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BRIEF COMMUNICATION

EFFECT OF HIGH VAPOR DENSITY ON CRITICAL HEAT FLUX PREDICTIONS AT LOW VOID FRACTIONS

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INTRODUCTION

Katto (1980a,b) has developed a series of dimensionless correlations for the critical heat flux, q''_{cr}, in uniformly heated round tubes. For low void, or DNB-type, critical heat flux conditions, Katto was able to correlate the available data by:

$$\frac{q''_{cr}}{Gh_{LG}} = 0.098\left(\frac{\rho_G}{\rho_L}\right)^{0.133}\left(\frac{\sigma\rho_L}{G^2 l}\right)^{0.433}\frac{(l/d)^{0.27}}{l + 0.0031\,(l/d)} \qquad [1]$$

where G is the mean mass flux through the tube, σ the surface tension, ρ_L the density of liquid, l the heated length, d the internal diameter of tube, ρ_G the density of vapor and h_{LG} is the enthalpy change on evaporation.

The foregoing held providing values of (ρ_G/ρ_L) were roughly below 0.15. However, at higher values of (ρ_G/ρ_L), it was necessary to correlate the data using:

$$\frac{q''_{cr}}{Gh_{LG}} = 0.0384\left(\frac{\rho_G}{\rho_L}\right)^{0.60}\left(\frac{\sigma\rho_L}{G^2 l}\right)^{0.173}\frac{l}{l + 0.280\left(\frac{\sigma\rho_L}{G^2 l}\right)^{0.233}\left(\frac{l}{d}\right)}. \qquad [2]$$

Data following [2] were said to be in the "high pressure" or "HP" regime.

In a fairly recent paper in this journal, Katto & Yokoya (1984) noted that earlier experimental data for helium failed to show the so-called "high-pressure regime". These earlier data tended to agree with [1] even though (ρ_G/ρ_L) was in the neighborhood of 0.4. Katto & Yokoya (1984) then presented a very careful set of new data for helium DNB. They concluded that [2] should apply at low values of the parameter $(\sigma\rho_L/G^2 l)$ and were able to show that their new data for helium did indeed agree with [2] under these conditions.

It is the purpose of this communication to point out that the need for a separate correlation for DNB data obtained at high values of (ρ_G/ρ_L) depends on the predictive approach taken. It will be shown that, with a new phenomenologically based approach, separate treatment of data at high vapor densities is not required.

PHENOMENOLOGICALLY BASED DNB PREDICTIONS

The DNB prediction of Weisman & Pei (1983), is based on the existence of a bubbly layer adjacent to the heated wall. The critical heat flux occurs when the bubbles in this layer agglomerate into a continuous film. It is assumed that the turbulent interchange at the outer edge of the bubbly layer is the limiting mechanism. By using a simple mass balance over the bubbly layer, it is found that:

$$q''_{cr}/(h_{LG}\,G') = (x_2 - x_1)\left(\frac{h_f - h_{ld}}{h_l - h_{ld}}\right) \qquad [3]$$

where

h_{LG} = heat of evaporation

x_2, x_1 = actual qualities in core and bubbly layer, respectively

h_f, h_l, h_{ld} = enthalpies of saturated liquid, actual liquid and liquid at point of initial bubble departure, respectively.

The values of x_2 is calculated as that quality which corresponds to the maximum void fraction which is possible in a layer of independent bubbles. This void fraction was estimated to be 0.82 for ellipsoidal bubbles. The value x_1 is obtained from a heat balance with proper allowance for thermodynamic nonequilibrium.

The quantity G' represents the mass flow rate due to turbulent interchange at the edge of the bubbly layer. This flow is determined by:

$$G' = \psi i_b G . \qquad [4]$$

The parameter i_b, representing the turbulent intensity at the bubbly layer-core interface, is calculated as the product of the single-phase turbulent intensity at the bubbly layer edge and a two-phase enhancement factor. The resulting expression is:

$$i_b = 0.462(k)^{0.6} (\mathrm{Re})^{-0.1} (D_p/d)^{0.6} [l + a(\rho_L - \rho_G)/\rho_G] \qquad [5]$$

where

a, k = constants

D_p = bubble diameter

Re = Reynolds number.

Through consideration of the velocity fluctuations that are effective in reaching the wall, the parameter ψ was computed to be:

$$\psi = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{v_{11}}{\sigma_v}\right)^2\right] - \frac{1}{2}\left(\frac{v_{11}}{\sigma_v}\right) \operatorname{erfc}\left(\frac{v_{11}}{\sqrt{2}\sigma_v}\right), \qquad [6]$$

where

v_{11} = radial velocity created by vapor generation at wall

v' = radial fluctuating velocity

σ_v = standard deviation of v'.

Weisman & Pei (1983) showed that this procedure predicted DNB heat fluxes in water, refrigerants, anhydrous ammonia, and liquid nitrogen with good accuracy. Weisman & Ying (1983) subsequently extended the work to lower mass velocities and to rod bundles (Weisman & Ying 1984, 1985).

APPLICATION OF THEORETICALLY BASED APPROACH TO RECENT DATA

The predictive approach of Weisman & Pei (1983) has been applied to both the helium and refrigerant 12 DNB data of Katto & Yokoya (1984,1982). The refrigerant 12 downstream-DNB data obtained at the highest pressure investigated (34.3 bar) all obeyed [2]. These refrigerant 12 data were therefore selected for comparison. Helium DNB data (some of which followed [1] and some of which followed [2]) from the 5 and 10 cm long test sections were also selected. Only those data points which were believed to be within the range of the Weisman–Pei approach were used.

In establishing the range of applicability of the Weisman & Pei prediction procedure it was noted that the lower mass flux limit of 1.8×10^6 kg/m²h established by Weisman & Ying (1983) could just as well have been stated in terms of a superficial liquid velocity, V_L. The specific gravities of the liquids examined by Weisman & Ying (1983) in the low velocity range were all similar. If the density of water at 110 bar is taken as typical, then the lower limit in terms of superficial liquid velocity is $V_L \geq 0.72$m/s. Although the reliable helium CHF data were all taken at mass fluxes below 0.32×10^6 kg/m²h, the unusually

Table 1

Fluid	Pressure (bar)	(ρ_G/ρ_L)	No. of Pts.
Helium	2.0	0.41	30
Refrigerant 12	34.3	0.31	59
Water	20.4–34.0	0.012–0.02	63

low density of liquid helium ($\sim$78 kg/m^3) leads to superficial liquid velocities between 0.12 and 1.13 m/s.

It was concluded that superficial liquid velocity was an equally appropriate index of the applicability of the Weisman & Pei predictive approach. The prediction procedure was therefore applied to helium data in the range $0.67 \leq V_L \leq 1.1$ m/s. Higher velocity data were excluded as Katto & Yokoya (1984) noted that these became irregular.

In addition to the helium and refrigerant 12 data, water data at low vapor densities were also selected for comparison. The round tube data for water compiled by Thompson & MacBeth (1964) for low pressures were chosen. Only those data between 20 and 34 bar, and in the range specified by Weisman & Pei (1983), were selected. These data had values of (ρ_G/ρ_L) between 0.012 and 0.02. All of the water data fall within the range of [1]. The significant parameters for each of the fluids examined are summarized in table 1.

The results of the comparison of the DNB data with the Weisman & Pei (1983) predictions are shown in figure 1. It may be seen that generally good agreement is obtained between predictions and measurements for all three fluids. The helium data tend to be slightly above the predictions while the refrigerant 12 data are slightly below predictions. Since the heat flux varies by more than four orders of magnitude, the difference between predicted and measured heat flux, expressed as a percentage of the measured heat flux, is an appropriate error index. It is found that the root mean square error for the combined helium and refrigerant 12 (high vapor density) data is 13.2% while the root mean square error for the water (low vapor density) data is 18.4%.

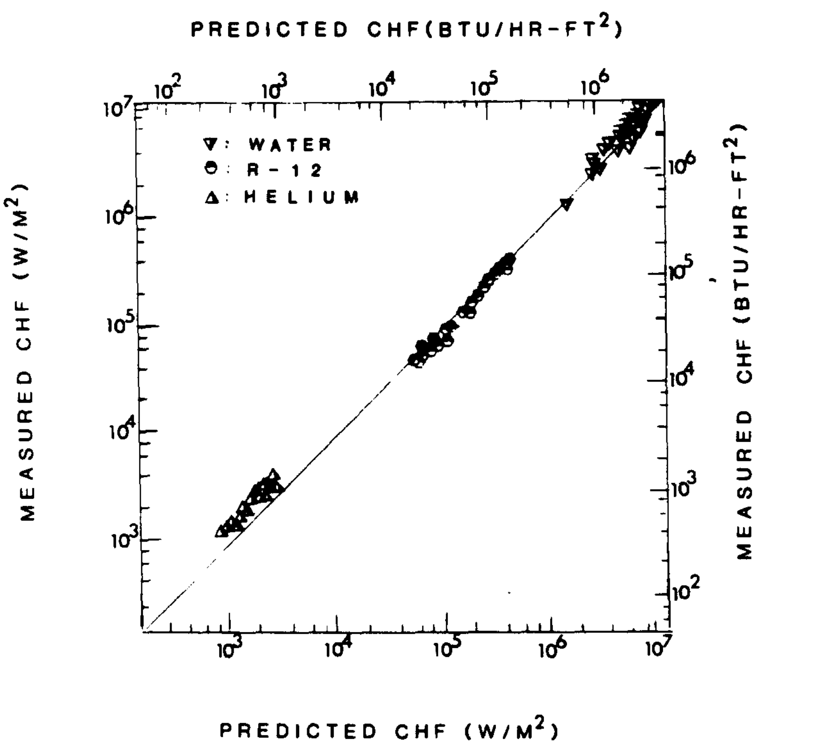

Figure 1. Comparison of predicted and measured critical heat fluxes for fluids with widely varying vapor densities.

The water data at low values of (ρ_G/ρ_L), plus the helium and refrigerant 12 data at high values of (ρ_G/ρ_L), are all handled with similar levels of accuracy. Thus the phenomenologically based predictive approach appears to be capable of providing satisfactory DNB estimates over the entire range of vapor densities and other fluid properties. The data also suggest that superficial liquid velocity may be a more useful parameter than mass flux in defining the lower limit of the Weisman–Pei prediction.

REFERENCES

KATTO, Y. 1980a General features of CHF of forced convection boiling in uniformly heated vertical tubes with zero inlet subcooling. *Int. J. Heat Mass Transfer* **23**, 493–504.

KATTO, Y. 1980b Critical heat flux of forced convection boiling in uniformly heated vertical tubes (correlation of CHF in HP regime and determination of CHF regime map). *Int. J. Heat Mass Transfer* **23**, 1573–1580.

KATTO, Y. & YOKOYA, S. 1982 CHF of forced convection boiling in uniformly heated vertical tubes: experimental study of HP regime by use of refrigerant 12. *Int. J. Multiphase Flow* **8**, 165–182.

KATTO, Y. & YOKOYA, S. 1984 Critical heat flux of liquid helium in forced convective boiling. *Int. J. Multiphase Flow* **10**, 401–414.

THOMPSON, B. & MACBETH, R. 1964 Boiling water heat transfer burnout in uniformly heated round tubes—A compilation of cooled data with accurate correlation. UKAE Rep. No. AEEW-R356.

WEISMAN, J. & PEI, B. S. 1983 Prediction of critical heat flux in flow boiling at low qualities. *Int. J. Heat Mass Transfer* **26**, 1463–1478.

WEISMAN, J. & YING, S. H. 1983 Theoretically based CHF prediction at low qualities and intermediate flows. *Trans. Am. Nucl. Soc.* **45**, 832–833.

WEISMAN, J. & YING, S. H. 1984 A theoretically based DNB prediction for rod bundles. *Trans. Am. Nucl. Soc.* **47**, 511–512.

WEISMAN, J. & YING, S. H. 1985 A theoretically based critical heat flux prediction for rod bundles at PWR conditions. *Nucl. Engng. Des.* **85**, 239–250.