoretical and semi-theoretical models of nucleate boiling heat transfer, which incorporate the heat transmission created by the Marangoni flow in the macrolayer and the evaporation at the stem–liquid and vapor–liquid interfaces, stressing the importance of the abovementioned involved mechanism.

Rajendra Prasad *et al.* (1985) attempted an analysis of heat transfer, taking the effect of the heater wall thickness into consideration but neglecting the variation of the macrolayer thickness caused by evaporation. Meanwhile, Pasamehmetoglu *et al.* (1993) performed a study, where a couple of transient two-dimensional heat conduction equations for the heater wall and macrolayer have been solved allowing for the timewise thinning of the macrolayer, leading to the results that dominant evaporation occurs near the liquid–vapor–solid contact point (a triple point in a broad sense) at the base of the vapor stem, while the evaporation at both the circumferential interface of the vapor stem and at the vapor–macrolayer interface is negligible (except near the CHF).

2.10.2. Experimental studies of the macrolayer in nucleate boiling at high heat flux

For water boiling at 1 atm on a disk heater of 42-mm dia, Bhat *et al.* (1986) measured the initial thickness δ_0 of the macrolayer formed between the heater surface and an overlying vapor mass via an electrical resistance probe at the center of the heater, giving an empirical correlation of $\delta_0 = 1.585 \times 10^5/q^{1.527}$, where δ_0 is in m and q is in W/m^2.

Rajvanshi *et al.* (1992) measured δ_0 for the boiling of water, methanol, ethanol, isopropanol, acetone and methy ethyl ketone, respectively, at 1 atm on a disk heater of 50-mm dia in a similar manner to that of Bhat *et al.* (1986), finding that these data agree, within an error $< \pm 20\%$ for every kind of fluid, with the double of the magnitude given by the RHS of the following generalized correlation used in the Haramura & Katto (1983) model:

$$\delta_0 = (\pi/2)\sigma\,[(\rho_L + \rho_G)/\rho_L\rho_G](A_v/A_w)^2(\rho_G H_{fG}/q)^2, \quad [5]$$

where A_v/A_w is the base area fraction of the tiny vapor stems standing on the heated surface [see figure 5(b)], given as

$$A_v/A_w = 0.0584(\rho_G/\rho_L)^{0.2}. \quad [6]$$

The double of [5] is equivalent to the use of the following A_v/A_w on the RHS of [5]:

$$A_v/A_w = 0.0584 \times 2^{1/2}(\rho_G/\rho_L)^{0.2} = 0.0826(\rho_G/\rho_L)^{0.2}. \quad [7]$$

Meanwhile, Shoji (1992) experimented on water boiling at 1 atm on a disk heater of 10-mm dia, measuring the departure frequency of the vapor mass, the distribution of the void fraction, the initial thickness of the macrolayer and the dry area fraction in the macrolayer. According to his data, the macrolayer thickness is correlated as $\delta_0 = 1.77 \times 10^4/q^{1.38}$, and the dry area fraction as $A_v/A_w \cong 0.17$ independent of q. [N.B. This value of $A_v/A_w \cong 0.17$ is determined from a one point measurement at the disk center by assuming the random occurrence of nucleation on the heater surface, though it is not necessarily consistent with the stationary state of active sites observed by Gaertner & Westwater (1960) by means of nickel plating during boiling.]

2.10.3. Analytical studies on the formation of the macrolayer

Bhat *et al.* (1983a) presented a model as to the formation of the macrolayer, assuming that the diameter of the vapor stems increases in the upward direction due to the vertical coalescence of bubbles successively emitted from the active site, and that the macrolayer is formed due to lateral coalescence of the vapor stems at the top position. Based on this model, the magnitude of δ_0 was derived theoretically, employing several existing empirical rules including those holding in "low" heat flux region alone.

Chappidi *et al.* (1991) attempted a semi-theoretical study on the proportionality between the mean macrolayer thickness and the mean vapor-stem diameter, considering the Helmholtz instability at the interface of the vapor stems. Meanwhile, Sadasivan *et al.* (1992) reviewed critically four possible mechanisms to determine the macrolayer thickness: (1) the Helmholtz critical wavelength [the Haramura & Katto (1983) model]; (2) vapor-stem coalescence at the top position [the Bhat *et al.* (1983a) model]; (3) the lateral coalescence of bubbles on the heater surface; and (4) stem vapor velocity interrupting the resupply of liquid to the macrolayer. Among these mechanisms, (1) and (2) were rated extremely low, while (3) was rated high because of the ability to take into account the effect of the surface condition on the macrolayer "thickness". [N.B. Pan & Lin (1990) in section 2.9.3. considered "area fraction" instead of "thickness".]

Based on the idea of the lateral coalescence of bubbles on the heater surface, Kumada & Sakashita (1992) conducted a semi-empirical analysis of the initial thickness δ_0 of the microlayer which resulted in the following involved expression:

$$\delta_0 = 6.9\{(\alpha_L^{15}\nu_L^{7}\sigma^{9})/[g^{5}(\rho_L - \rho_G)^5\rho_L^{4}]\}^{1/36}(\rho_G H_{fG}/q)^{5/6}, \quad [8]$$

where α_L is the thermal diffusivity of the liquid and ν_L is the kinematic viscosity of the liquid. Equation [8] is involved with g, which is inconsistent with the insensitive situation described in section 2.1.

2.11. The CHF in the Power Transient

Giarratano (1984) studied the "heat transfer" of liquid nitrogen boiling at 0.083 MPa on a horizontal platinum wire of 0.02547-mm dia and a thin platinum film (35 nm × 8 mm × 35 mm) supplied with a voltage pulse of various durations (1 ms–10 s). Okuyama *et al.* (1988) conducted experiments on the boiling of R-113 (0.1–1.8 MPa, subcooling 30 K) on a copper foil (7 μm × 4 mm × 14 mm) at large stepwise power generation, observing the bubble behaviors by high-speed ciné camera to disclose that the CHF at low pressures can be explained by the macrolayer dryout, while the CHF at high pressures occurs due to the filling of fine bubbles on the heater surface. Subsequently, Okuyama & Iida (1990) performed a similar study for liquid nitrogen boiling at 0.1 MPa on a horizontal wire of 0.1-mm dia at stepwise heat generation.

Pavlov & Babich (1987) studied a model of CHF in the power transient including three types of heat increase: stepwise, linear and exponential. In this analysis, the two-phase region adjacent to the surface is divided into two regions: the outer region, with a void fraction ε_0; and the wall-adjacent layer, with a void fraction of different magnitude ε. The thickness of the wall-adjacent layer δ is assumed to be equal to the largest diameter of bubbles growing on the heating surface, and if this wall-adjacent layer is vaporized away, then CHF occurs.

Pasamehmetoglu *et al.* (1990a) presented a model based on the macrolayer concept for predicting the CHF in saturated and subcooled boiling at exponentially increasing heat input:

$$Q = Q_0 \cdot \exp(t/\tau_e), \qquad [9]$$

where t is the elapsing time and τ_e is the exponential heat input period (constant). Their model has been established through various careful considerations, some of which are (1) a modification of the original $A_v/A_w = 0.0584(\rho_G/\rho_L)^{0.2}$ in the Haramura & Katto (1983) model [6] to

$$A_v/A_w = C_A(\rho_G/\rho_L)^{0.2}, \qquad [10]$$

where C_A is an empirical constant determined so as to agree with the data of Bhat *et al.* (1986) for water at 1 atm (cf. [7]); (2) a change in the hovering or growth period of a vapor mass due to subcooling; (3) 2 mechanisms governing the thinning of the macrolayer for a slow and a fast transient, i.e. at a slow transient, the macrolayer thins down by evaporation only, while at fast transient, a part of the macrolayer thinning depends on a decrease in the thickness of the stable macrolayer caused by an increase in the heat flux (cf. [5]); and (4) the effect of the heater's thermal storage on the CHF. The predicted CHF value compared well with the data measured by Sakurai & Shiotsu (1977) (saturated water at 1.08 and 2.06 MPa on a horizontal wire of 1.2-mm dia and $\tau_e = 0.005$ to 5 s), Kuroda (Serizawa 1983) (subcooled water at 0.933 MPa on a horizontal wire of 1.2-mm dia and $\tau_e = 0.005$ to 10 s) and Kataoka *et al.* (1983) (saturated water at 0.143–1.503 MPa on a vertical wire and $\tau_e = 0.005$ to 10 s).

3. THE CHF IN EXTERNAL FLOW BOILING

3.1. The CHF in Bulk Liquid Flow Parallel to the Heater Surface

Fully developed nucleate boiling on a small size heater surface flush-mounted on one side wall in a rectangular duct is included in this section, because it is easy to understand the physical aspects involved rather than the treatment as forced "internal flow boiling".

3.1.1. Experimental studies on the CHF

Yagov & Puzin (1984) experimented on the CHF in the boiling of R-12 at 0.84–2.54 MPa with slight subcooling of 0.5–2.5 K on a disk heater surface (D = 16 mm) flush with the lower side wall of a rectangular horizontal duct (17 × 29 and 5 × 20 mm) at a bulk liquid velocity $u = 0.5$ to 12.5 m/s. It was reported that the measured data of the CHF q_c are in good agreement with the following generalized correlation:

$$q_c/\rho_L u H_{fG} = 0.66(\rho_G/\rho_L)^{0.605}(\sigma/\rho_L u^2 D)^{0.415}, \qquad [11]$$

where H_{fG} is the latent heat of evaporation and σ is the surface tension.

Mudawar & Maddox (1989) experimented on the CHF in the boiling of dielectric fluorocarbon FC-72 (subcooling of 2.5–44 K) at near 1 atm on a square heater (12.7 × 12.7 mm) flush with one side wall of a vertical rectangular duct (12.7 × 38.1 mm) for bulk liquid velocity u = 0.22 to 4.1 m/s. At low flow velocities, the formation of a continuous vapor blanket and the dryout of the macrolayer beneath the vapor blanket were observed; while at high flow velocities, not only reduction of the vapor blanket thickness but also the blanketing of the heater surface by much smaller and discrete vapor clots were found. Mudawar & Maddox developed a new model for the CHF in the region of low velocities ($10^2 < \rho_L u^2 L/\sigma < 8 \times 10^3$, where L is the heater length), presenting a generalized correlation of the CHF composed of several dimensionless terms including

$(L/D_h)^{1/23}$, where D_h is the hydraulic diameter of the flow channel based on the heater perimeter. The small magnitude, 1/23, of the foregoing exponent suggests that the effect of the flow channel on the CHF is minor in the present case.

McGills *et al.* (1991) carried out experiments on the boiling of R-113 (subcooling of 7–33 K) at near 1 atm on a linear array of ten discrete square heaters (6.4 × 6.4 mm) mounted at intervals of 6.4 mm on one side wall of a vertical rectangular duct (1.9–6.4 × 12.7 mm) for inlet liquid velocity $u = 0.096$ to 1.039 m/s with the object of studying the combined effect of subcooling and velocity on the CHF. Tests were carried out for a flush and a 0.8-mm protruding heater, respectively, revealing that for a given subcooling and velocity, the CHF is significantly higher for the flush heater relative to the 0.8-mm protruding heater. Meanwhile, Willingham & Mudawar (1992) experimented on the boiling of FC-72 (subcooling of 3–36 K) at near 1 atm on a linear array of nine discrete square heaters (10 × 10 mm) flush-mounted on one side wall of a vertical rectangular duct (5 × 20 mm) for inlet liquid velocity $u = 0.13$ to 4 m/s, yielding various information relating to boiling and the CHF. The CHF for a heater at the foremost position agrees well with the foregoing Mudawar & Maddox (1989) correlation for a single heater.

Galloway & Mudawar (1992) experimented on FC-72 boiling on a rectangular heater (2.7-mm high and 12.7- to 50.8-mm long) flush-mounted on the inner wall of a cylindrical vessel (inner radius: 41.9 and 76.2 mm) equipped with a rotating central axis with two or four blades to stir the liquid. Considering the effects of the inner radius of the vessel, the number of stirrer blades and the heater length, they developed an empirical correlation in a generalized form.

3.1.2. Studies on the mechanism of the CHF

Galloway & Mudawar (1993a) carried out microscopic and macroscopic observations of the near-wall region for the boiling of dielectric fluorocarbon FC-87 at 1.37 atm and 8 K subcooling on a rectangular heater (1.6-mm wide and 12.7-mm long) flush-mounted on a vertical rectangular duct (1.6 × 6.4 mm). Visual observations were made by a 16 mm high-speed ciné camera for high flow velocity and by a video motion analyzer for velocities <2 m/s. It was concluded that the CHF was approached when the heat flux reached a sufficiently high level to cause coalescence of vapor bubbles into a wavy vapor layer, that vapor effusion into the vapor waves was caused by violent boiling and evaporation from the liquid subfilm and that the CHF was triggered by the separation of the liquid–vapor interface from the heater surface at the location of the upstream wetting front due to intense vapor effusion from the heater surface. Based on the foregoing observation, Galloway & Mudawar (1993b) developed a new theoretical CHF model incorporating: (1) the instability of the liquid–vapor interface; (2) the separated two-phase flow model; and (3) the criterion for the separation of the liquid–vapor interface from the heater surface. [N.B. Item (3) may give rise to the logical problem of whether or not the intense vapor effusion is possible from the dry heater surface.]

3.2. The CHF on a Cylinder in Crossflow

3.2.1. The CHF on a cylinder of comparatively small diameter in crossflow

Katto *et al.* (1987) performed experiments on the CHF on a cylinder of 1-mm dia in a crossflow of water, R-133 and R-12, respectively, in a very wide range of the vapor/liquid density ratio $\rho_v/\rho_L = 0.000624$ to 0.306. Analyzing the CHF data thus obtained for saturated boiling, together with other existing data for cylinders of $D = 0.81$ to 6.5 mm, they developed a semi-empirical generalized correlation based on the upper limit of the macrolayer thickness [5] to predict the CHF q_c at a sufficiently high liquid velocity u:

$$q_c/\rho_L u H_{fG} = K(\sigma/\rho_L u^2 D)^m \quad (10^{-5} < \sigma/\rho_L u^2 D < 10^{-1}), \tag{12}$$

where $K = 0.00588 + 0.500(\rho_G/\rho_L)^{1.11}$ and $m = 0.42(\rho_G/\rho_L)^{0.00428}$.

According to Lienhard (1988a), Lienhard and his coworkers have conducted detailed studies of the CHF on a cylinder in crossflow, deriving semi-empirical correlations. Considering the case of d.c. heating and high velocity, they obtained a generalized correlation of the following somewhat complicated form (based on the mechanical energy stability criterion):

$$\Phi = f(\eta, \mathrm{We}_G, \varphi), \qquad [13]$$

where $\varphi = \pi q_c/\rho_G u H_{fG}$, $\eta = 0.077(\rho_G/\rho_L)^{-0.314}\ \mathrm{We}_G^{-0.12}$ and $\mathrm{We}_G = \rho_G u^2 D/\sigma$.

Meanwhile, with the object of studying the effect of surface wettability, Sadasivan & Lienhard (1991) experimented on the boiling of acetone, isopropanol, methanol and water at 1 atm on cylinders of 0.3- to 2.41-mm dia. Their data for the CHF q_{cs} were correlated by the following dimensionless equation:

$$\pi q_{cs}/\rho_G u H_{fG} = 1.8 \times 10^{-6}(\rho_L/\rho_G)^{2.1}(\sigma/\rho_G u^2 D)^{1/3}(\pi - \beta_r)\mathrm{C}, \qquad [14]$$

where β_r is the retreating contact angle (see sections 2.6.1 and 2.9.2) and $\mathrm{C} = (1900\rho_G/\rho_L)^{0.625}$. It is quite impressive to read the following description in Sadasivan & Lienhard (1991): "... the observations indicate that the far-wake vapor sheet and bubble breakoff play only a minimal role, if any, in determining CHF. Visual observations also indicate that the vapor sheet is intact after CHF occurs. It appears that burnout is dictated by near-surface effects." This may perhaps be a denial of the mechanical energy stability criterion (see section 2.9.1).

Jensen & Pourdashti (1986) conducted an experimental study of the CHF in the boiling of R-113 at 0.207–0.414 MPa on a horizontal cylinder of 6.35-mm dia in upward crossflow at low velocity $u = 0.070$ to 0.298 m/s and quality $x = 0$ to $+0.3$. Correlating the measured data along with some other data, they gave the following empirical equation:

$$q_c/q_{c,kh} = 1 - 0.025(\rho_L/\rho_G)^{0.615}(u')^{-0.798}x, \qquad [15]$$

where $q_{c,kh}$ is the CHF value given by the Katto & Haramura (1983) analysis for the low upward velocity regime based on the macrolayer dryout model and $u' = u/[\sigma g(\rho_L - \rho_G)/\rho_G^2]^{1/4}$.

3.2.2. *The CHF on a cylinder in crossflow under other conditions*

Meyer *et al.* (1986) conducted an experimental study of the CHF in the crossflow boiling of R-11 and R-113 (subcooling of 1–16 K) on a horizontal cylinder of large diameter $D = 25.4$ mm placed perpendicularly to a horizontal uniform flow at velocity $u = 0.04$ to 1.2 m/s, showing the features of the CHF affected by subcooling and liquid velocity. Furthermore, under similar conditions, Meyer *et al.* (1990) experimented on the CHF for binary mixtures of R-11 and R-113, showing the characteristics of the CHF affected by the mole fraction of the components.

Yao & Hwang (1989) experimented on the CHF in the crossflow boiling of R-113 on a single heated tube of 19.1-mm dia placed at the center of the 13th row from the bottom in an unheated horizontal tube bundle (3 columns × 6 rows) under low velocity ($u = 0$ to 0.25 m/s) and low quality ($x = 0$ to $+0.143$) upward crossflow conditions. The abovementioned tube bundle was housed in a vertical channel of rectangular cross section (61.5 × 85.7 mm). Meanwhile Leroux & Jensen (1992) carried out a similar experiment under the following wide range of conditions: mass flux (50–500 kg/m^2 s), pressure (0.15–0.5 MPa), local quality (0 to +0.7) and test geometry (staggered and in-line bundle of 5 columns × 27 rows with a heated tube of 7.94-mm dia at the center of the 25th row from the bottom). Disclosing that the CHF-quality curve changes its characteristics at low, intermediate and high mass flux, respectively.

3.3. *The CHF on a Heater Cooled by an Impinging Jet*

3.3.1. *The CHF on a disk heater cooled by a circular jet*

Sharan & Lienhard (1985) analyzed the existing data for the CHF on a disk heater of diameter D with a jet of saturated liquid impinging at the disk center, giving the following correlation based on the mechanical energy stability criterion for the efflux velocity u from a nozzle of diameter d_N:

$$(q_c/\rho_G u H_{fG})(D/d_N)^{1/3} = f_2(r)(1000/\mathrm{We})^{A(r)}, \qquad [16]$$

where $f_2(r) = 0.00171r + 0.21$, $A(r) = 0.486 + 0.06052(\ln r) - 0.0378(\ln r)^2 + 0.00362(\ln r)^3$, r is the liquid/vapor density ratio ρ_L/ρ_G and $\mathrm{We} = \rho_L u^2 D/\sigma$.

Monde & Okuma (1985) studied experimentally the CHF on a disk heater ($D = 40$ and 60 mm) with an impinging jet of saturated R-113 flowing out of a nozzle ($d_N = 0.7$ to 4.13 mm) under the limiting condition of very low jet velocity u and very high magnitude of D/d_N. At the same time, Monde (1985) studied the generalized correlation of the existing data of the CHF on a disk heater with an impinging jet based on the upper limit of macrolayer thickness [5]. Then Monde (1987) performed experiments on the CHF on a disk heater employing saturated R-12 at comparatively high pressure, 0.6–2.8 MPa, and analyzed the data to give a generalized correlation consisting of three characteristic regimes—the V-, I- and HP-regime—though no general principle was given to predict the boundaries between each regime. Subsequently, based on a macrolayer model similarly to that used by Monde, almost all the existing data ($D/d_N = 3.9$ to 53.9 and $\rho_G/\rho_L = 0.000624$ to 0.189) were analyzed by Katto & Yokoya (1988) to give the following correlation in the form of a single equation (cf. [12] in section 3.2.1):

$$q_c/\rho_L u H_{fG} = K\{\sigma/[\rho_L u^2(D - d_N)(1 + D/d_N]\}^m, \qquad [17]$$

where $K = 0.0166 + 7.00(\rho_G/\rho_L)^{1.12}$ and m is given as $m = 0.374(\rho_G/\rho_L)^{0.0155}$, for $\rho_G/\rho_L \leqslant 0.00403$; and $m = 0.532(\rho_G/\rho_L)^{0.0795}$, for $\rho_G/\rho_L \geqslant 0.00403$.

Kandula (1990) postulated that the CHF process in the disk–jet system was governed by the relative velocity between the radially flowing liquid film and the upwardly moving vapor from the heater surface due to bubble generation, presenting the following CHF model consisting of two characteristic regions: in the first region, where the liquid film velocity is of the same order as the vapor velocity, the CHF is governed by the mechanical energy stability criterion (i.e. surface tension-controlled CHF); while in the second region, where the liquid film velocity is far in excess of the vapor velocity, the CHF is governed by the separation of the liquid film flow (i.e. liquid viscosity-controlled CHF).

3.3.2. The CHF in miscellaneous jet systems

Monde & Inoue (1991) experimented on the CHF of water of 1 atm on a disk heater ($D = 40$ and 60 mm) cooled by two, three or four circular jets ($d_N = 0.7$ to 4.13 mm), and attempted to correlate the CHF data by using the maximum straight-line distance measured from the position of jet impingement to the outer boundary of the disk heater.

Maceika & Skema (1990) conducted an experimental study on the CHF on a heater placed in the interaction zone of a circular jet submerged in a liquid pool (immersion depth = 200 mm) employing subcooled water at pressures <0.2 MPa.

Mudawar & Wadsworth (1991) performed a study on the CHF of dielectric fluorocarbon FC-72 boiling (subcooling of 0–40 K) in a system consisting of a square heating element (12.7 × 12.7 mm) and an opposite square flat wall with a perpendicularly-bored rectangular nozzle (0.127- to 0.508-mm wide) along the centerline of the wall (the height of a channel between the two parallel square walls: $H_c = 0.508$ to 5.08 mm). At medium nozzle exit velocities $u = 1.5$ to 7 m/s, a weak dependence of the CHF on the channel height H_c was observed; while at high velocity $u > 7$ m/s, a strong effect of H_c on the CHF was found. For the case of medium velocity, an empirical generalized correlation of the CHF was presented.

3.4. *The CHF in Liquid Film Flow Driven by Gravity or Centrifugal Force*

3.4.1. The CHF in liquid film flow on inclined and vertical surfaces

Baines *et al.* (1984) conducted experiments on the CHF for a falling film flow of saturated water and R-113 at 1 atm on a rectangular heater surface (66-mm wide and 114-mm long), inclined 45° or 80° to the horizontal. They developed a CHF model incorporating the assumptions that: (1) the liquid film flow separates at a small angle from the leading edge leaving a subfilm (macrolayer) on the surface; (2) liquid droplets ejected from the separated film return to the surface, replenishing the subfilm; and (3) as the heat flux is increased, the separation angle increases, throwing the ejected droplets further downstream from the surface to cause the CHF. Their analysis resulted in the following relationship:

$$q_c/\rho_G u H_{fG} \propto (\rho_L/\rho_G)^{2/3}(\sigma/\rho_L u^2 L)^{1/3}, \qquad [18]$$

where u is the film average velocity and L is the heater length. This relationship is quite similar to

$$q_c/\rho_G u H_{fG} = 0.0164(\rho_L/\rho_G)^{0.867}(\sigma/\rho_L u^2 L)^{1/3}, \qquad [19]$$

which was derived empirically by Katto & Ishii (1978) for the CHF on a rectangular heater surface fed with saturated liquid through a rectangular nozzle. However, it must be noted that Katto & Ishii's experiments were conducted with a downward-facing heater surface to avoid the effect of the returning droplets on the CHF.

Mudawwar *et al.* (1987) experimented on the CHF in a falling liquid film of dielectric fluorocarbon FC-72 (subcooling $\Delta T_{sub} = 1.0$ to 5.9 K) over a vertical rectangular heater surface (25.4-mm wide and 12.7- to 127-mm long). Detailed visual observations were made showing that, due to vigorous boiling prior to the CHF, most of the liquid film was separated from the heater surface; and the following generalized correlation equation was derived:

$$q_c/\rho_G u H_{fG} = 0.121(\rho_L/\rho_G)^{2/3}(\sigma/\rho_L u^2 L)^{0.42}[1+S]^{1/3}[1+0.16(\rho_L/\rho_G)S]^{2/3}, \qquad [20]$$

where $S = c_{pL}\Delta T_{sub}/H_{fG}$, and c_{pL} is the specific heat of the liquid.

3.4.2. *The CHF in liquid film flow driven by a strong centrifugal force*

Mudawwar *et al.* (1985) performed an experimental study on the CHF in a water film (pressure = 0.1 to 0.541 MPa; subcooling of 0–24 K) flowing along a ribbon heater (12 × 6.35 mm) mounted on a high-speed rotating disk (centrifugal acceleration: a/g = 36.5 to 460), such as illustrated in figure 7. This study reveals that because of a strong centrifugal force acting on the splashed droplets as well as on the vapor flow, the mechanism which causes the CHF in this case differs from those encountered in section 3.4.1. Namely, the CHF in this case depends on the behavior of individual downstream droplets rather than on the details of the film breakdown process and, hence, ordinary CHF correlations, such as those described in section 3.4.1, should be avoided for this boiling system. Mudawwar *et al.* proposed a CHF model based on the balance between the Coriolis force and the vapor drag acting on droplets formed from the shattered liquid film.

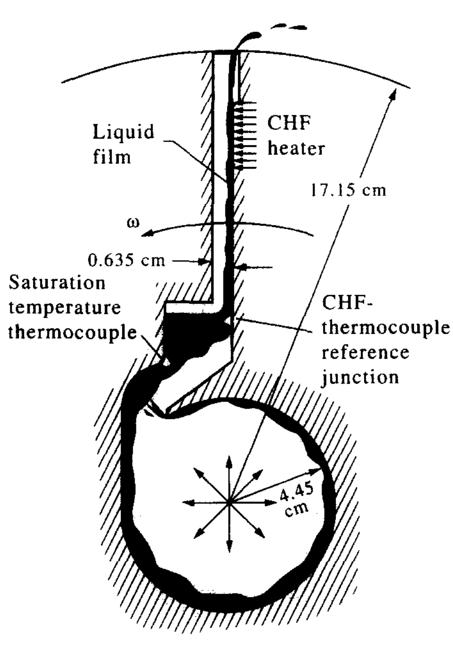


Figure 7. The CHF of boiling in the liquid film flow along a ribbon heater mounted on a high-speed rotating disk (from Mudawwar *et al.* 1985).

4. THE CHF IN FORCED INTERNAL FLOW BOILING

4.1. *Studies of the Transition Boiling Curve Including the CHF*

4.1.1. *Experimental studies on the transition boiling curve*

France *et al.* (1987) measured the steady-state transition boiling heat transfer by employing a vertical tube heated from the outside by a downward flow of liquid sodium along the tube wall (i.e. a temperature-controlled system). Tests were carried out for the convective boiling of water at 7–15.3 MPa in a tube (10.1-mm i.d. and 13.1-m long) in the range of mass flux $G = 700$ to 3200 kg/m^2 s. They derived the following equation to predict the mean heat transfer coefficient h over the inside wall surface of superheat ΔT:

$$h/h_c = (\Delta T_c/\Delta T)\exp[-C(\Delta T - \Delta T_c)], \quad \text{with } C = 0.0279 - 0.00556 \times 10^{-3}G, \qquad [21]$$

where h_c and ΔT_c are the heat transfer coefficient and the superheat at the CHF condition, respectively.

Weber & Johannsen (1990a) experimented on the transition boiling heat transfer for a flow boiling of water at 0.11–1.0 MPa (inlet subcooling of 5–30 K) in a circular channel (10-mm dia and 50-mm long) passing through an electrically heated cylindrical copper block (32-mm o.d. and 50-mm thick) for low mass fluxes $G = 25$ to 200 kg/m^2 s). They correlated the heat flux q at superheat ΔT in the transition boiling region as

$$q/q_c = (\Delta T/\Delta T_c)^{-n}, \qquad [22]$$

where q_c is the CHF value. Employing the same experimental apparatus, Weber & Johannsen (1990b) measured the CHF for the steady-state flow boiling of water at 0.11–1.2 MPa for comparatively low flow rates G = 10.8 to 301.4 kg/m^2 s (cf. section 4.7). Subsequently, Huang *et al.* (1993) used the same test section to compare the boiling curve between the "transient" and the "steady-state" mode for water boiling under the conditions of pressure p = 0.1 to 1.2 MPa, mass flux G = 25 to 500 kg/m^2 s and subcooling ΔT_{sub} = 3 to 30 K, showing that the data agree between quenching and steady-state boiling in the nucleate boiling region but disagree in the transition boiling region and the CHF (cf. sections 2.6 and 2.7 for the case of pool boiling).

4.1.2. *Transition boiling curve with a positive slope at very high flow rates*

Fukuyama & Hirata (1982) conducted experiments on the flow boiling heat transfer of R-113 at 1.37–2.28 MPa in a "horizontal" narrow tube (diameter d = 1.2 mm and length L = 61 mm) heated by an a.c. current for exceedingly high mass fluxes G = 28,300 to 51,400 kg/m^2 s, showing the existence of boiling curves with a positive slope in the transition boiling regime. Fukuyama & Hirata explained this phenomenon as being caused by an enhancement of the film boiling heat transfer up to the level of the CHF. Recently, Hosaka *et al.* (1990) reconfirmed this phenomenon via experiments on the flow boiling of R-113 at 1.1–2.4 MPa and inlet subcooling ΔT_{sub} = 50 to 90 K for d = 0.5 to 3.0 mm, L/d = 20 and 50 and G = 10,000–30 000 kg/m^2 s, showing substantially the same results as before.

Independent of the above studies, Groeneveld (1986) also reached a similar conclusion. Based on the experimental record of the surface temperature variation with time, Groeneveld classified CHF into four types: (1) the "fast CHF", with a sudden very large increase in the surface temperature; (2) the "stable CHF", with a sudden but moderate rise in the surface temperature; (3) the "unstable CHF", with a fluctuating surface temperature corresponding to the appearance and disappearance of dry patches; and (4) the "slow CHF", with a gradual increase in the surface temperature. Concerning the "slow CHF", Groeneveld stated that at high mass fluxes and/or high qualities, the film boiling heat transfer becomes more efficient and, consequently, the slope of the boiling curve changes from negative to positive. For boiling curves appearing with a positive slope in the transition boiling region, Groeneveld proposed new concepts to replace the normal ones at two critical points on the boiling curves: OID (onset of intermittent dryout) instead of CHF (critical heat flux); and ODS (onset of dry sheath) instead of MHF (minimum heat flux).

4.2. *Empirical Correlations of the CHF in Flow Boiling in Tubes*

4.2.1. *Correlations of the CHF based on the local quality (local conditions hypothesis)*

Groeneveld *et al.* (1986a) presented a revised version of the earlier "lookup table" for the CHF of water, on the basis of 15,000 data points, where the CHF values of water boiling in an 8-mm dia tube, $q_{cw,8}$, are listed in a table postulating the propriety of the following relationship:

$$q_{cw,8} = f(p, G, x), \qquad [23]$$

where p is the pressure (0.1–20 MPa), G is the mass flux (0–7500 kg/m^2 s) and x is the local quality at the CHF condition (-0.50 to $+1.00$). The CHF value for a tube of diameter other than 8 mm, $q_{cw,d}$, is estimated approximately by the empirical relationship $q_{cw,d} = q_{cw,8}(d/8)^{1/3}$ in the range $d = 4$ to 16 mm. Correction factors are also listed for applying the abovementioned table to many other geometries and flow conditions. At the same time, Groeneveld *et al.* (1986b) conducted a study on a procedure to predict the CHF for nonaqueous fluids, providing a "standard nondimensional CHF table" based on the scaling technique in the following form:

$$q_{c,8}/GH_{fG} = f(\rho_G/\rho_L, \psi_k, x), \qquad [24]$$

where $\psi_k = (G^2 d/\sigma\rho_L)^{1/2}$. For diameters other than 8 mm, $q_{c,d} = q_{c,8}(d/8)^{1/3}$ is employed, similarly to the case of water, in the range $d = 2$ to 16 mm. Meanwhile, Tain *et al.* (1993) experimented on the CHF of R-22, R-123 and R-134a (alternatives to the harmful substances which delete the ozone layer, such as R-11 and R-12), together with the CHF of R-11 and R-12 for $d = 4.2$ mm, $L/d = 120$ to 240, $G = 1000$ to 4000 kg/m^2 s, $p = 1$ to 2 MPa and $x = +0.07$ to $+0.6$. Their data were found to be in accord with the predictions of the foregoing Groeneveld correlation and the Shah correlation mentioned below.

Shah (1987) presented an improved version of his earlier "graphical" correlation of the CHF in vertical tubes, which consists of two correlations: the upstream condition correlation (UCC) and the local condition correlation (LCC). The CHF correlations under the UCC and the LCC are represented in the following forms, respectively:

$$q_c/GH_{fG} = f(L/d, Y, x_i) \text{ and } q_c/GH_{fG} = f(Y, L/d, p_r, x), \qquad [25]$$

where $Y(=Gdc_{pL}/k_L)(\rho_L^2 gd/G^2)^{-0.4}(\mu_L/\mu_G)^{0.6}$, c_{pL} is the specific heat of the liquid, k_L is the thermal conductivity of the liquid, g is the gravitational acceleration, μ_L and μ_G are the dynamic viscosities of the liquid and vapor, respectively, x_i is the inlet quality, p_r is the reduced pressure and x is the local quality at the CHF condition. The correlation covers the ranges $d = 0.315$ to 37.5 mm, $L/d = 1.3$ to 940, $G = 4$ to 29,051 kg/m^2 s, $p_r = 0.0014$ to 0.96, $x_i = -4$ to $+0.85$ and $x = -2.6$ to $+1$; and indicates good agreement with the CHF data. [N.B. The Shah correlation, although it is an empirical one, includes two questionable points if viewed physically: (1) the extensive use of g in Y on the RHS of [25] (except in a region of very low flow rate) for forced flow boiling; and (2) the positive inlet quality $x_i = 0$ to $+0.85$, i.e. the mixed condition, allowing nonunique flow patterns at the inlet section of the heated tube.]

4.2.2. *Correlations of the CHF based on a concept different from the local quality*

Weisman & Ying (1986) presented a comment on the HP-regime (high pressure region) classified in the earlier Katto (1980a, b) empirical correlation that it is an unsubstantial region whose appearance is solely to the predictive approach taken (note that the same situation is found in the foregoing Shah correlation also). With regard to the correlation of the CHF at high ρ_G/ρ_L ratios, a series of experimental studies were conducted by Katto & Ashida (1982) for R-12 ($\rho_G/\rho_L = 0.109$ to 0.306, $d = 5$ mm, $L/d = 50$ and $G = 700$ to 7000 kg/m^2 s), by Katto & Yokoya (1984) for liquid helium ($\rho_G/\rho_L = 0.409$, $d = 1$ mm, $L/d = 25$ to 200 and $G = 11$ to 108 kg/m^2 s) and by Katto & Ohno (1984) for R-12 ($\rho_G/\rho_L = 0.109$ to 0.306, $d = 10$ mm, $L/d = 100$ and $G = 120$ to 2100 kg/m^2 s). Based on the accumulation of such experimental studies, Katto & Ohno (1984) revised the foregoing Katto correlation into an improved version:

$$q_c/GH_{fG} = f(\rho_G/\rho_L, \sigma\rho_L/G^2L, L/d, \Delta H_i/H_{fG}), \qquad [26]$$

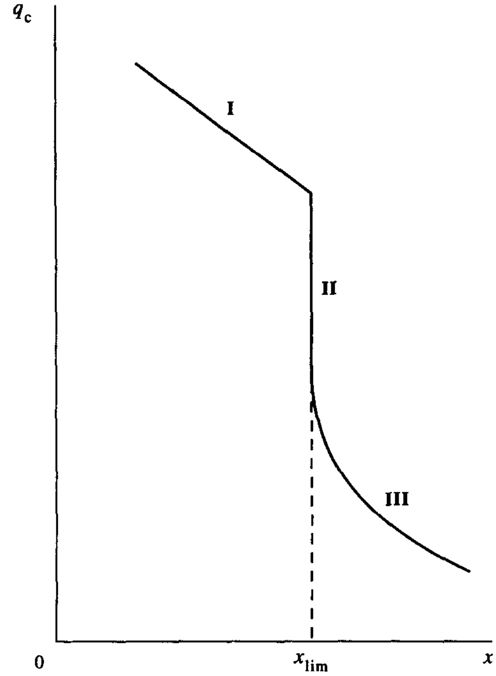


Figure 8. Relationship of the CHF q_c vs the exit quality x postulated for flow boiling in a uniformly heated tube with fixed p, d and G.

where ΔH_i is the inlet subcooling enthalpy. In this new correlation, the difficulty in discriminating between the characteristic regimes in the earlier correlation was eliminated except for between two regions: $\rho_G/\rho_L < 0.15$ and $\rho_G/\rho_L > 0.15$. Furthermore, Katto & Yokoya (1987) experimented on the CHF in the flow boiling of R-12 at $\rho_G/\rho_L = 0.0735$ in comparatively narrow tubes of $d = 3$ to 8 mm and $L/d = 50$ to 800 for $G = 510$ to 6055 kg/m^2 s, revealing a trend for a gradual decrease in the prediction accuracy for very narrow tubes of $d \leqslant 5$ mm.

4.2.3. Correlations involving the acceleration of gravity and other topics

4.2.3.1. The problem of gravity. As mentioned in section 4.2.1, the Shah correlation involves the acceleration of gravity. Similarly, the correlations derived in the following three studies involve the effect of gravity. First, Subbotin *et al.* (1982) experimented on the CHF in the flow boiling of liquid helium at 0.1–0.2 MPa in a tube of $d = 1.63$ mm and $L/d = 110$ for low mass fluxes $G = 80$ to 320 kg/m^2 s, and they correlated the data by dimensionless formulas applied to the low and high quality regions, respectively, interposing the limiting quality $x_{\rm lim}$ (mentioned in section 4.2.3.2 below) between the two regions. Second, Ünal (1985) analyzed the data for R-12 and R-113 obtained at comparatively low pressures to provide empirical CHF correlations for uniformly and nonuniformly heated tubes. Finally, Avkesentyuk (1988) was convinced of the ability of the Kutateladze correlation for the CHF in pool boiling ([2] in section 2.5.1) to deal with the CHF in the forced flow boiling of both subcooled and saturated liquids, and he derived a correlation in the form of the Kutateladze correlation multiplied by a complicated correction term for flow boiling.

4.2.3.2. Other topics. Postulating the q_c–x curve to appear in the form illustrated in figure 8, Doroschuk *et al.* (1970) advocated that region I relates to DNB, while regions II and III relate to dryout, and that the CHF in region II takes place at a constant exit quality $x_{\rm lim}$, i.e. the limiting quality. A dimensionless correlation of $x_{\rm lim}$ was derived by Morozov (1987) based on the assumption of heat transfer deterioration due to the breakup of the liquid film.

Cuta (1983), Cheng & Chin (1986) and Siikonen & Vanttola (1986) compared the prediction accuracies of the existing empirical correlations via a comparison with the experimental data of the CHF for water flow boiling.

4.3. *Studies of the CHF in the Region of High Quality*

4.3.1. *Experimental studies*

Kottowski *et al.* (1991) carried out experiments on the CHF for sodium and potassium, and derived the following empirical correlation based on 170 data points, including their own data and some others:

$$q_c/GH_{fG} = 0.216(d_H/L)^{0.8}(1-2x_i)G^{-0.193}, \quad \text{where } G \text{ is in kg/m}^2\,\text{s;} \qquad [27]$$

covering the following ranges of the hydraulic diameter $d_H = 4$ to 6 mm, the length/hydraulic diameter ratio $L/d_H = 30$ to 125, the inlet quality $x_i = -0.4$ to 0 and the mass flux $G = 50$ to 800 kg/m^2 s. Equation [27] is close to the relationship $q_c/GH_{fG} = 0.25\ (d_H/L)$ for the complete evaporation of saturated liquid at the CHF.

Milashenko *et al.* (1989) conducted experiments on the CHF in the upflow, in the high quality boiling of water at 3–10 MPa in a vertical tube of 13.1-mm dia and 1.8-m long (heated length = 0.15 to 1.0 m) for a normal mass flux range G = 1000 to 3000 kg/m^2 s, measuring the distribution of liquid between the core vapor flow and the wall liquid film flow at the end of the heated section, and at the same time, measuring the liquid film flow rate at the onset of annular dispersed flow as well as at the CHF condition. The following three matters have been reported: (1) that the suppression of droplet deposition due to vaporization is observed; (2) that the entrainment rate of droplets is strongly dependent on the heat flux; and (3) that the film flow rate at the location of the onset of the CHF is generally greater than zero.

4.3.2. *The CHF model based on the concept of liquid film dryout in annular flow*

Govan *et al.* (1988) conducted a study relating to the annular flow code HANA, which predicts the onset of the CHF in an evaporating vapor–liquid upflow in a vertical channel by calculating the point at which the liquid film flow rate reduces to zero, allowing for evaporation, droplet entrainment and droplet deposition. These authors carried out measurements of droplet deposition in high velocity air–water flows in a tube of 31.8-mm dia, and developed a new deposition correlation. Then, through combination with a new correlation for the entrainment rate, an improved version of the CHF modeling code was developed which showed good predictions not only for equilibrium entrainment in adiabatic flow but also for entrainment and CHF in heated tubes.

The magnitude of the CHF predicted by the ordinary liquid film dryout model tends, in general, to increase excessively when the quality decreases beyond a certain value. Katto (1984) analyzed this problem, showing that if the upper limit of the macrolayer thickness given by [5] (section 2.10.2) is taken into account in the evaluation of the liquid film thickness at the onset point of annular flow, the abovementioned undesirable tendency is readily corrected.

Sugawara (1990) developed a CHF prediction model, which was based on the zero film flow rate model, but gave consideration to the following: (1) the use of a three-fluid model, consisting of a liquid film, a continuous vapor and entrained droplets suspended in vapor, employing the correlations derived by Sugawara for the deposition coefficient and the entrainment rate; (2) the suppression of droplet deposition due to vaporization; and (3) the maximum liquid film thickness restricted by the macrolayer thickness δ_0 of [5], in which an empirical correlation was developed to evaluate A_v/A_w so as to agree with the CHF data.

Leung *et al.* (1982) performed CHF tests in annuli with direct and indirect heating of the inner rod, finding that the heating method is insensitive to the CHF and that the experimental results of CHF can be well-predicted by a multifluid model in which the CHF is postulated to occur when the liquid on the inner rod surface drys out.

4.4. *Experimental Studies on the CHF Mechanism Under the Subcooled Condition*

Del Valle M. (1983) experimented on the CHF in subcooled water boiling at 1 atm in a vertical channel of rectangular cross section (12 × 15 mm) electrically heated on one side wall, with a glass window forming the front wall for a high-speed ciné photographic study of the flow structure near the CHF. Experiments were carried out for very thin wall thicknesses of 0.08, 0.13 and 0.20 mm, mass flow rates of 800, 1700 and 2000 kg/m^2 s and exit qualities from −0.12 to 0. A strong effect of wall thickness on the CHF and related phenomena, such as flow configuration, temperature fluctuation and dryout area formation, was reported. Subsequently, Del Valle M. & Kenning (1985) employed the same experimental apparatus to observe the bubble behaviors and to measure the distribution of active nucleation sites in subcooled flow boiling at high heat fluxes, 70–95% CHF.

Ueda & Kim (1986) performed experiments on the subcooled flow boiling of R-113 at 0.147 MPa in a vertical annular passage composed of a heated inner tube (8-mm o.d., 0.5-mm thick and 400-mm long) and an unheated transparent shroud (18-mm i.d.). The wall temperature variation prior to and at the CHF condition was measured, and the behavior of large coalesced bubbles (vapor mass) was observed. One of the conclusions says that the CHF condition seems to be initiated when the rise in the wall temperature, due to the partial disruption of the liquid film beneath the vapor mass, becomes greater than the drop in wall temperature resulting from the quenching caused by the succeeding liquid flow.

4.5. CHF Models for Subcooled and Low Quality Flow Boiling

Studies of CHF models for flow boiling at comparatively high pressures (higher than, say, 7 MPa in the case of water) are reviewed in this section, and the problem of the CHF at low pressures, including 1 atm, will be dealt with in section 4.6.

4.5.1. The CHF model based on the critical bubbly layer mechanism

Weisman & Pei (1983) presented a theoretical CHF model for subcooled and low quality flow boiling in a tube, postulating a bubbly layer between the heated wall and the core flow, and assuming that the CHF occurs when the "volume fraction of vapor" in the bubbly layer just exceeds a certain critical value, which is brought about through the balance between the outward flow of vapor bubbles and the inward flow of liquid at the interface between the bubbly layer and the core flow. This model applies to the condition of the void fraction in the core flow being <0.6. Comparisons of the predicted CHF value with the experimental data of water, R-11, R-113, liquid nitrogen and anhydrous ammonia indicate good agreement.

Ying & Weisman (1986) then extended the study to include higher quality in the core flow and lower velocities than the foregoing model by allowing for a nonuniform radial void profile in the core flow at void fraction >0.6, resulting in a high-void correction procedure with which the previous Weisman–Pei model can be extended to void fractions in the core flow of up to 0.8. Subsequently, Weisman & Ileslamlou (1988) considered the highly subcooled region, where the original Weisman–Pei model tends to overpredict the experimental data, and they succeeded in revising the Weisman–Pei model, to extending its range of application to qualities from $x > 0.12$ up to $x > -0.7$.

Lim & Weisman (1990) studied a procedure to apply the foregoing Weisman–Pei model with Ying–Weisman's high-quality correction procedure to predict the CHF in annuli with a heated inner rod and an unheated shroud. In addition, Yang & Weisman (1991) applied the flow configuration assumed in the foregoing models to the prediction of the "heat transfer" in subcooled flow boiling at high heat flux, showing that the predicted boiling curve was in reasonable agreement with the experimental heat transfer data.

Chang & Lee (1989) presented a CHF model, which is the same as the foregoing model of Weisman and coworkers except for the procedure to evaluate the mixing mass flux across the bubbly layer interface, adopting the concept of momentum balance instead of the concept of turbulent intensity used in the model of Weisman and coworkers. Subsequently, Lee & Chang (1990) conducted an analytical study with the objective of improving their earlier model at several points and of extending the applicability to include cryogenic fluids. The prediction of this refined model compared well with water data in the following ranges of pressure = 0.1 to 20 MPa (which includes the low pressure range, <7 MPa, dealt with in section 4.6) and mass flux = 345 to 8000 kg/m^2 s, as well as with the data of liquid helium and nitrogen.

4.5.2. The CHF model based on the liquid sublayer (macrolayer) dryout mechanism

Lee & Mudawar (1988) developed a mechanistic CHF model based on the dryout of a thin liquid sublayer (macrolayer) beneath an intermittent vapor blanket due to a Helmholtz instability at the sublayer–vapor interface. The length of the vapor blanket was determined by the Helmholtz critical wavelength, and the thickness of the liquid sublayer was determined through the force balance of the vapor blanket in the radial direction. The three empirical constants employed (a_1, a_2 and a_3) were evaluated through comparison with the experimental data. The prediction accuracy of the model was tested against the CHF data of water.

Lin *et al.* (1989) presented a version of the abovementioned Lee–Mudawar model by increasing the number of empirical constants from three to four, in order to increase the prediction accuracy. Similarly to the Lee–Mudawar model, this model applies to water only and its range of applicability covers pressure = 4.9 to 17.6 MPa, tube diameter = 4 to 16 mm, subcooling < 50 K, void fraction < 0.7 and mass flux = 1000 to 5000 kg/m^2 s.

Katto (1990a, b) proposed a CHF model, which is based on the same principle as the foregoing Lee–Mudawar model, but has the following particular features: (1) the assumption of a similarity in the macrolayer condition between pool and flow boiling (both in the DNB condition with bulk liquid near the heater surface), i.e. the evaluation of the macrolayer thickness by employing [5] in section 2.10.2; (2) the avoidance of applying simplistic mechanistic assumptions to the complicated state of two-phase flow near the vapor–liquid interface including condensation, i.e. the use of the vapor velocity coefficient k_v correlated empirically as a function of three flow parameters as

$$k_v = f(\mathrm{Re}, \rho_G/\rho_L, \varepsilon), \tag{28}$$

where Re is the Reynolds number (assuming homogeneous two-phase flow in a tube), ρ_G/ρ_L is the density ratio and ε is the void fraction (see the N.B. in section 4.6.3 regarding the role of k_v); (3) the avoidance of the use of any empirical parameters or constants other than k_v; and (4) the capability of the model to apply to not only water but also various nonaqueous fluids.

Yagov & Puzin (1985) derived a theoretical correlation of the CHF based on the concept that the CHF occurs through a sharp increase in the dry spot area on the heater surface underneath a vapor mass which is generated by the coalescence of small bubbles in the viscous sublayer of turbulent flow at high heat flux. Yagov *et al.* (1987) derived a predictive equation for the CHF through an analysis of the steady-state flow and evaporation, which are assumed to appear in liquid-film meniscuses underneath a large vapor mass, and compared the prediction with the data of water and liquid helium.

4.6. *The CHF in Subcooled Flow Boiling at Low Pressure and High Flow Rate*

Due to the requirement of extremely high CHF values for the heat removal of fusion reactor components, such as diverters, plasma limiters, neutral beam calorimeters, ion dumps etc. the CHF in water flow boiling at relatively low pressures (say 0.1–2.5 MPa) in narrow tubes under the conditions of a very high flow rate and high subcooling has been studied recently.

4.6.1. *Experimental studies of the CHF in subcooled flow boiling*

Boyd *et al.* (1986, 1987) carried out experiments on the CHF of water at 1.6 MPa in a "horizontal" tube of 10.2-mm dia (length-to-diameter ratio $L/d = 115.56$) for a mass flux of $G = 630$ to 3500 kg/m^2 s and a quality at the CHF condition of $x \cong 0$; and the data were compared with the three existing empirical correlations, resulting in their overprediction. Subsequently, Boyd (1988) experimented on the CHF of water at 0.77 MPa in a "horizontal" tube of 3-mm dia ($L/d = 96.6$) for very high mass fluxes of $G = 4600$ to 40,600 kg/m^2 s and subcooling at the CHF of 30–74 K; then Boyd (1989) conducted experiments under almost the same conditions as before except for the pressure of 1.66 MPa; and, finally, Boyd (1991) compared the data obtained in the foregoing two studies with the Gambill (1963) correlation, concluding that this correlation adequately predicts the CHF data at 1.66 mPa, but underpredicts the CHF at 0.77 MPa for $G > 14{,}000$ kg/m^2 s.

Nariai *et al.* (1987) experimented on the CHF of water flow boiling at near 1 atm in vertical tubes of 1- to 3-mm dia and 10- to 100-mm long in the range $G = 7000$ to 20,000 kg/m^2 s, and compared the data with the four existing empirical correlations, showing that, on the whole, the agreement was unsatisfactory. Then, with the object of studying the effect of tube diameter on the CHF and on the discontinuity in the CHF characteristics between the subcooled and quality region, Nariai *et al.* (1989) conducted experiments on the CHF for water boiling at 1 atm in vertical tubes of 1- to 3-mm dia ($L/d = 33$ to 50) for $G = 7000$ to 11,000 kg/m^2 s and $x = -0.06$ to $+0.06$. Meanwhile, Inasaka & Nariai (1989) experimented on the CHF of water boiling at 0.3–1 MPa in a tube of 3-mm dia and 100-mm long for $G = 5500$ to $30{,}000\ \mathrm{kg/m^2\,s}$ and $x = -0.20$ to -0.05, and they compared the data with the three existing empirical correlations as well as the Tong correlation modified by Inasaka & Nariai themselves (see [29] and [30] in section 4.6.2).

Celata *et al.* (1990) conducted experiments on the CHF of water boiling at 0.1–2.2 MPa in vertical tubes of 2.5- to 5.0-mm dia ($L/d = 80$ to 100) for $G = 2000$ to $33{,}500\ \mathrm{kg/m^2\,s}$ and subcooling at the CHF of 15–120 K, and compared the data with the eight existing empirical correlations, showing a general inadequacy in predicting the CHF. Celata *et al.* (1992) performed more detailed experiments under almost the same experimental conditions as before, and the data obtained were compared with the Westinghouse empirical correlation (Tong *et al.* 1968) as well as two recent mechanistic CHF models (Lee & Mudawar 1988; Katto 1992a). Subsequently, Celata *et al.* (1993a) performed an experimental study for subcooled water boiling at 0.6–2.5 MPa in a vertical tube of 2.5-mm dia ($L/d = 40$) for $G = 11{,}000$ to $40{,}000\ \mathrm{kg/m^2\,s}$ and subcooling of 50–136 K at the CHF condition. The data points obtained in this study were compared with the six existing empirical correlations, including the Tong correlation modified by Celata *et al.* themselves (see [31] in section 4.6.2) and three mechanistic models (Weisman & Ileslamlou 1988; Lee & Mudawar 1988; Katto 1992a), showing the good predictions attained in the Tong correlation modified by Celata *et al.* and the Katto model. Furthermore, Celata *et al.* (1993b) discussed the relationship between the CHF and tube diameter based on the existing experimental data.

4.6.2. *Empirical correlations of the CHF for water in subcooled flow boiling*

Based on the boundary layer separation assumption, Tong (1968) previously proposed an empirical correlation of the CHF in subcooled water boiling at a pressure of 7–14 MPa:

$$q_c/GH_{fG} = C_{Tong}(\mu_L/Gd)^{0.6}, \quad \text{with } C_{Tong} = 1.76 - 7.433x + 12.222x^2, \qquad [29]$$

where μ_L is the dynamic viscosity of water and x is the local quality at the CHF condition. Now, for the purpose of correlating the CHF data at low pressures, Inasaka & Nariai (1987) replaced C_{Tong} in the first equation of [29] by C, defined as follows:

$$C/C_{Tong} = 1 - (52.3 + 80x - 50x^2)/[60.5 + (10p)^{1.4}], \qquad [30]$$

where C_{Tong} is given by the second equation of [29] and p is the pressure measured in MPa (recommended region: 0.1–5.3 MPa).

Meanwhile, Celata *et al.* (1993a) modified [29] by changing the exponent from 0.6 to 0.5 as follows:

$$q_c/GH_{fG} = C'(\mu_L/Gd)^{0.5}, \quad \text{with } C' = (0.27 + 5.93 \times 10^{-2}p)\psi, \qquad [31]$$

where $\psi = 0.825 + 0.986x$, for $x > -0.1$, $\psi = 1$, for $x < -0.1$, and p is the pressure in MPa (recommended region: 0.1–20 MPa).

4.6.3. *Theoretical models including the low pressure region*

Katto (1992a) extended his earlier model (see section 4.5.2) to the region of low pressures (say, 0.1–2.5 MPa) through an extension of the applicable range of the vapor velocity coefficient $k_v = f(\mathrm{Re}, \rho_G/\rho_L, \varepsilon)$ to low values of ρ_G/ρ_L. Though this extension was made on the basis of the limited CHF data for water obtained by Boyd (1988), Inasaka & Nariai (1987) and Celata *et al.* (1992), the extended Katto model (which covers the pressure range 0.1–20 MPa) can predict the CHF in the low pressure region considerably well [see figure 9, reproduced from Celata *et al.* (1994)]. In addition, judging by the unified structure of this model, there is the possibility that it could be applied to nonaqueous fluids at low values of ρ_G/ρ_L.

Celata *et al.* (1994) developed a new liquid sublayer dryout model with an operating range $p = 0.1$ to 8.4 MPa, eliminating all the empiricism involved in the Lee–Mudawar and Katto models. Of course this model includes no empirical constants determined so as to agree with the experimental data. Considering the Lee–Mudawar model, for the sake of convenience, it employs three empirical constants a_1, a_2 and a_3 as follows: (1) a_1 is used in the analysis for evaluating the temperature T_m of the liquid entering the sublayer; and (2) a_2 and a_3 are used in the analysis for evaluating the lateral force on the vapor blanket necessary to calculate the sublayer thickness δ. Against this, Celata *et al.* developed a procedure for evaluating the key quantities, such as T_m and δ, in the above model by utilizing the temperature distribution across the tube cross section, such as that proposed by Martinelli. Figure 9 shows the superiority of the Celata model in predicting the CHF value under the abovementioned pressure range. [N.B. In the Lee–Mudawar and Celata models, the vapor blanket velocity is evaluated from the balance between the drag and the "buoyant force" acting on the vapor blanket moving along the vertical tube wall. However, the CHF values at very high flow rates show, in general, no significant difference between horizontal and vertical tubes.]

4.7. *The CHF in a Vertical Channel at Low Pressure and Low Flow Rate*

Studies on the CHF of upward and downward flow boiling in a vertical channel at low pressure and low flow rate have so far been carried out in relation to the problems of removing the decay heat in loss-of-coolant accidents (LOCAs) in nuclear reactors. In this case, one must pay attention to the following: (1) that experiments on the CHF at near 1 atm are often subject to insufficient throttling conditions upstream of the test section; and (2) that the effect of gravity on the CHF cannot be neglected at low flow rates.

4.7.1. The CHF in upward or downward flow boiling

Rogers *et al.* (1982) experimented on the CHF in an upward flow of water at 0.156 MPa in annuli composed of a heated inner tube of 13.1-mm o.d. and a glass shroud of 22- to 30.2-mm i.d. for mass fluxes of $G = 60$ to $1200\ \mathrm{kg/m^2\,s}$, showing that the CHF data are lower than the predicted values of the existing four CHF correlations, and that the experimental CHF differs in characteristics between $G > 180$ and $G < 180\ \mathrm{kg/m^2\,s}$. El-Genk *et al.* (1988) conducted experiments on the CHF in upward flow of water at 0.118 MPa in vertical annuli composed of a heated inner tube of 12.7-mm o.d. and an unheated shroud of 20- to 25.4-mm i.d. for $G = 0$ to $260\ \mathrm{kg/m^2\,s}$, and developed CHF correlations according to flow patterns at the CHF condition.

Ozawa *et al.* (1993) experimented on the CHF of vertical upward (and horizontal) flow boiling of water at 0.101 MPa in a tube of 5.0-mm dia under oscillatory conditions (mean flow rate $G_m = 70$

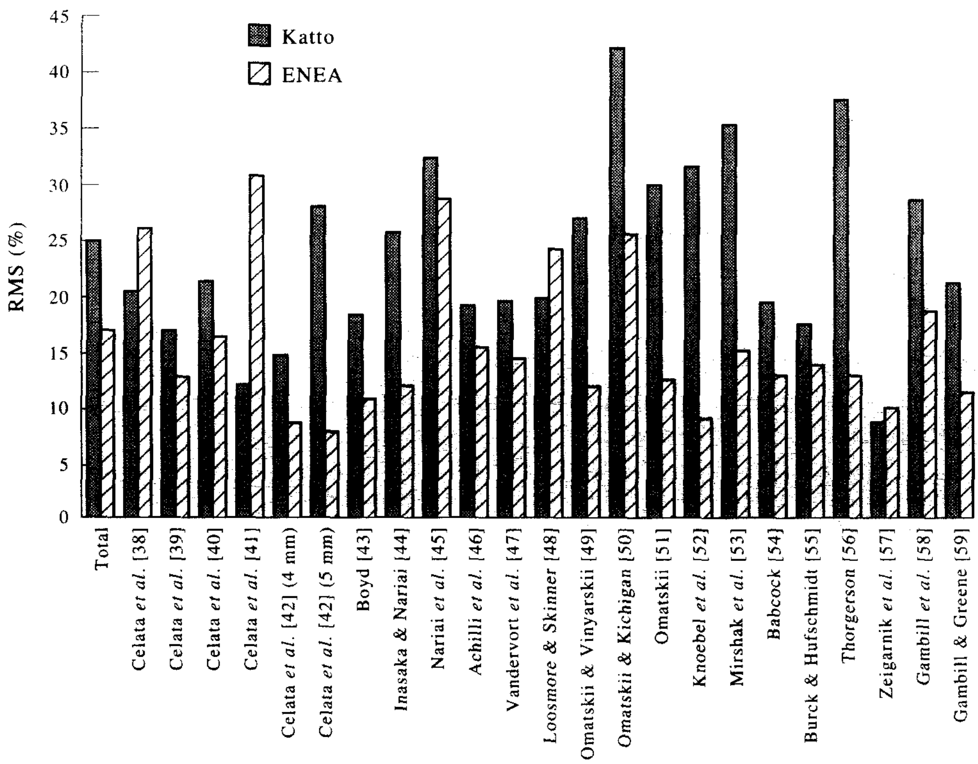


Figure 9. RMS errors of prediced CHF vs single data sets, for the Celata (ENEA) and Katto models (from Celata *et al.* 1994). The numerals in square brackets are the reference numbers used by Celata *et al.* (1994) and most of the data, [48]–[59], were obtained over 25 years ago (1958–1969).

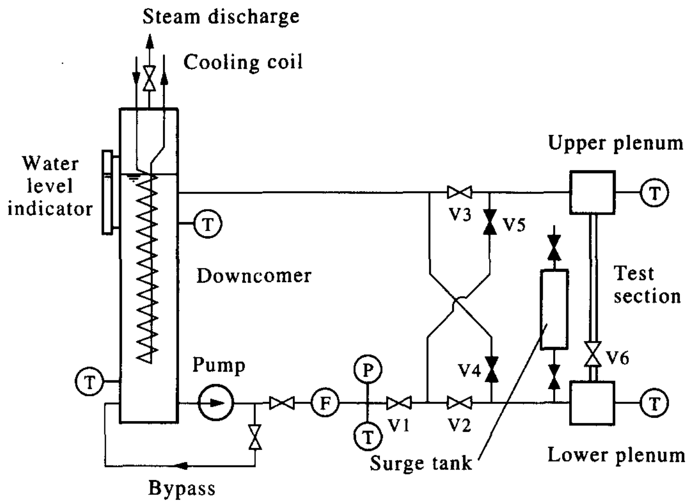


Figure 10. Schematic diagram of the test loop with a vertical test section in it employed by Mishima and coworkers and Sudo and coworkers (from Mishima *et al.* 1985).

to 450 kg/m^2 s; amplitude of the flow rate $\Delta G/G_m = 0.209$ to 3.77; and oscillation period $\tau = 2$ to 6 s), showing that the CHF decreases with increasing $\Delta G/G_m$ and τ.

On the other hand, Khabenskii *et al.* (1988) experimented on the CHF in a "downward" flow of water at 0.1 MPa through a vertical rectangular duct (3.5-mm gap × 70-mm wide and 100-mm long; heating both sides) connected to an upper plenum with a free liquid level in it, for $G = 0$ to 800 kg/m^2 s and inlet subcooling of 0–85 K. The CHF data obtained for this downward flow boiling were analyzed on the basis of the flooding concept (cf. section 5.2 for countercurrent flow boiling).

4.7.2. The CHF in [upward ($G > 0$) and downward ($G < 0$)] flow boiling

Because of the need to evaluate the CHF in nuclear research reactors, the CHF of water flow boiling at near 1 atm was studied by the following two research groups with a vertical test section setup in a special loop, as shown in figure 10. This test loop has a downcomer of large volume with a free liquid level in it and, in addition, an upper and a lower plenum, so there may be the possibility that flow instabilities exert some unknown effects on the CHF.

Mishima & Nishihara (1985) experimented on the CHF of the forced flow boiling of water at 1 atm in a thin vertical rectangular channel (2.4-mm gap × 30-mm wide and 350-mm long) in the flow rate ranges: $G = 0$ to 110 kg/m^2 s (upward flow) and $G = -7$ to -280 kg/m^2 s (downward flow) for the case of one heated side wall; and $G = 0$ to 360 kg/m^2 s (upward flow) and $G = -7$ to -610 kg/m^2 s (downward flow) for the case of both side walls heated. They also studied the CHF correlations allowing for the flow direction and the flow rate. Then Mishima *et al.* (1985) conducted experiments for a circular tube of 6-mm dia and 33-mm long under conditions similar to the preceding study, and thereby examined the effects of buoyancy, upstream compressibility and inlet valve throttling in upward and downward flows. Subsequently, Mishima & Nishihara (1987) attempted an analytical study of the CHF depending on the experimental CHF data.

Meanwhile, employing a test loop similar to figure 10, Sudo *et al.* (1985) also conducted an experimental study on the CHF of the upward and downward flow boiling of water at 0.1–0.12 MPa in a rectangular channel with a narrow gap (2.25- to 2.80-mm gap, 50-mm wide), and analyzed the data together with some other data to present a scheme of the CHF correlation. Sudo & Kaminaga (1989) and Sudo *et al.* (1991) performed experiments on the flooding limit of countercurrent flow in vertical channels by employing an air–water system at 1 atm, and presented an empirical correlation of the CHF in downflow including the effect of subcooling. Finally, analyzing the existing CHF data for the upward and downward flow boiling of water in vertical rectangular channels at low pressures, Sudo & Kaminaga (1993) presented an empirical CHF correlation scheme for water boiling in rectangular channels heated from both sides, in the range $p = 0.1$ to 4 MPa and $G = -25{,}800$ to $+6250$ kg/m^2 s (including stagnant flow conditions), covering the exit end condition from subcooling of 0–74 K to a quality of 0–1.0.

Then, Cheng (1991) conducted an analytical study of the CHF in the downflow and upflow near $G = 0$ in a thin rectangular channel, assuming a steady-state countercurrent two-phase flow subjected to interfacial friction, which increases in magnitude with increasing liquid film thickness, and postulating the CHF to occur by the interfacial instability. The predicted CHF values agree well with the experimental data obtained by Nishima & Nishihara (1985) and Sudo & Kaminaga (1989), explaining why the minimum CHF value of downflow boiling appears not at $G = 0$ but at $G \neq 0$.

Oh & Englert (1993) employed a test loop similar to that in figure 10, but their loop had neither an upper nor a lower plenum chamber and the downcomer had no free liquid level in it. In addition, their experiments were conducted at very low pressures, 0.02–0.085 MPa, and at low flow rates $|G| = 30$ to 80 kg/m^2 s (upward and downward, respectively). Their data were found to disagree with the existing CHF correlations derived from the data at near 1 atm, and hence a new correlation was proposed.

4.8. *The CHF in Transients of Mass Flow Rate, Thermal Power and Pressure*

Celata *et al.* (1986) conducted experiments of R-12 flow boiling in a tube of 7.5-mm dia and 2300-mm long at 1.25–3.00 MPa (covering PWR and BWR conditions with respect to the magnitude of ρ_G/ρ_L) and a specific mass flow rate of $G = 1010$ to 1470 kg/m^2 s. They measured the time interval from the start of the flow transient to the onset of the CHF, i.e. the initiation of the wall temperature excursion under constant heat flux. The steady-state CHF correlations were found to be inadequate in predicting the onset of the CHF in the case of a fast flow transient (half-flow decay time $t_h < 5.0$ to 6.0 s), and a simple design correlation of the transient time prior to the onset of the CHF was presented. Subsequently, under similar experimental conditions, Celata *et al.* (1989) studied the CHF during transients caused by simultaneous changes in the flow rate and thermal power (for an exponential decrease in the mass flow rate and ramp- and stepwise increases in power) under constant pressure condition. Then, Celata *et al.* (1991) studied the CHF in the case of transients caused by simultaneous variations in either two or three of the parameters pressure, mass flow rate and thermal power (an exponential decrease in pressure, an exponential decrease in flow rate and ramp- and stepwise increases in power). In the above two studies, the analyses were conducted on the basis of the local conditions hypothesis (cf. section 4.2.1) as well as the quasi-steady-state assumption.

Iwamura (1987) experimented on the CHF in transients caused by a linear reduction in the mass flow rate under constant pressure and heat flux. Tests were carried out for water boiling at 0.1–3.9 MPa in either a tube (10-mm dia and 800-mm long) or annuli (a heated inner tube of 10-mm o.d. and 800-mm long with a glass shroud of 12.8- to 14.0-mm i.d.). The observations suggested that the CHF was caused by the "dryout of a liquid sublayer" on the heated surface, and a method was proposed to predict the transient time before the onset of the CHF based on the "local conditions hypothesis".

Meanwhile, Pasamehmetoglu *et al.* (1990b) presented a theoretical analysis of the CHF during power transients in flow boiling at low qualities (DNB conditions) based on the "macrolayer dryout" concept. The power transient CHF model was based on similar considerations to those in the case of pool boiling (see section 2.11). The predicted values of the CHF in the case of an exponential power increase, $Q = Q_0 \cdot \exp(t/\tau_e)$ (cf. [9], where τ_e is the exponential heat input period), were compared with the experimental data obtained by Kataoka *et al.* (1983) for upward flow boiling of water at 0.143–1.503 MPa for subcooling of 0–70 K and a liquid velocity of 1.35–4.04 m/s along a heated wire of 0.8- to 1.5-mm dia located along the centerline of a vertical shroud tube of 38-mm i.d. Very good agreement with the data was seen over a wide range of the exponential heat input period $\tau_e = 0.005$ to 10 s.

5. THE CHF IN COUNTERCURRENT FLOW BOILING SYSTEMS

5.1. *The CHF in a Closed Two-phase Thermosyphon*

The closed two-phase thermosyphon is usually a simple vertical tube, closed at both ends, charged with a definite quantity of liquid and divided into three adjoining parts: the upper cooled (condenser), middle adiabatic and lower heated (evaporator) sections (note that another branch of the CHF in countercurrent flow boiling has already been included in section 4.7).

5.1.1. Experimental studies

Imura *et al.* (1983) studied the effect of a liquid charge fraction F_c (in the range 0.04–1.0) on the CHF value q_c, leading to the classification of the three regimes: (1) the "small F_c", where q_c increases with F_c; (2) the "middle F_c", where q_c is constant and independent of F_c; and (3) the "large F_c", where a periodic burst of boiling and noise occurs. Among them, the "middle F_c" is a regime of practical use, and Imura *et al.* (1983) analyzed their own CHF data along with other existing data to give the following CHF correlation:

$$q_c/\rho_G H_{fG} = 0.16[\sigma g(\rho_L - \rho_G)/\rho_G^2]^{1/4} \cdot (d/L)(\rho_L/\rho_G)^{0.13}, \qquad [32]$$

where d is the tube diameter and L is the length of the "heated section". This correlation was derived empirically by modifying the Kutateladze correlation (see [2] in section 2.5.1) derived for the CHF in pool boiling.

Fukano *et al.* (1983) studied the characteristics of the wall temperature excursion at the CHF, resulting in the classification of three types: (1) "the first type", characterized by the temperature oscillation, which is caused by a cyclic phenomenon of liquid accumulation by flooding in the upper cooled section and the spreading of the dryout area in the lower heated section; (2) "the second type", due to the liquid film dryout at the middle F_c; and (3) "the third type", due to the CHF (in DNB conditions) at the large F_c. Fukano *et al.* (1986) continued the foregoing study, reporting that the abovementioned first type of temperature oscillation appears near $F_c = 0.33$. Fukano *et al.* (1987) also attempted to derive a generalized correlation of the CHF data obtained for $F_c = 0.10$ to 0.50.

5.1.2. Theoretical models

Dobran (1985) conducted an analytical study of the closed two-phase thermosyphon, based on the three governing equations of continuity, momentum and energy, allowing for interfacial friction between the two phases and assuming a liquid film thickness δ_m common to all the cooled, adiabatic and heated sections. Reed & Tien (1987) extended the foregoing lumped model by assuming individual mean liquid film thicknesses δ_c, δ_a and δ_e for each of the three sections; and their analysis suggests that the CHF occurs when the countercurrent flow reaches the point where there is a sharp increase in the liquid film thickness.

5.2. *The CHF in a Heated Bottom-closed Vertical Tube with an Upper Saturated Liquid Reservoir*

A heated vertical tube closed at the bottom end, and open at the top end to an upper saturated liquid reservoir of large volume, is a useful device for the basic study of the CHF mechanism in the closed two-phase thermosyphon, because the liquid reservoir acts as a pressurizer capable of stabilizing the system pressure at any prescribed magnitude.

5.2.1. Experimental studies

Chang & Yao (1983) conducted an experimental study on the CHF of boiling in very narrow vertical annuli closed at the bottom (composed of an unheated inner cylinder of 63.5-mm o.d. and a heated shroud of 25.4- to 76.2-mm long with gap sizes of 0.32–2.58 mm), employing water and acetone at 1 atm and R-113 at 1–4.04 atm; and they derived an empirical CHF correlation based on the famous Wallis correlation of flooding.

Meanwhile, Smirnov (1984) performed an experimental study on the CHF of water boiling in bottom-closed vertical tubes, annuli and rod bundles, respectively. Then, based on the Kutateladze two-phase flow stability criterion (cf. Pushkina & Sorokin 1969), he derived empirical correlations of the CHF data. In the case of a tube, the following correlation has been given for $d = 6$ to 23 mm, $L/d = 20$ to 400 and pressure in the wide range 0.2–12 MPa (i.e. $\rho_G/\rho_L = 0.00120$ to 0.347):

$$q_c/\rho_G H_{fG} = 0.163[\sigma g(\rho_L - \rho_G)/\rho_G^2]^{1/4} \cdot (d/L)(\rho_L/\rho_G)^{0.1}. \quad [33]$$

It is really surprising to see two quite similar correlations, [32] and [33], derived in mutually independent studies (as mentioned in sections 5.1.1. and 5.2.1).

Katto & Hirao (1991) and Katto & Watanabe (1992) conducted experiments on the CHF of water boiling at 0.1–0.4 MPa in bottom-closed vertical tubes of $d = 8$ to 12 mm and $L/d = 20$ to 120, clarifying the following matters: (1) after a slight stepwise increase in the heat flux up to the CHF, a rather long time lag is often observed prior to the onset of the wall temperature excursion; (2) a slow and irregular wall temperature excursion appears at the CHF condition, being different from a sudden and sharp rise in the ordinary CHF (which may correspond to the "unstable CHF" in section 4.1.2); (3) the temperature excursion commences at an intermediate location along the tube length; and (4) the CHF is insensitive to the liquid level in the reservoir. The foregoing items (1)–(3) suggest the need for careful detection of the onset of the wall temperature excursion for the correct measurement of the CHF value.

5.2.2. Theoretical models

Katto & Watanabe (1992) and Katto (1994) presented a theoretical model of the CHF in a bottom-closed vertical tube heated uniformly and connected with an upper saturated liquid reservoir. This model is an improved version of the so-called "envelope theory" of flooding, one of the flooding theories (Bankoff & Lee 1986) which predicts the limit condition from the flow limit of a "steady-state" separated two-phase flow in an nonevaporative gas–liquid countercurrent flow tube. In contrast to the nonevaporative tube, in the case of the evaporative bottom-closed tube, the mass flow rate of either the vapor or liquid changes in magnitude continuously along the tube length, with the highest value at the top end. In other words, the trigger condition leading to the onset of the CHF at the intermediate location of the tube is concentrated at the top end, suggesting that the improved envelope theory predicts the CHF on the basis of the local condition at the top end alone. In fact, the abovementioned theoretical model predicts the CHF well, and reveals that the CHF can occur when the interfacial friction is increasing in magnitude with increasing liquid film thickness. [N.B. The foregoing trigger condition concentrated at the top end differs from the concept of the "top flooding" in quenching (cf. Collier 1982; Osakabe & Kawasaki 1989).]

On the other hand, Lock (1993) considered the CHF in the evaporative thermosyphon from the standpoint of the ordinary flooding limit. Assuming that the limit is characterized by a balance between the inertial force, buoyancy and surface tension acting on a curved liquid–vapor interface, he discussed the role of the Bond, Froude, Weber and Kutateladse numbers, leading to a criterion in the form of $\mathrm{Ku} = f(T/T_c, \rho_G/\rho_L, \mathrm{geom})$, where T_c is the critical temperature. Lock (1993) insists that (1) the role of interfacial friction is minor, (2) the thickening of the liquid film may have a plausible role, but is not an indispensable factor and (3) the factors of importance are the buoyancy and surface tension.

6. CONCLUSIONS

This paper presents a synthetic review of recent studies on the CHF, showing a variety of facets of the CHF phenomenon together with the present status as to how the onset of the CHF can be explained physically, and predicted empirically or theoretically, under various configurations of two-phase flow. The range of conditions under which the experiments were carried out have been mentioned regardless of the complexity, because such information is important at the present stage in the study of the CHF phenomenon. The author hopes that this review will be useful in directing future studies toward a better understanding of the CHF, as well as in developing new CHF technologies in the field of engineering.

Finally, it is to be noted that, due to space limitations and other reasons, the description of several tributary subjects and some speculative studies has been omitted.

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