COUNTERFLOW CRITICAL HEAT FLUX

Peter Griffith
C. T. Avedisian
and
J. P. Walkush

Upflow, counterflow, and downflow CHF (critical heat flux) data have been taken on a rod in the low (less than 200 000 lb/hr-ft^2) mass velocity region for Freon 113 at 14.7 and 200 lb/in.^{2} abs pressure. A low flow CHF correlation, based on pool boiling from a vertical surface, is proposed. The correlation is to be used to calculate if and where CHF will occur during a loss of coolant accident in a nuclear reactor when the flow passes through zero early in the accident. A preliminary comparison of the CHF predictions for high pressure water with the heat flux level found in PWR's indicates that CHF is not likely to occur at the first flow reversal.

INTRODUCTION

During the calculated loss of coolant accident for a pressurized water nuclear reactor, the flow reverses in the core. Using the usual statement of the energy equation to calculate the quality, one then calculates that as the flow approaches zero, the quality rises to 100%. Critical heat flux is then calculated to occur either owing to high quality or low mass velocity, even though there is still a lot of water present in the core. This calculated CHF probably does not occur but is a consequence of an inappropriate means for calculating when CHF, in a low velocity up, down, or counterflow flow regime, is to be expected.

It is proposed here to change the method of calculating for CHF in a low mass velocity flow. This is done by using void rather than quality to describe the state of the system. The importance of this change can be illustrated by considering, for a moment, an extreme example.

Imagine a small vertical tube, in upflow, with saturated low pressure steam passing through it at a velocity greater than, say, 50 ft/s. Whether the pipe starts full or empty, soon only steam will be found in it. Only steam enters the tube, and only steam will be found in it. Any heat transfer coefficient measured for this tube will be characteristic of steam in forced convection flow, that is, quite low. The quality, obviously, will be 100%.

If, however, the same steam flow is passed through a large pipe, initially full of water, it will simply bubble up through the pool. The water will be saturated. The quality will again be 100%. If now, for the large pipe, we transfer heat at the wall, we will find a heat transfer coefficient characteristic of pool boiling from a vertical surface. If we increase the heat flux sufficiently, at some point CHF will occur. The heat flux for this CHF will be similar to that obtained for boiling from a vertical surface. We can say then that when the velocity level is low enough, it is not what is passing through which determines the value of the CHF, rather it is what is there that counts. Void describes what is there so that a CHF vs. void correlation might be appropriate for correlating low mass velocity CHF data.

To be more specific, it is proposed to develop experimentally a CHF vs. void correlation which applies at low mass velocities. Low in this case means a mass velocity such that the liquid travels appreciably slower than the vapor and is normally concentrated at the wall rather than in the core. There is considerable evidence that the flow pattern characteristic of subcooled boiling, that is, a bubble layer on the wall with a core consisting largely of liquid, can persist into the saturated region at high mass velocity. This flow regime does not provide nearly as good cooling as the one in which the liquid is predominately on the wall. When the CHF data are compared to an existing CHF correlation later in this paper, we shall expand on this point further. In any case, the CHF vs. void correlation proposed in this paper applies only if the velocity level is low enough so that the liquid can flow back and only to the flow regime in which the liquid is concentrated at the walls.

Massachusetts Institute of Technology, Cambridge, Massachusetts. C. T. Avedisian is with Bell Laboratories, New Jersey. J. P. Walkush is with General Atomic, San Diego, California.

0065-8812-78-1355-0174-$00.95.

In the following sections we shall describe the experiments which were run to obtain the CHF vs. void correlations. We shall then expand on the meaning and consequences of these experiments in connection with the calculated loss of coolant accident. Finally, we shall suggest a way in which this correlation can be used to calculate whether CHF will occur when passing through the first flow reversal in the loss of coolant accident.

EXPERIMENTAL PROGRAM

The objective of the experimental program was to determine a CHF vs. void curve that could be used to predict when and where CHF would occur during the LOCA (loss of coolant accident). To this end, a number of experiments were run. Avedisian (*1*), Crossland (*2*), and Walkush (*3*) all ran experiments on apparatuses which were different. The details of these experiments are reported in references *1* through *3*. Two of the sets of data that were taken above are not reported here: Crossland's and Avedisian's early works. Crossland's experiments were run on a vertical surface with an approximately constant void. There were only a few points, and they generally confirmed the reported results of Walkush and Avedisian. To save space, they will not be reported as they do not change the conclusions. The other set is a series of experiments run by Avedisian early in his work which was performed in a tube, rather than on a rod. In order to avoid flooding in these experiments, it was necessary to make the test section so short that it was felt the results were not even approximately representative of reactor practice. All the data were high compared to the data reported here. They are reported in reference *1*, however. The remainder of Avedisian's data, taken on a rod, is reported here.

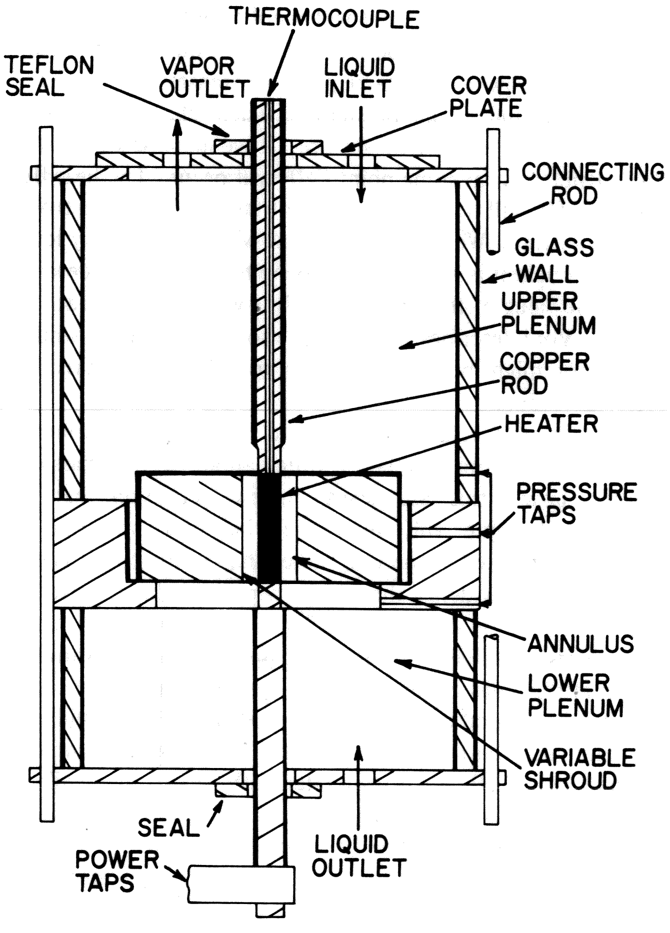

Fig. 1. Low pressure apparatus.

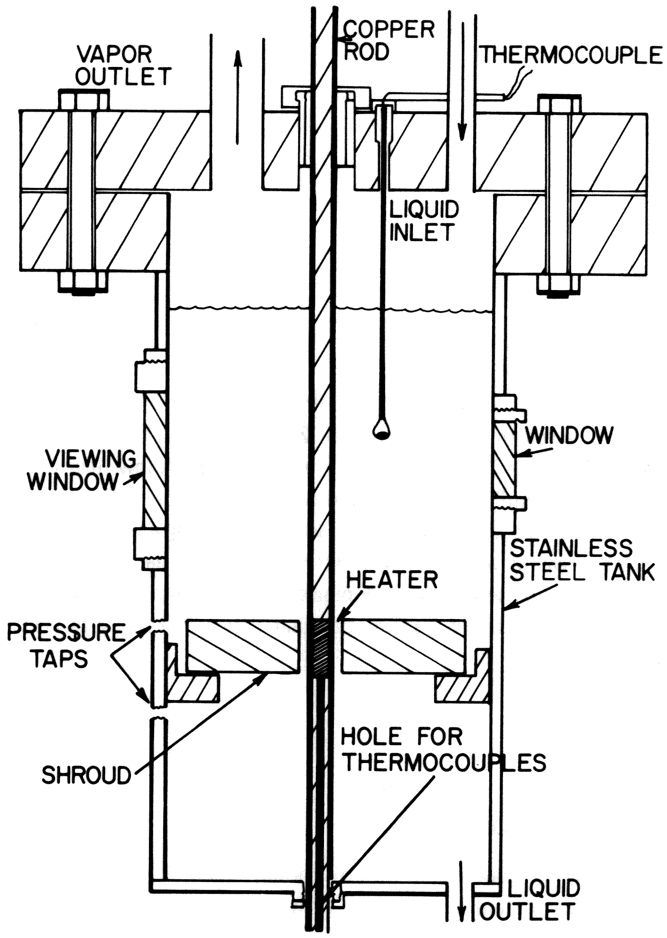

Fig. 2. High pressure test section.

The reported experiments were run in the test sections illustrated in Figure 1 for low pressure and in Figure 2 for high pressure runs. A schematic of the external loop for counterflow operation is shown on Figure 3.

Turning to Figure 3, we can see how the experiment operated. The heater, in this case, is either a 1 or 2 in. rod in the middle of the test chamber. Liquid Freon 113 came in the top of the chamber, while the vapor which was formed rose out the top. A window in the top of the tank (Figure 3) allowed one to see the top of the heater. A shroud of variable size surrounded the heater. As both the mass velocity down and the shroud diameter could be varied, a single value of the void (and CHF) could be obtained with several heater-shroud combinations. By changing the loop piping a few up-up and down-down flow points were also obtained. The points were taken to show that the CHF vs. void curves were valid even though the apparatus was not in counterflow.

When the experiments were run, it was possible to see the top of the test section and watch the vapor as it came out into the upper plenum during counter or upflow. In counterflow, there may have been a little vapor carried down too, but if more than a few small bubbles were carried down, a large bubble collected underneath the shroud which periodically burped back through the gap into the upper plenum. This caused an early CHF indication as the void was substantially higher when this happened than it was when the test section was operating steadily. As the early CHF and the periodic discharge of vapor were easy to see, these points were excluded from those reported.

The void was measured by means of pressure taps leading to a manometer connected across the shroud as shown in Figures 1 and 2. The manometer, of course, measured pressure drop. It was then necessary to convert the pressure drop reading to average void and then convert the average void reading to the maximum void in the test section. This is necessary, as the maximum rather than the average void determines when CHF will be observed. It was concluded from the error analysis described in references *1* and *3* that for the low pressure data (*1*), the momentum and friction pressure drop terms, which are ignored in the data reduction, constituted less than 5% of the overall pressure drop for any void less than 75%. Above 80%, the measured voids can be considerably in error, though it appears that the data taken, and reported here, are consistent. In any case, high void CHF measurements are continuing.

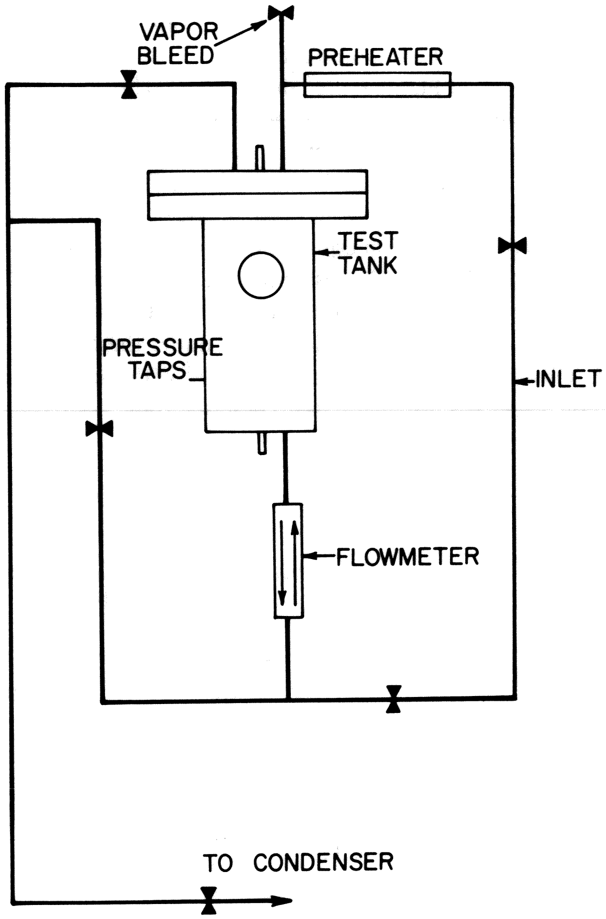

Fig. 3. Schematic of loop for counterflow CHF experiments.

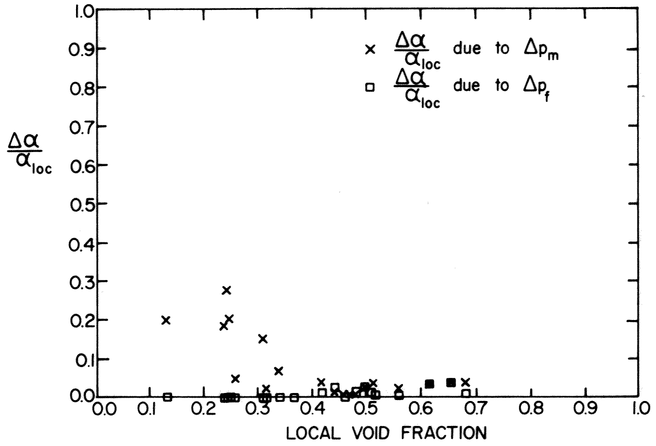

Fig. 4. Significance of momentum and friction terms in calculating void fraction.

For the high pressure data, the errors are larger because the manometer sensitivity is reduced. This is primarily a result of the reduced Freon density in the test section compared to the Freon in the manometer.

An error analysis of the high pressure data is shown on Figure 4. Here, estimates of the friction and momentum pressure drops were converted to equivalent voids. They were then divided by the local void to get a fractional error. The high pressure runs were terminated at higher void because the errors became unacceptable. As can be seen, where the void is appreciable, the error is about 5%. At low void, the fractional error in void may be large, but, as will be shown, the effect of

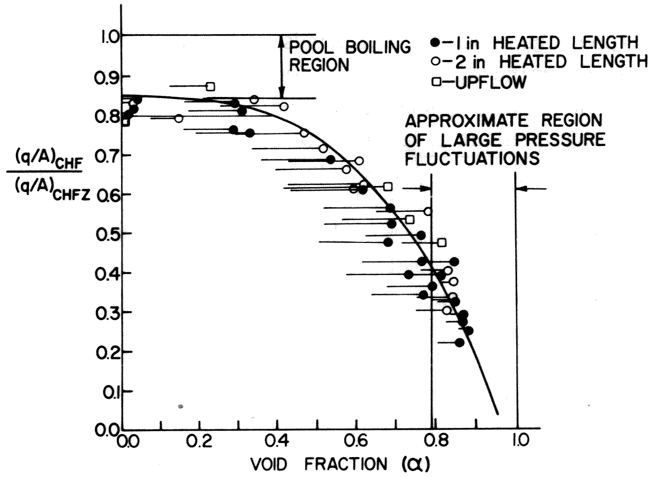

Fig. 5. The relation between counterflow CHF, void fraction, and pool boiling from a vertical surface for low pressure.

these errors on the critical heat flux prediction is negligible. The voids reported on Figure 5 were corrected for the momentum pressure drop.

If we look now at the problem of relating the local void at the CHF point to the average measured void, we see several problems. First, an entirely satisfactory prediction of the void from the vapor and liquid flow rates is not possible because our knowledge of two-phase flows is still not that complete. The only established model which will handle the counterflow regime is the drift flux model so it was used. The constants used in the drift flux model will be given later.

To use the drift flux model, it is still necessary to evaluate the vapor flow rate and make the assumption of thermal equilibrium. For the low voids, though, the assumption of thermal equilibrium is a poor one (*4*). Instead of this assumption, it was decided to assume that the vapor flow up is directly proportional to the distance from the bottom of the heated section and use the measured average void to evaluate the maximum void. That is, the vapor flux J_g at any distance X from the bottom is

$$J_g = J_{g2} \frac{X}{L} \tag{1}$$

The void fraction can be determined, in general, from the separated flow model as

$$\alpha = \frac{J_g}{C_o J + V_{gj}} \tag{2}$$

The average void then becomes

$$\alpha_{avg} = \frac{1}{L} \int_0^L \alpha_{loc}\, dX \tag{3}$$

Substituting (1) for the local vapor flux and (2) for the local void into (3) and integrating, one obtains the relationship between the known average void and the unknown vapor flux at the (vapor) exit at the top of the annulus. This equation is then solved by trial and error for J_{g2}. One then substitutes Equation (2) to determine the local void at the CHF point (the top of the annulus). The details of the data reduction scheme are in the Appendix. The constants which were used in Equation (2) are tabulated in Table 1.

The high pressure data had problems, some of which were not found in the low pressure data. The bubbles were smaller and the flow was more like a boundary-layer flow around a heated rod than a regular two-phase flow. The smaller bubbles did not fill the gap as readily, even for the same void, as the larger, low pressure bubbles did. As a result, an s shaped velocity distribution apparently occurred in the annulus, with a low density bubbly mixture rising near the rod and solid liquid going down near the shroud. The drift flux model does not represent this flow regime very well, so the constants appearing in Table 1 may appear unreasonable. For the high pressure data, they include a C_o of 0.8, which indicates that the bubbles were concentrated in the low velocity region near the wall. This C_o is lower than we are accustomed to when describing a usual two-phase flow.

TABLE 1. CONSTANTS USED IN EQUATION (2)

Experiments	Heat D_o, in.	Shroud D_i in.	C_o	V_{gj}, ft/s
Low pressure counter-current flow (*1*)	0.40	5.375	1.197	0.576
	0.40	1.27	1.187	0.590
	0.40	1.186	1.186	0.595
	0.40	1.0	1.182	0.626
	0.40	0.977	1.182	0.626
	0.40	0.751	1.174	0.639
	0.40	0.546	1.150	0.649
	0.40	0.475	1.144	0.660
Downflow at high pressure (*3*)	0.40	0.751	0.8	0.660
High pressure counter-current flow	0.40	0.546	1.150	0.649
	0.40	0.977	1.182	0.626

The heater was either 1 or 2 in. long.

The low pressure data are presented in Figure 5 and the high pressure data in Figure 6. For these figures, the heat flux is obtained from the current and voltage on the heater. The average void is measured and is the left-hand end of the lines in Figures 5 and 6, while the right end on Figures 5 and 6 is the maximum void calculated as just described. The lines drawn are the best fits to the data. It is recommended that the straight line on Figure 6 be used.

Some points on Figure 6 are labeled counterflow plus 0.1. For these points, substitution of the constants in Table 1 into Equation (2) gave a negative denominator in spite of the fact that vapor was obviously still being discharged into the upper plenum. As the maximum void must be larger than the average, a guess of a correction equal to 0.1 was added to the measured void. For the purpose intended, the magnitude of this correction is not very important, and it is thought that this is the best estimate of the local void under these conditions. Obviously, the separated flow model with the constants given on Table 1 is not adequate to describe these points.

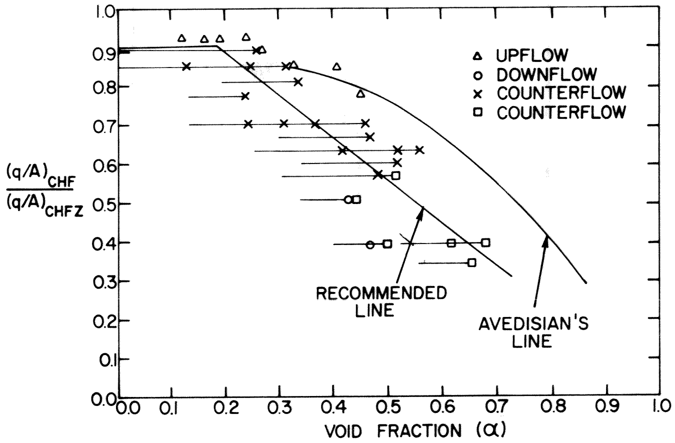

Fig. 6. Unflooded CHF data in an annulus for high pressure.

They are valid measurements of average void and CHF, however, so they have been included. If the reader finds the 0.1 correction on void offensive, then the raw data can be used with the assurance that the CHF prediction so obtained is conservative.

Some of the data that were taken turned out to have been taken under flooding conditions. These data were excluded because the assumptions implicit in the calculations relating local to average void were incorrect. That is, the cluster of Equations (1), (2), and (3) does not describe a flooded two-phase flow. For the low pressure data of Figure 5, Equation (4) from Shires, Pickering, and Blacker (*5*) was used to distinguish the flooded from the unflooded points:

$$J_g^{*1/2} + J_f^{*1/2} = 1.20 \qquad (4)$$

All points where $J_g^{*1/2} + J_f^{*1/2}$ were greater than 1.2 were excluded.

At high pressure, an entirely satisfactory flooding correlation does not exist. The flooding data reported in reference *5* only went up to a J_f^* of 0.5. Some of the data reported in reference *6*, however, show a break in the line at higher J_f^*'s. On the basis of this, the flooding correlation for the high pressure data, shown on Figure 7, has been used. Open points are unflooded, solid points are flooded. All flooded points are excluded from Figure 6.

The range of conditions encompassed by the data shown on Figures 5 and 6 is shown on Table 2. The shroud and heater geometries are shown on Table 1. Recommendations on when to use the suggested CHF vs. void correlation will be made after a discussion of the significance of the curves on Figures 5 and 6.

The heat fluxes shown on Figures 5 and 6 are nondimensionalized, using the pool boiling value of Zuber's as adapted by Leinhardt (*7*) for vertical surfaces. The heaters used here were long enough so that, as Leinhardt indicates, the length should not have played a role. The asymptote at zero void should be about 0.9. The values of heat flux used to nondimensionalize the data are given in Table 3.

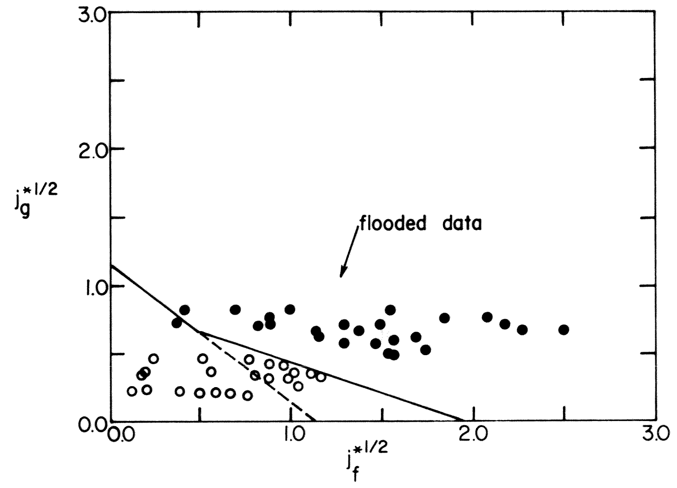

Fig. 7. CHF data graphed on dimensionless axes to determine flooded points.

TABLE 2. VELOCITY RANGE TESTED FOR CHF DATA OF FIGURES 5 AND 6

		(Superficial liquid velocity) ft/s	
Pressure	Flow direction	Maximum	Minimum
	Upflow	3.3	0.12
	Counterflow	1.24	0.0
	Downflow	3.67	2.7
14.7 lb/in.^{2} abs	Upflow	0.329	0.0316
	Counterflow	0.417	0.0
	Downflow	None	

TABLE 3. NON-DIMENSIONALIZING HEAT FLUXES USED TO REDUCE DATA OF FIGURES 5 AND 6 FOR FREON 113

Pressure (psia)	$(q/A)_{CHFZ}$ (BTU/hr ft^2)
14.7	64,925
200	112,022

DISCUSSION

There is no universal CHF vs. void curve that can be used to predict when CHF will occur. The way the phases are distributed in the section, in addition to the void, is of vital importance. We describe the void distribution in a typical CHF correlation by means of a test section length and diameter, the quality, the mass velocity, and perhaps a heat flux variation parameter. Given these considerations, exactly when is it appropriate to use the proposed CHF vs. void correlation?

All the data presented in this paper were taken in the same flow regime. In the annulus, it was possible to see bubbles comparable in size to the gap between the rod and the shroud. This flow regime might be characterized as a bubble or slug flow. For both of these regimes, a drift flux model is appropriate, as the liquid is concentrated at the wall.

Specifically excluded is the flow regime in which a bubble layer exists near the wall with a solid liquid core. This flow regime is characteristic of subcooled or low quality boiling at high mass velocity. Because of experimental limitations on void measurement, higher mass velocities than those presented in Table 2 were not made. Certainly, if one stays within the velocity range covered in Table 2, a satisfactory CHF prediction can be made.

The picture we imagine for this flow regime is as follows. At the CHF point on the surface there is a thin layer of liquid that is replenished each time a bubble passes. While a bubble is passing by, the surface of this film is depleted by drainage and evaporation. The void fraction is an adequate measure of how often this film is replenished, as the superficial liquid velocity is sufficiently lower than the vapor velocity so that the liquid velocity hardly affects the void fraction at all. Most of the liquid motion, as seen by a point on the surface, is due to the passage of the bubbles through it. Whether the liquid velocity is up, down, or zero is of little consequence as long as liquid is present and the bubble (or vapor) velocity is substantially higher. For the dimensions and properties used in these experiments, the bubble rise velocity is about 0.6 ft/s (Table 1). As long as the liquid velocity is of this order or less, we would not expect it to have much effect on the critical heat flux.

It may seen quite arbitrary to use a CHF correlation for pool boiling from a horizontal surface to nondimensionalize the heat fluxes measured in a vertical annulus. A little thought, however, will show that this is not really the case. For a horizontal surface, the liquid must migrate to the heater surface against a stream of rising bubbles, while for a vertical surface, the liquid must migrate sideways across a stream of bubbles to make it to the heater surface. In both cases, however, the bubbles are rising owing to gravity and at about the same velocity. The sidewise velocity of liquid getting around a rising bubble is comparable to the vertical velocity. Under the circumstances one would expect the same dimensionless groups with slightly different coefficients to be significant for correlating CHF for both horizontal and vertical surfaces. This is, in fact, the case (*7*).

Annuli are probably not much different vertical surfaces either because the splashing due to bubble rising in the gap (or in a tube for that matter) probably doesn't look much different from the splashing due to the bubbles rising close to a vertical surface in a pool. As will soon become apparent, the exact value of the CHF is not of any great consequence anyway because the CHF value predicted for water from these experiments is so much higher than the heat fluxes commonly found in water cooled nuclear reactors.

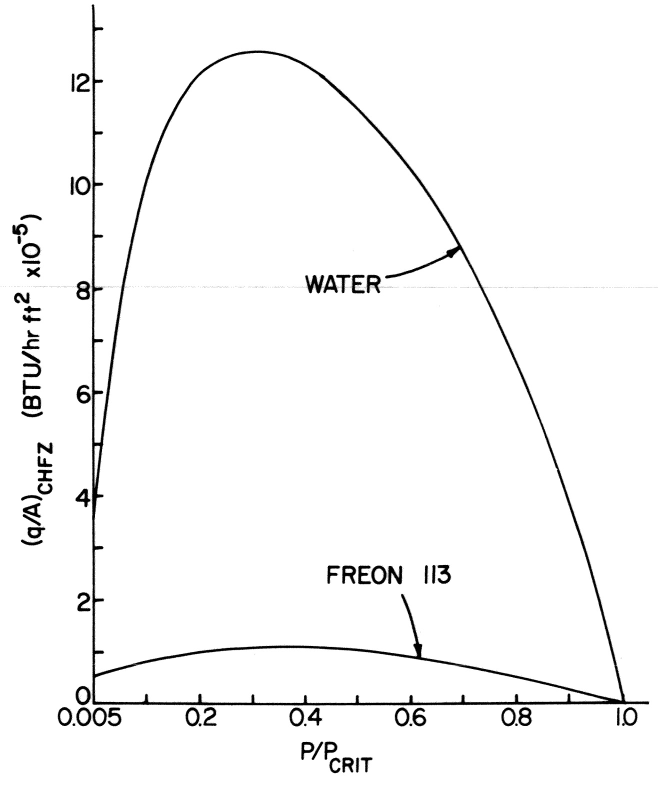

Fig. 8. Variation of pool boiling CHF with pressure using Zuber's flat plate.

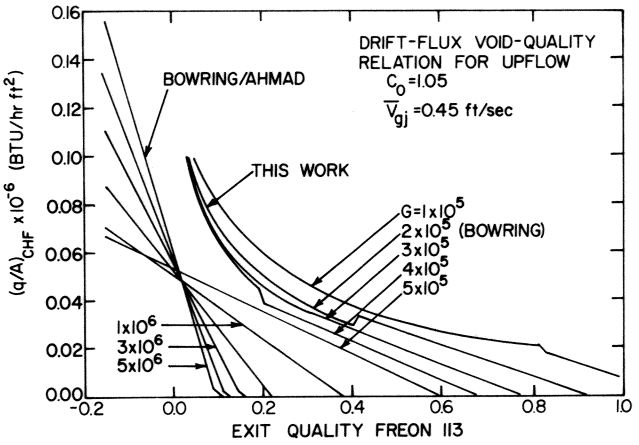

Fig. 9. CHF prediction from Bowering and this work showing how predictions from the CHF vs. void plot join with the CHF prediction for Freon 113 at 200 lb/in.^{2} abs in upflow.

Let us look at CHF levels. The Zuber CHF correlation for water and Freon 113 has been worked out and is shown on Figure 8. A typical PWR has heat flux levels around 350 000 Btu/hr-ft^2. The first flow reversal after a large pipe bursts in a LOCA occurs when the pressure is between 1 000 and 2 000 and the void fraction is less the 20%. The pool boiling CHF is at 900 000 to 1 100 000 Btu/hr-ft^2 for water under these conditions. It is clear that as long as the void fraction is low, the exact value of the CHF is of no consequence. We will never see CHF at the heat flux of 350 000.

Let us now see how the proposed correlation fits in with an existing upflow, round tube CHF correlation. It should fit here because at low velocity void rather than velocity is the important variable. An immense variety of CHF correlations has been proposed. That due to Bowering (*1*) has been chosen for comparison purposes because it is of a functional form which does not give an answer of zero or infinity when the mass velocity approaches zero. It is also suited to constant heat flux application. If the Bowering upflow correlation is plotted for Freon 113, the straight lines on Figure 9 result. As the mass velocity approaches zero, a limit is approached which is not shown but which is almost coincident with the $G = 1 \times 10^5$ lb/hr-ft^2 mass velocity line. The curved lines are the CHF vs. void predictions worked out as indicated in this work. The boundary is $J_g^* = 1.0$ and has been placed here because even local counterflow no longer is possible above this value. The purpose in presenting Figure 9 is to show that the CHF correlation proposed here joins smoothly with an existing upflow CHF correlation when the velocity level is low enough.

A word is appropriate on how we converted the CHF vs. void correlation to the coordinates on Figure 9. This was done using the drift flux model (with constants as shown on Figure 9) to calculate the void. Quality is defined as usual for up flow.

While the unique application of this correlation is to the counterflow region (where a CHF vs. quality correlation will not work), this correlation apparently can be applied to upflow too without giving absurd answers. The exact velocity range to which it can be applied still remains to be determined, but a $J_g^* < 1.0$ in upflow appears appropriate. The downflow limits remain to be delineated.

Some additional mention should be made of the geometric effects on CHF when using the proposed CHF vs. void correlation. We also tested an eccentric annulus where the gap on one side was about twice the gap on the other. No effect of eccentricity was noted. On the basis of these observations and the fact that the CHF's are so high anyway, it is suggested that geometric effects should be ignored for reactor application.

CONCLUSIONS AND SUMMARY

1. The CHF vs. void curve (for void less than 80%) shown on Figure 6 should be used to predict CHF in the counterflow regime, that is, the regime in which the vapor flows up and the liquid flows down. This regime is bounded by the flooding limits appropriate for the geometry, fluid, and pressure of interest.
2. Low mass velocity up and downflow CHF data can also be predicted by this curve, though the limits of its applicability have not been explored.
3. Geometric effects do not appear important as far as the LOCA application of interest is concerned, primarily because the CHF's predicted by the CHF vs. void curve are so much higher than the design values current in PWR's.

ACKNOWLEDGMENT

This work was initiated by the Yankee Atomic Energy Corporation and has subsequently been entirely supported by the Electric Power Research Institute. Without the long time frame which they have allowed us and the freedom they have given us to explore the implications of some of our findings, this work never could have been undertaken.

APPENDIX: THE RELATIONS BETWEEN AVERAGE AND MAXIMUM VOID

In this appendix, the equation actually used to relate the average to the maximum void will be developed. Starting with Equation (1), we assume the vapor flow rate at any section is proportional to the distance from the entrance to the test section; that is

$$J_g = J_{g2} \frac{X}{L} \tag{1}$$

The local void is determined from this relation using Equation (2):

$$\alpha_{\text{loc}} = \frac{J_g}{C_o J + V_{gj}} \tag{2}$$

The constants for Equation (2) have been obtained from Table 1. One then substitutes (1) and (2) into (3):

$$\alpha_{\text{avg}} = \frac{1}{L} \int_0^L \alpha_{\text{loc}}\, dX \tag{3}$$

The result of this substitution is

$$\alpha_{\text{avg}} = \frac{1}{C_o} + \left[\frac{V_{gj} - C_o J_{f2}}{C_o^2 J_{g2}} \right] \ln \left[\frac{-C_o J_{f2} + V_{gj}}{C_o (J_{g2} - J_{f2}) + V_{gj}} \right] \tag{A1}$$

In Equation (A1), the experimental value of α_{avg} is used along with known values of J_{f2} to find, by trial and error, the value of J_{g2} which satisfies the equation. The value of J_{g2} is then substituted into Equation (2) to obtain the local value of α. This is the desired quantity.

LITERATURE CITED

1. Avedeisian, C. T., and P. Griffith, "Critical Heat Flux in Countercurrent Flow," *Rept. No. 80620-84*, ME Dept., Mass. Inst. Technol., Cambridge (Feb., 1974).
2. Crossland, G., "A Study of Critical Heat Flux and Void Fraction on a Vertical Surface," S.B. thesis, ME Dept., Mass. Inst. Technol., Cambridge.
3. Walkush, J. P., "High Pressure Counterflow CHF," *Rept. No. OSP 82157-94*, ME Dept., Mass. Inst. Technol., Cambridge (Sept., 1974).
4. Griffith, P., "The Prediction of Low Quality Boiling Voids," ASME Paper No. 63-HT-20 (1963).
5. Shires, G. L., A/P. Pickering, and P. T. Blacker, "Film Cooling of Vertical Fuel Rods," *AEEW-R 3431* (1964).
6. Wallis, G. B., "Flooding Velocities for Air and Water in Vertical Tubes," *AEEW Rept. No. R 123* (1962).
7. Leinhardt, J. H., and V. K. Dhir, "Hydrodynamic Prediction of Peak Pool Boiling Heat Fluxes from Finite Bodies," ASME Paper No. 72-WA/HT-10 (1973).
8. Bowering, R. W., "A Simple But Accurate Round Tube Uniform Heat Flux Dryout Correlation Over the Pressure Range .7-17 MN/m^2 (100-2500 psia)," *AEEW-R 789* (1972).
9. Ahmad, A. Y., "Fluid to Fluid Modeling of Critical Heat Flux—A Composed Distortion Model," *AECL 3663* (Dec., 1971).