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POINT OF NET VAPOR GENERATION AND VAPOR VOID FRACTION IN SUBCOOLED BOILING

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ABSTRACT

An analysis is presented directed at predicting the point of net vapor generation and vapor void fraction in subcooled boiling. It is shown that the point of net vapor generation depends upon local conditions - thermal and fluid dynamic. Thus, at low mass flow rates the net vapor generation is determined by thermal conditions, whereas at high mass flow rates the phenomenon is hydrodynamically controlled. Simple criteria are derived which can be used to predict these local conditions for net vapor generation. These criteria are used then to determine the vapor void fraction in subcooled boiling. Comparison between the results predicted by this analysis and experimental data presently available, show good agreement for wide range of operating conditions, fluids and geometries.

NOMENCLATURE

- a : Thermal diffusivity, m^2/hr
- C_o : Nondimensional distribution parameter
- c_p : Specific heat, kcal/kg ^oC
- D_h : Hydraulic diameter of the channel, m
- G : Mass velocity, kg/m^2 hr
- g : Acceleration due to gravity, m/hr^2
- i : Enthalpy, kcal/kg
- Δi_{fg} : Latent heat of vaporization, kcal/kg
- k : Thermal conductivity, kcal/m hr ^oC
- Nu : Nusselt number
- P : Pressure, bar (1 bar = 10^5 N/m^2)
- Pe : Peclet number
- $\dot{q}''$: Heat flux, kcal/m^2 hr
- St : Stanton number
- T : Temperature, ^oC
- T_{sat} : Saturation temperature, ^oC
- ΔT : Local subcooling ($T_{sat} - T_f$), ^oC
- v_{fi} : Inlet velocity of fluid, m/hr
- $\bar{V}_{gj}$: Weighted mean vapor drift velocity, m/hr
- x : True vapor quality
- x_{eq} : Equilibrium vapor quality
- x_λ : Equilibrium vapor quality at the point of net vapor generation
- z : Axial distance along the heated wall, m
- $\langle\alpha\rangle$: Area average vapor void fraction
- ρ : Density, kg/m^3
- $\Delta\rho$: $\rho_f-\rho_g$, kg/m^3
- σ : Surface tension, kg/hr^2

Subscripts

- f : Liquid phase
- g : Vapor phase
- s : Saturation value
- λ : Value at the point of net vapor generation

INTRODUCTION

The ability to predict the vapor void fraction in the subcooled boiling region is of considerable interest to the nuclear reactor technology because the presence of voids affects the steady state and transient response of a reactor. Furthermore, recent investigations have shown that vapor voids in the subcooled boiling region have an effect on the inception of two phase instabilities, that is, flow excursions and/or oscillations. It was shown in /1/ that the ability to predict accurately the vapor void fraction depends upon the ability to predict the point of net vapor generation.

The vapor generation along the length of a heated channel is shown qualitatively in Figure 1. The existenceof two regions, as shown in Figure 1, has been confirmed through several experimental investigations /2,3,4/. In region I, the surface temperature and, therefore, the liquid temperature near the surface are high enough to permit nucleation of small bubbles. But, due to the high subcooling prevailing at the liquid core, this bubble layer cannot grow significantly until the point B is reached. At this point the thermal as well as the hydrodynamic conditions are such that a rapid increase in vapor void fraction is initiated, although the liquid bulk temperature is still below the corresponding saturation temperature. The region I can be quite important when considering the local heat transfer coefficient and the pressure drop of the system, but usually it is of little significance as far as the vapor void fraction is concerned. Therefore, for all intents and purposes, the point B can be regarded as the point of net vapor generation. The problem is to determine the location of this point as function of system parameters.

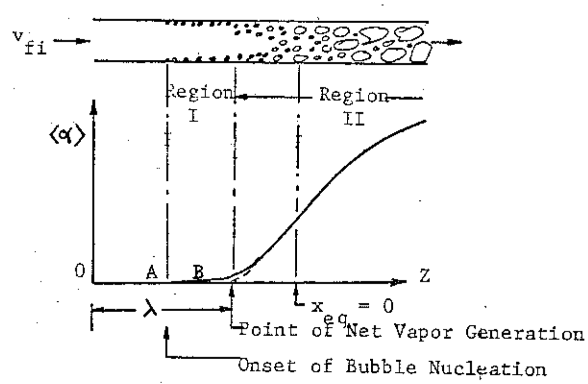

Fig. 1 VAPOR VOID FRACTION ALONG THE LENGTH OF A HEATED CHANNEL

PREVIOUS WORK

One of the earlier attempts to predict the initial point of net vapor generation is due to Bowring /3/. Since his correlation is not dimensionless it is of limited usefulness. However, Bowring introduced the idea of bubble detachment which forms the basis of two later models /5,6/. In these models it is postulated that no bubble is detached from the surface in region I. and the point of net vapor generation, i.e. the point B, is characterized by "bubble detachment" from the heated surface. These models /5,6/ are identical in nature and will be briefly discussed here.

Both Levy /5/ and Staub /6/ assumed a bubble attached to the surface. The point of bubble detachment was established from two considerations. First, a force balance on the bubble was used to determine the mean diameter of departing bubbles. Then, a temperature distribution was assumed from the top of the bubble to the center line of the channel. The final expressions had two constants which were determined from the then existing data. Although these two models were reasonably successful in correlating the early data, three shortcomings should be mentioned. First, the expressions for predicting the local subcooling at the point of bubble detachment are very complicated so that their use in dynamic studies is rather limited. Secondly, it has been shown recently in /7/ that the results predicted by these two models are not satisfactory for low mass flow rates. Finally, the experimental observations of Dix /4/ indicate that the bubble detachment criterion alone is not sufficient to represent the point of net vapor generation.

A model based on bubble agitation and a postulated heat transfer coefficient was proposed by Ahmad /7,8/. The results predicted by this model although good for high mass flow rates, is not satisfactory for low mass flux data of Dix /4/ and Rouhani /9/.

Few other correlations, namely those of Dix /4/, and Costa /10/ and Rouhani /11,12/ are available in literature. However, as these correlations are restricted to the data from which they were derived, they will not be discussed in the present paper.

PRESENT ANALYSIS: POINT OF NET VAPOR GENERATION

From the previous section it is quite clear that at present there is no general model or correlation which can adequately describe the physical situation at the point of net vapor generation and can predict the point accurately for all mass flow rates. The purpose of the present investigation is, therefore, to re-examine this problem and come up with a simple, easy-to-use general correlation.

As stated earlier, the point of net vapor generation must satisfy both the thermal as well as the hydrodynamic restraints. If the situation is such that the bubbles are detached from the surface, but the local subcooling is so high that the bubbles are immediately condensed as they move to the liquid core, then the void fraction profile cannot grow. In that case, to initiate a rapid increase in void fraction the bubbles have to flow further along the wall until the liquid subcooling is reduced significantly so that the effect of vapor condensation is compensated by the rate of evaporation close to the wall. This is in agreement with the observation of Dix /4/. On the other hand, if the bubbles do not detach from the surface even when the local subcooling is low, the void fraction cannot increase significantly. However, as soon as the hydrodynamic conditions will permit it, bubbles will start detaching from the wall. New bubbles will be formed at the wall and the process will manifest itself by the rapid increase in void fraction. This is the situation assumed in the bubble detachment models.

From experimental data /13,14/ it has been observed that for high and moderate inlet subcooling the point of net vapor generation is almost independent of the inlet subcooling. Dix /4/ also observed that the bubble layer thickness at initial bubble ejection was independent of liquid inlet temperature. Therefore, it can be argued that the point of net vapor generation is dependent only on local thermal conditions, which determine the rates of vapor condensation and evaporation at the wall. In order to make an estimate of these two rates we can assume that the rate of evaporation at the wall will be proportional to heat flux whereas the rate of condensation will be proportional to the local subcooling. Furthermore, at low mass flow rates the condensation will be governed by a diffusion process. Consequently, for the thermally controlled region, that is, at low mass flow rates we can expect that the local Nusselt number

$$Nu = \frac{\dot{q}'' D_h}{k_f(T_{sat} - T_\lambda)} \qquad (1)$$

will be the similarity parameter.

On the other hand, at high mass flux rates, where bubble detachment models have met with reasonable success, the phenomenon may be hydrodynamically controlled. If we regard that attached bubbles may affect the flow as surface roughness, then detaching bubbles should correspond to a particular scale of roughness. Furthermore, if we assume that Reynolds analogy holds, then at high mass flow rates we could expect that the local Stanton number

$$St = \frac{\dot{q}''}{G\, c_{pf}(T_{sat} - T_\lambda)} \qquad (2)$$

will be the appropriate scaling group.

In order to determine whether or not equation (1) and equation (2) are the appropriate scaling groups it is desirable to eliminate the dependent variable, that is, the local subcooling from one of these two equations. This can be achieved by introducing the Peclet number which is, by definition the ratio of the Nusselt number and the Stanton number. Therefore, it was decided to plot various existing data for the point of net vapor generation on a St-Pe co-ordinate system. Data used for this purpose are shown in Table 1. It should be noted that three different fluids (water, freon-22, and freon-114) with wide range of system pressure, mass flow rate, heat flux and various channel geometries have been considered. The result of the plot is shown in Fig. 2.

Table 1. DATA USED IN THE PRESENT CORRELATION

Author/Ref/	Fluid	Geometry	Pressure (bar)	Symbol in Fig. 2
Dix /4/	Freon-114	9.5 mm I.D, 18.6 mm O.D	3.16 and 8.48	●
Rouhani /9/	Water	12 mm I.D, 25 mm O.D	9.8 - 39	o
Egen, et al /14/	Water	25.4 mm X 2.6 mm CHAN.	138	⊠
Maurer /15/	Water	25.4 mm X 2.2 mm CHAN.	83 and 110	×
Martin /16/	Water	50 mm X 2.8 mm CHAN.	78.5 and 138	△
Staub, et al /17/	Water	63 mm X 6.3 mm CHAN.	1.2 and 3.1	◇
Staub, et al /17/	Water	10 mm ID	41.4 and 69	□
Staub, et al /17/	Freon-22	10 mm ID	13 to 34	▼
Bartolemei, et al /18/	Water	15.4 mm and 24 mm ID	15 to 45	⊗
Evangelisti, et al /19/	Water	7 mm ID, 13 mm OD	1.01	▽

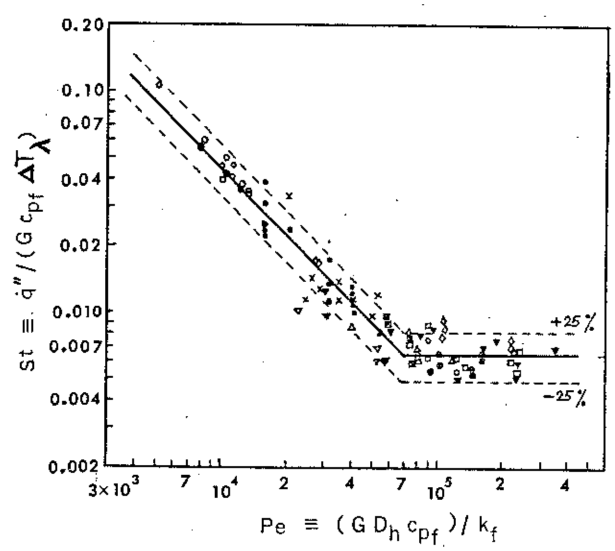

Fig. 2. PECLET NUMBER VS STANTON NUMBER AT THE POINT OF NET VAPOR GENERATION.

Two distinct regions can easily be identified in Figure 2. Up to Peclet number equal to 70,000 data fall on a straight line having the slope of minus one which implies a constant value for the local Nusselt number. Beyond the Peclet number of 70,000 data fall on a constant Stanton number. The entire correlation for the point of net vapor generation can be expressed as:

$$Nu = \frac{\dot{q}'' D_h}{k_f \, \Delta T_\lambda} = 455 \qquad \text{if } Pe \leq 70{,}000 \tag{3}$$

and

$$St = \frac{\dot{q}''}{G \, c_{pf} \, \Delta T_\lambda} = 0.0065 \qquad \text{if } Pe > 70{,}000 \tag{4}$$

Recognizing that the equilibrium vapor quality at the point of net vapor generation λ, is given by

$$x_\lambda = - \frac{c_{pf} \, \Delta T_\lambda}{\Delta i_{fg}} \tag{5}$$

the above correlation can also be expressed as

$$x_\lambda = - 0.0022 \, \frac{\dot{q}''}{\rho_f \Delta i_{fg}} \, \frac{D_h}{a_f} \, , \qquad Pe < 70{,}000 \tag{6}$$

and

$$x_\lambda = -154 \, \frac{\dot{q}''}{\rho_f \Delta i_{fg}} \, \frac{1}{v_{fi}} \, , \qquad Pe > 70{,}000 \tag{7}$$

INTERPRETATION OF THE CORRELATION

It can be recognized that for Peclet number less than 70,000 the local subcooling, ΔT_λ, at the point of net vapor generation is independent of flow velocity. Therefore, this is the thermally controlled region. On the other hand, for Peclet number greater than 70,000 the local Stanton number is found to be a constant. From the analogy between heat and momentum transfer, this implies that the friction factor at the point of net vapor generation is a constant. This behavior is very similar to that of turbulent flow in sand-roughened pipes /20/. Therefore, it appears that bubbles, attached to the wall may act like roughness heights. The attached bubbles will grow until a characteristic value of roughness parameter, k_s/D is reached at which point they detach from the surface. For Prandtl number equal to one, this characteristic value of k_s/D is about 0.02 which corresponds to the Stanton number value of 0.0065.

From the above criterion, the bubble will be detached from the surface as soon as the local Stanton number becomes 0.0065. At low mass flow rates, i.e. Pe < 70,000, local Nusselt number still remains below 455. This means that the local subcooling is still high and the detached bubbles are forced to stay near the heated wall. The bubbles flow downstream while remaining close to the wall, until the local Nusselt number becomes 455. At this point the local subcooling is low enough to initiate a rapid increase in void fraction. This was precisely what Dix observed in his experiments /4/. We call this region (Pe < 70,000) as the thermally controlled region. On the other hand, for high mass flow rates, i.e. Pe > 70,000, Stanton number reaches the value of 0.0065 at a point where Nusselt number is already higher than 455. Therefore, as soon as the bubbles are detached from the wall they can

move to the liquid core without being rapidly condensed. This results in a rapid increase in vapor void fraction at the point of bubble detachment. And, this explains why the previous bubble detachment models were reasonably successful at high mass flow rates. We call this region (Pe > 70,000) as the hydrodynamically controlled region.

PREDICTION OF VAPOR VOID FRACTION

It is desirable to test whether equation (6) or equation (7) can be used to predict the void fraction in subcooled boiling.

As shown in /1,21/, the average void fraction can be expressed in general as

$$\langle\alpha\rangle = \frac{x}{Co\left[\frac{x\Delta\rho}{\rho_f} + \frac{\rho_g}{\rho_f}\right] + \frac{\rho_g \overline{V}_{gj}}{G}} \tag{8}$$

C_o is the distribution parameter, $\overline{V}_{gj}$, is the weighted mean vapor drift velocity which, for upward bubbly churn flow, can be given by

$$\overline{V}_{gj} = 1.41\left[\frac{\sigma g\Delta\rho}{\rho_f^2}\right]^{1/4} \tag{9}$$

and the true vapor quality x, is given by

$$x = \frac{x_{eq} - x_\lambda \exp\left[\frac{x_{eq}}{x_\lambda} - 1\right]}{1 - x_\lambda \exp\left[\frac{x_{eq}}{x_\lambda} - 1\right]} \tag{10}$$

where the equilibrium vapor quality is by definition

$$x_{eq} = \frac{i - i_{fs}}{\Delta i_{fg}} \tag{11}$$

The vapor void fraction predicted by equation (8) with the local equilibrium quality x_λ (at the point of net vapor generation) determined from equation (6) or equation (7) are shown in Figures 3,4,5. It can be seen that the agreement between predicted results and experimental data appears to be satisfactory.

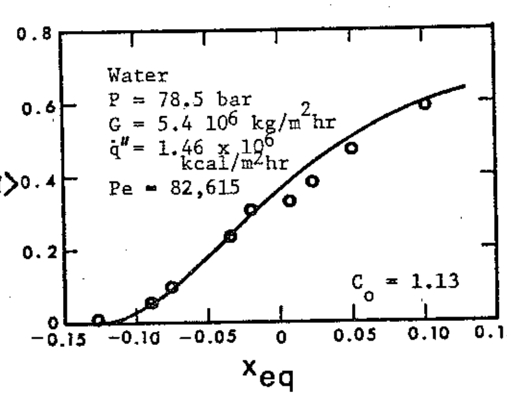

Fig. 3 COMPARISON BETWEEN PREDICTED AND MEASURED VAPOR VOID FRACTION. DATA OF MARTIN/16/.

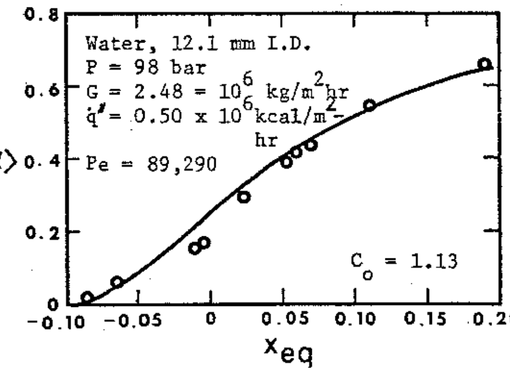

Fig. 4 COMPARISON BETWEEN PREDICTED AND MEASURED VAPOR VOID FRACTION. DATA OF LOBACHEV, et,al /22/.

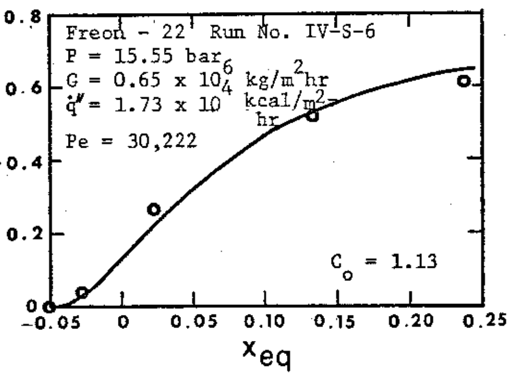

Fig. 5 COMPARISON BETWEEN PREDICTED AND MEASURED VAPOR VOID FRACTION. DATA OF STAUB, et,al /17/

CONCLUSIONS

The results presented in this paper indicate that the point of net vapor generation is determined by local conditions - thermal and fluid dynamic. At low mass flow rates the net vapor generation is determined by thermal conditions, whereas at high mass flow rates it depends upon hydrodynamic conditions. Simple criteria are derived which can be used to predict the value of the equilibrium quality at the point of net vapor generation. It is shown that this local equilibrium vapor quality can be used to predict the vapor void fraction in subcooled boiling.

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