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CRITICAL HEAT FLUX FOR FREE CONVECTION BOILING IN THIN RECTANGULAR CHANNELS

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ABSTRACT

A review of the experimental data on free convection boiling critical heat flux (CHF) in vertical rectangular channels reveals three mechanisms of burnout. They are the pool boiling limit, the circulation limit, and the flooding limit associated with a transition in flow regime from churn to annular flow. The dominance of a particular mechanism depends on the dimensions of the channel. Analytical models were developed for each free convection boiling limit. Limited agreement with data is observed. A CHF correlation, which is valid for a wide range of gap sizes, was constructed from the CHFs calculated according to the three mechanisms of burnout.

NOMENCLATURE

A	Flow area
A_H	Heated area
C_f	Fanning friction factor at interface
C_p	Thermal heat capacity at constant pressure
D_H	Hydraulic diameter
f	Friction factor
G	Mass flux
g	Gravitational acceleration
h_{fg}	Latent heat of vaporization
j	Superficial velocity
Ku	Kutateladze number
L	Height of heated channel
p	Pressure
q	Heat flux
ΔT_{sub}	Degree of liquid subcooling
V	Phase velocity
W	Channel width
x	Flow quality
z	Axial Location

Greek Symbols

α	Void fraction
δ	Liquid film thickness
ϕ_{lo}^2	Two-phase friction multiplier
ϕ^*	Correction to Reynolds number
μ	Dynamic viscosity
ρ	Density
$\Delta\rho$	$\rho_f - \rho_g$
σ	Surface tension
τ	Wall shear stress

Subscripts

a	Acceleration
c	Critical or dryout condition
CHF	Critical heat flux
e	Exit
f	Saturated liquid
F	Flooding limit
g	Vapor phase
h	Hydrostatic head
i	Interface or inlet
l	Liquid phase
L	Channel length or circulation limit
m	Two-phase mixture
P	Pool boiling limit
w	Wall

Superscripts

*	Non-dimensional parameter with respect to 2W
—	Average value

INTRODUCTION

An important mode of heat transfer in research and test nuclear reactors is free convection boiling in thin, rectangular channels. To minimize the need for support structures above the reactor core, many research and test reactors have downward coolant flow. When conditions are upset, such as by a loss of forced flow, the removal of decay heat from the reactor fuel is by natural circulation. Free convection boiling in a coolant channel provides the buoyancy force required to initiate the transition from downward flow to natural circulation. As many research and test reactors use plate-type fuel elements, the coolant channels are thin rectangular channels. An understanding of the dryout mechanism associated with free convection boiling in thin vertical rectangular channels is, therefore, of interest in evaluating the safety of such reactors. The ability to predict critical heat flux (CHF) in a confined space, such as in a thin rectangular channel, is also an important factor in the cooling of electronic components by immersion in a liquid.[1] Here the CHF determines the maximum safe heat load a component can generate without causing thermal excursion and temperature overshoot.

Monde[2] and Fujita[3,4] have studied CHF of free convection boiling in water in vertical rectangular channels. In both sets of experiments, the channels were formed by two vertical surfaces of length L and width W, with a spacing, S, between them. Uniform heating was applied to one surface of the channel (measured L x W) that was submerged in saturated water at one atmosphere. Burnout was detected by observing the temperature excursion in the channel wall.

An examination of the Monde CHF data[2] shows that CHF in a thin vertical rectangular channel decreases in a roughly hyperbolic fashion with increasing L/S. As $L/S \rightarrow 0$, the CHF data approaches the pool boiling CHF. Yet, as L/S increases to ≈100, the measured CHF is only about one-tenth that of the pool boiling CHF.

Using CHF data obtained in four different liquids (water, ethanol, freon 113, and benzene), Monde[2] formulated a generalized correlation of the CHF data. The correlation, which agrees with the data within ±20%, has the form,

$$\frac{q_c/\rho_g h_{fg}}{\left(\sigma g \Delta\rho/\rho_g^2\right)^{1/4}} = \frac{0.16}{1 + 6.7\times10^{-4}\left(\rho_f/\rho_g\right)^{0.6} L/S} \qquad (1)$$

It is noted that when $L/S = 0$, equation (1) reduces to the Kutateladze correlation for pool boiling CHF.[5]

Fujita's data[3,4] on free convection boiling CHF show that, for a given vertical rectangular channel of height L, CHF increases with gap size, S. In Fujita's experiment, the maximum gap size was 2 mm, while the heights of the two channels tested were 30 mm and 120 mm, respectively. The L/S ratio was much larger than unity, and the measured critical heat fluxes were less than the pool boiling CHF. Fujita et al.,[3,4] observed that CHF in thin vertical rectangular channels may be predicted from the limiting condition that the homogeneous flow of a vapor and liquid mixture in a vertical duct, driven by natural circulation, is completely vaporized at the top exit of the heated channel. This burnout mechanism has been called a circulation-limited burnout[6] that occurs when the flow is low and the vapor quality at the exit approaches 100%.

In their study of critical heat flux under conditions of low flow in a vertical annulus, Mishima and Ishii[7] suggested that another mechanism of burnout may result from a transition in flow regime from churn-turbulent to annular. They observed that this type of burnout occurred over the same range of mass velocity as circulation-limited burnout. Mishima and Nishihara[8] measured CHF at low mass upflow in thin vertical rectangular channels and they also observed a correspondence between CHF and flow regime transition.

The above discussion reveals three mechanisms of free convection boiling burnout in vertical rectangular channels. They are the pool boiling limit, the circulation limit, and the flow regime transition limit. All three mechanisms can be modeled by analyzing the hydraulics in a rectangular channel. In the present study, the required steam flow to effect a transition from churn to annular flow is derived from a flooding condition imposed on the liquid film along large churn-flow bubbles. A homogeneous two-phase flow model is used to predict the circulation-limited CHF. The three dryout mechanisms are then discussed in the context of existing data. Observations also are made on the relationship between the dryout mechanisms and the dimensions of the rectangular channels.

FLOW REGIME TRANSITION BURNOUT

According to a mechanism of flow regime transition suggested by Mishima and Ishii,[9] a criterion for the transition from churn to annular flow is obtained by postulating a reversal of flow in the liquid film along large bubbles. Locally, reversal in a draining liquid film occurs when the interfacial drag is high enough to levitate the film. This condition is equivalent to the case of zero liquid penetration in counter-current flow limitation (CCFL). It is then reasonable to treat a burnout caused by a transition in flow regime as a limiting case of the so-called circulation and flooding limited burnout. The cause of a circulating and flooding limited burnout is that all the liquid entering the flow passage from the bottom (the circulation part of the flow) is vaporized, and the liquid from the top is limited by flooding due to high steam flow, resulting in a dryout on the heated surface. For a burnout caused by a transition in flow regime, the steam flow is high enough to prevent liquid flow from the top.

An analytical expression for predicting flooding (CCFL) in thin rectangular channels was recently derived from the two-component momentum equations for the liquid and gas phase.[10] The flooding correlation was also successfully applied to predict flooding-limited CHF in thin rectangular channels.[11] This previously derived flooding model is used to establish the required steam flow that effects a transition in flow regime. As shown in Figure 1, the flooding model assumes that the liquid downflow is in a film along the narrower, unheated side walls of the channel, while the gas flow occupies the wide span of the rectangular channel. The following development of the flooding model has previously been reported[10,11] and is summarized here for completeness.

A force balance from using two-phase separated flow momentum equations for the liquid and gas phase gives,

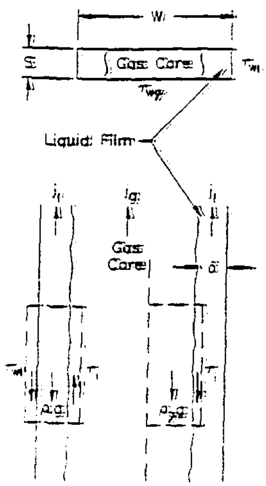

Figure 1. Momentum balance for separated two-phase flow in a thin rectangular channel.

$$\Delta\rho g = \frac{2\tau_i}{\alpha W(1-\alpha)} - \frac{2\tau_{wl}}{W(1-\alpha)} + \frac{2\tau_{wg}}{S} \tag{2}$$

The void fraction is approximated by,

$$\alpha \cong 1 - \frac{2\delta}{W} \tag{3}$$

The average film thickness δ is related to the rate of gas flow through a stability criterion suggested by Richter[12]; it has the form,

$$\delta \cong \frac{\sigma}{2\rho_g (j_g/\alpha)^2} \tag{4}$$

A crucial parameter in the force balance is the interfacial friction. The flooding model uses an interfacial friction factor developed by Wallis[13] for annular flow, namely,

$$f_i = C_f[1 + 75\,(1-\alpha)] \tag{5}$$

The recommended value for the Fanning Friction factor (C_f) is 0.005. A constant C_f of 0.005 was shown to be appropriate for the prediction of flooding-limited CHF in thin rectangular channels.[11]

At the point of zero liquid penetration, the liquid wall shear (τ_{wl}) in equation (2) is zero, and the interfacial shear is simply,

$$\tau_i = \frac{f_i}{2}\rho_g\left(\frac{j_g}{\alpha}\right)^2 \tag{6}$$

The wall shear for the gas flow is expressed as,

$$\tau_{wg} = \frac{f_{wg}}{2}\rho_g\left(\frac{j_g}{\alpha}\right)^2 \tag{7}$$

As a first approximation, set $f_{wg} = C_f$

The force balance in equation (2) is finally reduced to provide the rate of gas flow which stops the liquid film flow. The non-dimensional superficial gas velocity j_g^* at the point of zero liquid penetration or the point of transition in the flow regime is given implicitly by the relation,

$$j_g^{*2}\left[\frac{W^{*2}}{\alpha^2} j_g^{*2} + 150 + \frac{2W}{S}\right] - \frac{2\alpha^2}{3C_f} = 0 \tag{8}$$

where

$$j_g^* = \frac{j_g}{[2Wg\Delta\rho/\rho_g]^{1/2}} \tag{9}$$

and

$$W^* = \frac{2W}{[\sigma/g\Delta\rho]^{1/2}} \tag{10}$$

The void fraction α is solved in terms of j_g^* using equations (3), (4), (9), and (10).

$$\alpha = \frac{\left[1 + 8/W^{*2} j_g^{*2}\right]^{1/2} - 1}{4/W^{*2} j_g^{*2}} \tag{11}$$

The non-dimensional superficial gas velocity j_g^* also can be written in terms of the Kutateladze number Ku, i.e.,

$$j_g^* = \mathrm{Ku}/W^{*1/2} \tag{12}$$

where,

$$\mathrm{Ku} = \frac{j_g}{[\sigma g\Delta\rho/\rho_g^2]^{1/4}} \tag{13}$$

Equation (8) approaches a constant Kutateladze number asymptotically when $W^* \to \infty$ and $\alpha \to 1$,

$$\lim_{\substack{W^* \to \infty \\ \alpha \to 1}} \mathrm{Ku} = \left(\frac{2}{3C_f}\right)^{1/4} \tag{14}$$

With a $C_f = 0.005$, the asymptotic value for the Kutateladze number at the zero liquid penetration point is Ku = 3.4 which is very close to the 3.2 value obtained by Pushkina and Sorokin[14] from experiments in large pipes. Previously, Taitel et al.[15] have suggested that transition to annular flow in a vertical pipe occurs when the Kutateladze number exceeds 3.1. Therefore, the criterion for flow regime transition developed here is consistent with their proposed model.

The critical heat flux corresponding to a transition in flow regime from churn to annular is obtained from a heat balance. According to this dryout mechanism, when burnout occurs, the heat energy that goes from the heated wall to the flow channel is equivalent to the amount of energy required to generate the steam flow given in equation (8). Thus, burnout heat flux of a flow regime transition is given by,

$$q_{c,F} = \frac{A}{A_H} j_g^* \left[2Wg\Delta\rho/\rho_g \right]^{1/2} \rho_g \left(h_{fg} + C_p \Delta T_{sub} \right) \quad (15)$$

where ΔT_{sub} is the liquid subcooling and j_g^* is evaluated from equation (8) that provides implicitly the required steam flow to effect a transition in flow regime.

CIRCULATION LIMITED BURNOUT

In a circulation-limited burnout, dryout occurs when the vapor quality at the exit reaches 100% in a heated channel that is fed by natural circulation flow. The critical power then is equivalent to the power required to convert all the natural circulation flow entering the heated channel into saturated steam. In calculating a burnout heat flux, the only difference between the flow regime transition limit and the circulation limit is the determination of the limiting mass flux.

Imagine a heated channel immersed in a large pool of saturated water. The driving pressure that establishes natural circulation flow through the channel is

$$\Delta p_h = \left(\rho_f - \bar{\rho} \right) gL \quad (16)$$

where $\bar{\rho}$ is the average density of the mixture in the channel and is evaluated as,

$$\bar{\rho} = \rho_f - \Delta\rho\bar{\alpha} \quad (17)$$

In a uniformly heated channel with a saturated inlet liquid flow and a homogeneous two-phase flow in the channel, the average void fraction $\bar{\alpha}$ is given in terms of the exit void fraction α_e,

$$\bar{\alpha} = \frac{1}{(1-\psi)} \left\{ 1 + \left(\frac{1}{\alpha_e (1-\psi)} - 1 \right) \ln \left[1 + \alpha_e (1-\psi) \right] \right\} \quad (18)$$

where $\psi = \rho_g/\rho_f$ and,

$$\alpha_e = \frac{x_e}{\psi + (1-\psi) x_e} \quad (19)$$

When the exit quality x_e becomes 1, so does the exit void fraction.

The single-phase inlet pressure loss Δp_i is the sum of a local loss and an acceleration pressure drop due to a change in area,

$$\Delta p_i = 1.5 \left(\frac{G^2}{2\rho_f} \right) \quad (20)$$

The frictional pressure drop through the channel is,

$$\Delta p_L = \frac{G^2}{2\rho_f D_H} \int_0^L f \phi_{lo}^2 \, dz \quad (21)$$

A homogeneous two-phase friction multiplier is used,

$$\phi_{lo}^2(z) = 1 + \left(\frac{\Delta\rho}{\rho_g} \right) x(z) \quad (22)$$

where, for a uniformly heated channel with zero inlet quality,

$$x(z) = x_e \, z/L \quad (23)$$

The friction factor f is evaluated from the Blasius equation with a correction for the viscosity suggested by McAdams,[16] and a correction ϕ^* for the Reynolds number in a rectangular channel suggested by Jones,[17]

$$f = 0.316 \left(\frac{\phi^* G \, D_H}{\mu_m} \right)^{1/4} \quad (24)$$

where

$$\mu_m = \frac{1}{(1-x)/\mu_f + x/\mu_g} \quad (25)$$

and

$$\phi^* = \frac{2}{3} + \frac{11}{24} \frac{S}{W} \left(2 - \frac{S}{W} \right) \quad (26)$$

A good approximation to the integral in equation (21) is to use the mean value of the quality in equations (22) and (25).

The acceleration pressure drop in the channel due to boiling is,

$$\Delta p_a = \frac{G^2}{\rho_f} \left[\frac{(1-x_e)^2}{1-\alpha_e} + \frac{\rho_f \, x_e^2}{\rho_g \, \alpha_e} - 1 \right] \quad (27)$$

There is essentially no pressure loss at the channel's exit since the kinetic energy recovered from an area expansion is approximately equal to the local loss.

The sum of all pressure losses must equal the driving pressure, i.e.,

$$(\rho_f - \bar{\rho}) gL = 1.5 \left(\frac{G_L^2}{2\rho_f} \right) + \left(\frac{G_L^2}{2\rho_f} \right) \left(\frac{fL}{D_H} \right) \left(1 + \frac{1}{2} \frac{\Delta\rho}{\rho_g} \right) + \left(\frac{G_L^2}{\rho_f} \right) \left(\frac{\rho_f}{\rho_g} - 1 \right) \quad (28)$$

To be consistent with the circulation-limited burnout mechanism, the exit quality is set to unity in equation (28), while the mean quality is equal to 1/2.

Once the circulation flow, G_L, is determined from equation (28), the circulation-limited, CHF, is calculated by,

$$q_{c,L} = \frac{A}{A_H} G_L h_{fg} \qquad (29)$$

We note that when the inlet flow is subcooled, the pressure balance in equation (28) must be modified to reflect a non-boiling and a boiling section in the channel, i.e., replacing the heated length (L) with the boiling length. Similarly, equation (29) must be changed to account for the contribution from sensible heating, i.e., replacing h_{fg} with $h_{fg} + C_p \Delta T_{sub}$.

PREDICTION OF FREE CONVECTION CHF

Experimental observations suggest that there are three free convection boiling dryout mechanisms in narrow channels. The classical pool boiling CHF is observed when the L/S ratio in a rectangular channel approaches zero.[2] Thus, when the channel is somewhat thick, burnout is due to vapor blanketing, and the CHF can be predicted by the Kutateladze correlation for pool boiling (in saturated liquid),

$$q_{c,P} = 0.16\, \rho_g h_{fg} \left[\sigma g \Delta\rho / \rho_g^2 \right]^{1/4} \qquad (30)$$

The free convection boiling data obtained by Monde et al.,[2] suggest that CHF decreases with a reduction in the gap size of a rectangular channel. When the data from Monde are plotted, in terms of the Kutateladze number, defined in equation (13), a pattern emerges (Figure 2). For W/S > 5, the CHF data obtained in the shorter channels (L = 20 mm and 35 mm) follow the trend predicted by the criterion for the flow regime transition expressed in equation (8). The CHF data obtained in the longer channel (L = 50 mm) are all above the flow regime transition curve when W/S is greater than 5. This suggests that another burnout mechanism is probably responsible for dryouts occurring in longer channels. Equation (8) shows that a higher friction factor C_f results in a lower steam flow at the point of zero liquid penetration. The two curves in Figure 2, using a C_f of 0.005 and 0.008, respectively, clearly demonstrates this trend. It is also evident that the theory of flow regime transition burnout only applies to small gap sizes.

Focusing on free convection boiling CHF in somewhat thin rectangular channels (with W/S > 5), Figures 3 and 4 show the water CHF data obtained by Monde, et. al.[2] and Fujita, et. al.,[3,4] respectively. Also displayed are the predictions of CHF based on the criterion for flow regime transition (equation (15)) and the circulation-limited criterion (equation (29)). The predictions generally follow the trend of the data. No attempt was made to fine tune the model parameters (such as friction factors) to achieve better quantitative agreement between data and theory.

As seen in Figure 3, with W = 10 mm and channel gaps in the order of 1 mm, the circulation-limited CHF is higher than the CHF based on a transition in flow regime. Monde's CHF data for the shorter channel (L/W = 2) are closer to the flow regime transition CHF than the circulation-limited CHF. The data for the longer channel (L/W = 5) lie midway between the critical heat fluxes predicted by the two burnout mechanisms.

Fujita's CHF data were obtained using wider channels (W = 30 mm). In Figure 4, the two burnout mechanisms give similar critical heat fluxes for the shorter channel (L/W = 1).

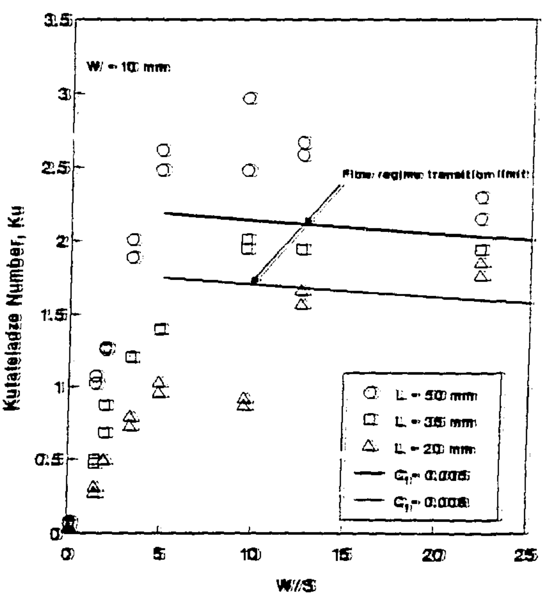

Figure 2. Monde's CHF data (saturated water) in terms of the Kutateladze number.

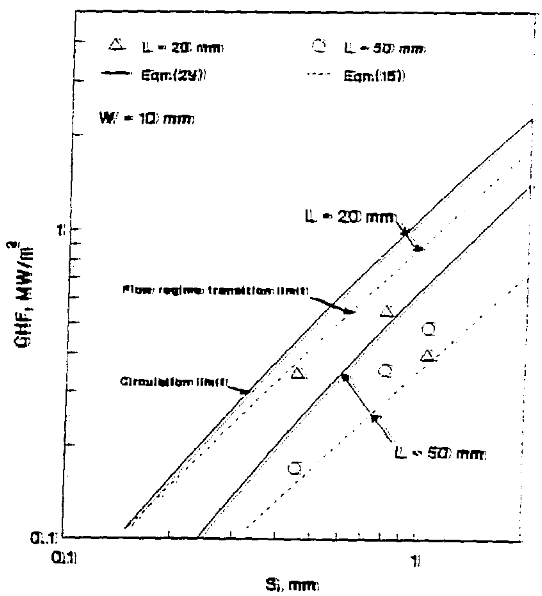

Figure 3. Comparison of circulation limited CHF, flow regime transition CHF and Monde's CHF data (saturated water at atmospheric pressure).

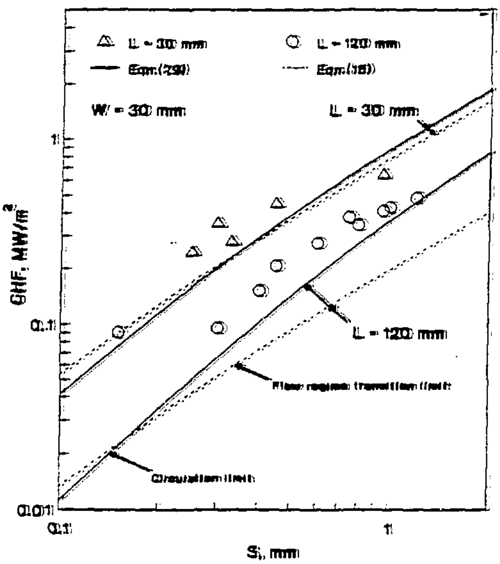

Figure 4. Comparison of circulation limited CHF, flow regime transition CHF and Fujita's CHF data (saturated water at atmospheric pressure).

and Fujita's data are reasonably predicted. For the longer channel used by Fujita ($L/W = 4$), the circulation-limited CHF is generally higher than the flow regime transition CHF, and the data are better predicted by the circulation limit.

EFFECTS OF CHANNEL DIMENSIONS ON BURNOUT MECHANISM

From the predictions shown in Figures 3 and 4 there appears to be a correlation between the L/W ratio and the ratio between the critical heat flux predicted by the criterion for flow regime transition and the circulation-limited criterion. The circulation limit gives higher heat fluxes than the flow regime transition when the ratio L/W is greater than one. This trend can be explained by a closer look at the model equations. From a simplified analysis of flooding, it was shown[10] that at the point of zero liquid penetration in a thin rectangular channel $j_g^* = (\pi/4)^{1/2}$ or,

$$j_{g,F} = 0.9\left[\frac{2Wg\Delta\rho}{\rho_g}\right]^{1/2} \tag{31}$$

When the loss of pressure due to acceleration becomes dominant on the RHS of equation (27), circulation flow can be approximated by,

$$G_L = \left[(\rho_f - \bar{\rho})\rho_g gL\right]^{1/2} \tag{32}$$

Noting that $(\rho_f - \bar{\rho}) \approx \Delta\rho$, equation (32) is further simplified to give,

$$G_L = \left(\rho_g \Delta\rho\, gL\right)^{1/2} \tag{33}$$

or,

$$j_{g,L} = \left[\frac{Lg\Delta\rho}{\rho_g}\right]^{1/2} \tag{34}$$

A comparison between equations (31) and (34) yields,

$$\frac{j_{g,L}}{j_{g,F}} = \left[\frac{L}{1.6W}\right]^{1/2} \tag{35}$$

This simplified analysis shows that the circulation-limited CHF will exceed the CHF given by the criterion for flow regime transition when the height of a heated channel is approximately one and one-half times greater than the width. This approximation is consistent with the calculations shown in Figures 3 and 4. It is noteworthy that a typical coolant channel in a research reactor has a L/W ratio of about 10, and a W/S ratio of about 25. Therefore, the free convection boiling burnout in a research reactor is dictated by the circulation limit and not by the flooding phenomenon associated with a transition in flow regime.

So far, the discussions on free convection boiling CHF have focused on channels that are either very thick or very thin. The pool boiling limit explains the burnout mechanism in "thick" channels. Burnouts in "thin" channels are caused by the circulation limit for "long" channels, and the criterion for flow regime transition for "short" channels. A CHF correlation that is valid for a wide range of gap sizes, from thick to thin channels, can be constructed from the CHFs calculated according to the three burnout mechanisms discussed. One of the simplest forms of such a correlation is,

$$q_c = \frac{1}{1/q_{c,P} + 1/q_{c,L}} \tag{36}$$

for "long" channels with $L/W > 1.5$, and,

$$q_c = \frac{1}{1/q_{c,P} + 1/q_{c,F}} \tag{37}$$

for "short" channels with $L/W < 1.5$.

The critical heat fluxes, $q_{c,P}$, $q_{c,L}$, and $q_{c,F}$ are given by equations (15), (29), and (30), respectively. Similar to the empirical correlation suggested by Monde (equation (1)) equations (36) and (37) reduce to the pool boiling limit when the channel gap (S) becomes large. For small gap sizes, the equations approach the circulation limit and the flow regime transition limit, respectively. Comparisons of the two correlations (equations (36) and (37)) with three sets of CHF data from Monde are shown in Figures 5 through 7. These data were taken from somewhat "long" channels, i.e., $L/W > 1.5$, and as expected, they are well predicted by equation (36). It is noted that the correlations generally under-predict Fujita's data that were all from somewhat thin channels.

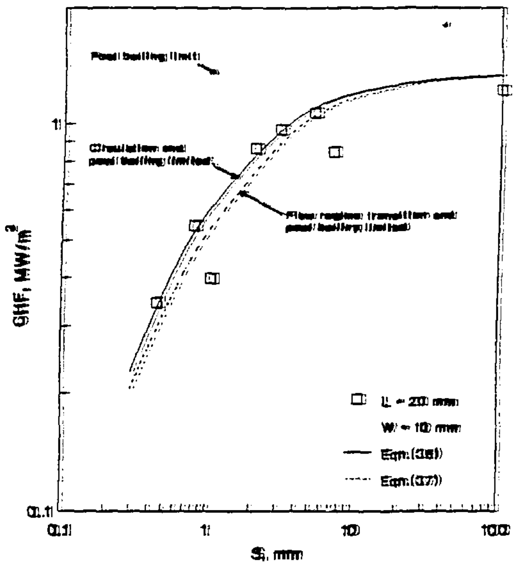

Figure 5. Comparison of CHF correlations with Monde's saturated water CHF data (L = 20 mm).

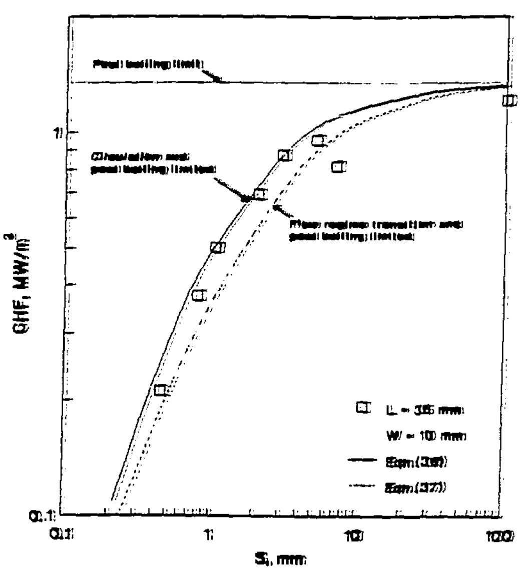

Figure 6. Comparison of CHF correlations with Monde's saturated water CHF data (L = 35 mm).

CONCLUSIONS

Three mechanisms of free convection boiling burnout in vertical rectangular channels have been identified. For a somewhat thick channel, where $L/S \rightarrow 0$, the mechanism of burnout is vapor blanketing, similar to dryout in pool boiling. In somewhat thin channels, with $W/S > 5$, burnout in short channels ($L/W < 1.5$) is due to local flooding associated with a transition in flow regime, while in long channels ($L/W > 1.5$), burnout is dictated by the circulation limit. Given the dimensions of the coolant channels of a typical research reactor, free convection boiling is limited by circulation-limited burnout. The analytical models developed to predict critical heat fluxes due to different burnout mechanisms are shown to agree qualitatively with experimental data.

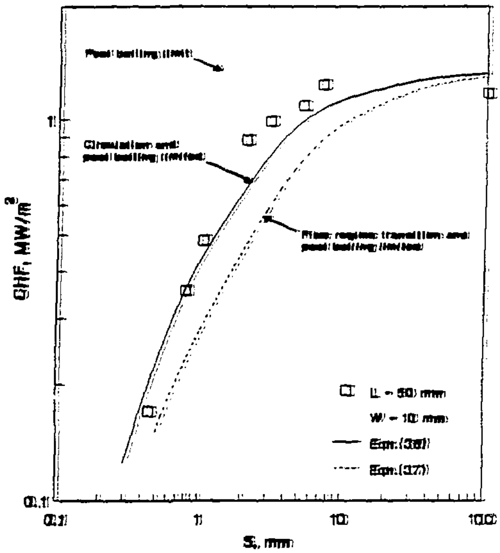

Figure 7. Comparison of CHF correlations with Monde's saturated water CHF data (L = 50 mm).

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REFERENCES

1. G.P. PETERSON and A. ORTEGA, "Thermal Control of Electronic Equipment and Devices," Advances in Heat Transfer, Volume 20, Academic Press, Inc., New York, (1990).

2. M. MONDE, H. KUSUDA, and H. UEHARA, "Critical Heat Flux during Natural Convective Boiling in Vertical Rectangular Channels Submerged in Saturated Liquid," J. Heat Transfer, 104, p 300-303, (1982).

3. Y. FUJITA, H. OHTA, S. UCHIDA, and K. NISHIKAWA, "Nucleate Boiling Heat Transfer and Critical Heat Flux in Narrow Space between Rectangular Surfaces," Int. J. Heat Mass Transfer, 31, No. 2, p 229-239, (1988).

4. Y. FUJITA, and S. UCHIDA, "Boiling Heat Transfer and Critical Heat Flux in a Confined Narrow Space," Proc. 9th Int. Heat Transfer Conference, Hemisphere Publishing Corporation, New York, (1990).

5. S.S. KUTATELADZE, "Heat Transfer in Condensation and Boiling," AEC-tr-3770, (1952).

6. D. BARNARD, F. DELL, and R. STINCHCOMBE, "Dryout at Low Mass Velocities for an Upward Boiling Flow of Refrigerant-113 in a Vertical Tube," HTFS Symposium, AERE-R7726, (1973).

7. K. MISHIMA and M. ISHII, "Critical Heat Flux Experiments Under Low Flow Conditions in a Vertical Annulus," NUREG/CR-2647, (1982).

8. K. MISHIMA and H. NISHIHARA, "The Effect of Flow Direction and Magnitude on CHF for Low Pressure Water in Thin Rectangular Channels," Nuc. Eng. & Design, 86, p 165-181, (1985).

9. K. MISHIMA and M. ISHII, "Flow Regime Transition Criteria for Upward Two-Phase Flow in Vertical Tubes," Int. J. Heat Mass Transfer, 27, No. 5, p 723-737, (1984).

10. L. CHENG, "Counter-Current Flow Limitation In Thin Rectangular Channels," Proc. Int. Topical Meeting on the Safety Status and Future of Non-Commercial Reactors and Irradiation Facilities, ANS, (1990).

11. L. CHENG, "Counter-Current Flow Limited CHF in Thin Rectangular Channels," Proc. 3rd ASME-JSME Thermal Engineering Joint Conference, ASME, (1991).

12. H. RICHTER, "Flooding in Tubes and Annuli," Int. J. Multiphase Flow, 7, p 647-658, (1981).

13. G.B. WALLIS, One-Dimensional Two-Phase Flow, McGraw-Hill, New York, (1969).

14. D. PUSHKINA and Y. SOROKIN, "Breakdown of Liquid Film Motion in Vertical Tubes," Heat Transfer-Soviet Research, 1, No. 5, p 56-64, (1969).

15. Y. TAITEL, D. BORNEA, and A. DUKLER, "Modelling Flow Pattern Transitions for Steady Upward Gas-Liquid Flow in Vertical Tubes," AIChE Journal, 26, No. 3, p 345-354, (1980).

16. W. MCADAMS, et al., "Vaporization Inside Horizontal Tubes, II. Benzene-Oil Mixtures," Trans. ASME, 64, p 193, (1942).

17. O. JONES, Jr., "An Improvement in the Calculation of Turbulent Friction in Rectangular Ducts," J. Fluids Engineering, p 173-181, (1976).