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DETERMINATION OF THE INITIAL POINT OF NET VAPOR GENERATION IN FLOW BOILING SYSTEMS

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Abstract—A correlation to determine the initial point of net vapor generation for water and Refrigerant-22 is given. The range of data correlated is as follows: geometry: circular tubes, rectangular channels and annuli; pressure: 0·1–15·8 MN/m^2; hydraulic diameter: 0·004–0·020 m; subcooling: 3·2–42 K; heat flux: 0·02–1·92 MW/m^2; mass velocity: 132–2818 kg/m^{2}s; accuracy: 30 per cent. A scaling law to predict this point for other liquids than those mentioned above has also been established.

Experimental determination of the initial point of net vapor generation for water has been carried out with a high-speed photographic technique at 13·9 and 15·8 MN/m^2.

NOMENCLATURE

- C, constant, defined by equation (2) [W/m^{2}K^n];
- d_1, inner diameter of an annulus [m];
- d_2, outer diameter of an annulus [m];
- G, mass velocity [kg/m^{2}s];
- h, single-phase forced convection heat-transfer coefficient [W/m^{2}K];
- Nu, Nusselt number;
- n, constant, defined by equation (2);
- P, pressure [N/m^2];
- Pr, Prandtl number;
- Re, Reynolds number;
- q, heat flux [W/m^2];
- Δt, superheating of the liquid (i.e. difference between wall temperature and saturation temperature of the liquid) [K];
- Θ, subcooling of the liquid (i.e. difference between saturation temperature and bulk liquid temperature) [K];
- V, liquid bulk velocity [m/s].

Subscripts

- b, refers to bulk condition;
- F, refers to condition for pool boiling or fully developed boiling;
- I, refers to condition at the initial point of net vapour generation;
- W, refers to water;
- R-22, refers to Refrigerant-22.

INTRODUCTION

DURING the subcooled nucleate flow boiling of a liquid in a channel, there is a point beyond which the void fraction increases rapidly with the heated length. Before this point is reached, the void fraction is very low and the bubbles are attached to the heated wall at high subcoolings. This point is mostly referred to in the literature as the I(nitial) P(oint) of N(et) V(apor) G(eneration), and is of importance for the prediction of void fraction in subcooled nucleate flow boiling and the dynamic stability conditions of evaporators.

The existing correlations for the prediction of the IPNVG are from Griffith *et al.* [1], Bowring [2], Rouhani [3], Levy [4], and Staub [5]. The last two workers have extensively investigated the IPNVG, and each of them has given a semi-empirical correlation to evaluate the subcooling at this point, by considering a force balance on a departing bubble from the heated surface and the temperature and velocity profiles in a channel.

Since the correlations presented in the literature are either applicable to a limited range of conditions or cumbersome to use in practical calculations, dimensional analysis has been applied in this paper to correlate the data for the IPNVG available in the literature. In the meantime an experimental determination of the IPNVG has been carried out for water with a high-speed photographic technique at high-pressure conditions, making it possible to study the bubble pattern visually at this particular point.

DETERMINATION OF THE IPNVG

The IPNVG is in fact a transition point, which can be related to a group of dimensionless numbers, and these numbers are expected to be constants for certain conditions.

In order to obtain these dimensionless numbers, the following heat-transfer equation for subcooled nucleate flow boiling, derived by the author of this paper [6] will be used:

$$q = C\Delta t^n + h\Theta. \quad (1)$$

The first term on the r.h.s. of equation (1) is the heat flux due to boiling and the second term is the heat flux due to suppressed forced convection. The basic concepts to establish such an equation will be briefly explained below.

It is well known that the heat-transfer rate in fully developed boiling is not affected by fluid velocity, and can be predicted from the pool boiling equation in accordance with the work of Borishanskii *et al.* [7], Forster and Greif [8], Kutateladze [9] and Rohsenow [10]:

$$q = C\Delta t^n \tag{2}$$

where n is a constant for a given fluid and C is a constant for a given pressure and surface–fluid combination.

Subcooled nucleate flow boiling is a transition between the forced convection and the fully developed boiling regimes, and the heat-transfer rate in this type of boiling will consequently be affected by the forced convection and the boiling heat-transfer modes. Therefore equation (1) has been found convenient to describe the above type of heat transfer and to express the fact that liquid velocity has no influence on the heat-transfer rate in fully developed boiling. Equation (1) has also been verified with the experimental data given by Bergles and Rohsenow [11], using the n- and C-values proposed by Rohsenow [10], and has been found to fit the data well [6].

The procedure to determine the heat flux in accordance with equation (1) is shown in Fig. 1. When the heat

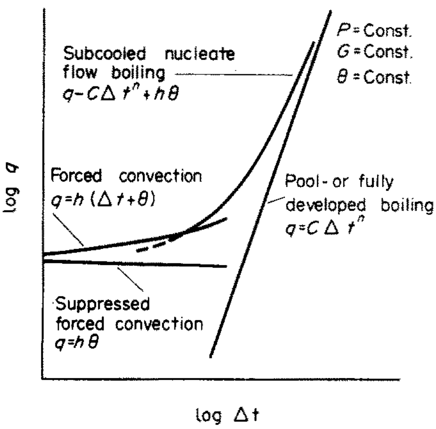

FIG. 1. Subcooled nucleate flow boiling curve.

flux calculated with the forced-convection equation exceeds that given by equation (1), the latter is recommended to predict the heat flux in the subcooled nucleate flow boiling regime. The other procedures to draw the subcooled nucleate flow boiling curve are from Bergles and Rohsenow [11], Forster and Greif [8], Kutateladze [9], McAdams *et al.* [12], and Rohsenow [13]. The procedure presented here is in fact a modification of the superposition method of the last-mentioned author.

The heat flux at the IPNVG can be given by equation (1):

$$q_I = C\Delta t_I^n + h_I \Theta_I. \tag{3}$$

For a constant heat flux system, the following equation applies to fully developed boiling:

$$q_I = C\Delta t_F^n. \tag{4}$$

Equation (3) can be reduced to a non-dimensional form by the use of equation (4):

$$\frac{h_I \Theta_I}{q_I} = \left[1 - \left(\frac{\Delta t_I}{\Delta t_F}\right)^n\right] \tag{5}$$

For the determination of the conditions in which the dimensionless number on the l.h.s. of equation (5), $h_I\Theta_I/q_I$, is a constant, its value has been calculated using our data (i.e. the values of Θ_I and q_I; see Table 2), and the data of Egen *et al.* [14]; Maurer [15], as reported by Bowring [2]; Ferrell [16]; Rouhani [17], as reported by Levy [4]; Cook [18], as reported by Kroeger and Zuber [19]; Evangelisti and Lupoli [20]; and Staub *et al.* [21]. Six water tests of the last mentioned investigators were conducted with small amounts of additives. The forced convection heat-transfer coefficient, h_I, in the dimensionless number given above has been evaluated with the well-known correlation, $Nu_b = \alpha Re_b^{0.8} Pr_b^{0.4}$, in which α is equal to 0·023 for circular tubes and rectangular channels, and to $0{\cdot}020\,(d_2/d_1)^{0{\cdot}53}$ for annuli [22]. The physical properties of water and Refrigerant-22 have been determined in accordance with the data given by the ASME [23], Hirschberg [24], and Du Pont de Nemours [25]. The conditions covered by the experiments are given in Table 1.

Table 1. Range of data used

Parameter	Type of liquid: Water	Refrigerant-22
Geometry	Circular tubes, rectangular channels, annuli	Circular tube
Pressure, MN/m^2	0·1–15·8	1·2–3·3
Mass velocity, kg/m^{2}s	132–2818	180–1391
Hydraulic diameter, m	0·004–0·020	0·01
Subcooling at the IPNVG, Θ_I, K	3·7–42	3·2–7·3
Heat flux at the IPNVG, q_I, MW/m^2	0·15–1·92	0·02–0·06
Number of data used	75	13

Analysis of the calculated dimensionless numbers yields the following results:

(i) For a given liquid, regardless of channel geometry, pressure, heat flux, subcooling and mass velocity, there are two velocity regions in which:

$$\frac{h_I \Theta_I}{q_I} = a = \text{constant}. \tag{6}$$

These two velocity regions are sharply separated by a given value of velocity, $V = 0{\cdot}45$ m/s. This velocity is connected to bubble growth and is close to the velocity at which forced convection ceases to affect the bubble growth rate in subcooled nucleate flow boiling as shown experimentally by Snyder and Robin [26], and semi-theoretically by Ünal [27].

(ii) For water, $a = 0{\cdot}24$ for $V \geqslant 0{\cdot}45$ m/s and $a = 0{\cdot}11$ for $V < 0{\cdot}45$ m/s.

(iii) For Refrigerant-22, $a = 0{\cdot}18$ for $V \geqslant 0{\cdot}45$ m/s and $a = 0{\cdot}11$ for $V < 0{\cdot}45$ m/s.

$a/(h_I\Theta_I/q_I)$ is shown vs reduced pressure in Fig. 2. Correlation of the data appears quite feasible, taking into account that the experimental determination of Θ_I may involve some errors, and that there are some inconsistencies in the test results, as indicated by Levy [4].

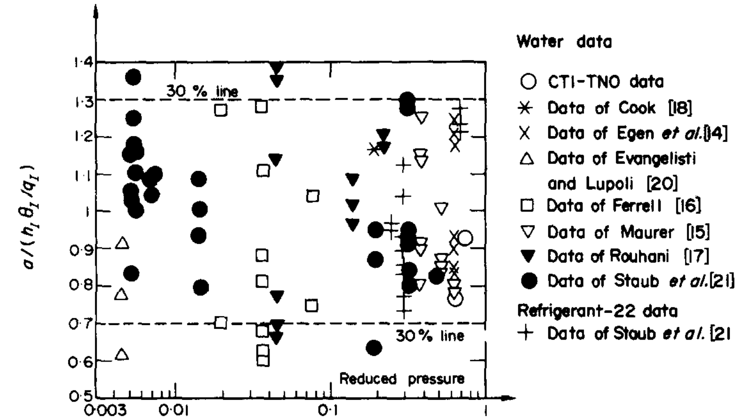

FIG. 2. Correlation of the IPNVG data.

For instance, the data of Egen *et al.* [14], and Ferrell [16] show that an increase in mass velocity, at constant heat flux and pressure, increases Θ_I. The data of Evangelisti and Lupoli [20], Maurer [15], Rouhani [17], and Staub *et al.* [21] show the reverse trend, however.

For all the data correlated, the RMS-error is 19 per cent, and it appears that nearly all the correlated data are within a 30 per cent error band, with the exception of a few low-pressure data.

The correlation given by equation (6) has also been compared with the correlations of Bowring [2] and of Levy [4] with the aid of the data of Evangelisti and Lupoli [20] and the data used by these workers to establish their correlations. Equation 6 correlates the data better than the correlations of Levy, and Bowring by 24 and 56 per cent respectively.

In order to predict Θ_I by the use of equation (6) in a channel where the operating conditions (i.e. pressure, mass velocity, heat flux and inlet subcooling) are known, it is clear that h_I and Θ_I have to be iterated.

A SCALING-LAW FOR THE IPNVG

When the pool boiling curve of a liquid is known, the IPNVG for this liquid can be determined. This will now be shown.

For water, n in equation (2) is reported to be $n = 3$ by Rohsenow [10], and Borishanskii *et al.* [7]. For the pool boiling of Refrigerant-22, Ratiani and Avaliani [28] report $n = 3$, based on rather limited data. For fully developed boiling of this liquid, n can be taken equal to approximately $n = 2{\cdot}65$ as suggested by Zuber *et al.* [29] based on fairly extensive data; therefore this n-value is considered here.

Using $n = 3$ for water and $n = 2{\cdot}65$ for Refrigerant-22 and the above established relation, $a = h_I\Theta_I/q_I$, the dimensionless number on the r.h.s. of equation (5) has been calculated for both water and Refrigerant-22:

$$\left(\frac{\Delta t_I}{\Delta t_F}\right)_W \cong \left(\frac{\Delta t_I}{\Delta t_F}\right)_{\text{R-22}} \cong 0{\cdot}92 \quad V \geqslant 0{\cdot}45\,\text{m/s} \tag{7}$$

$$\left(\frac{\Delta t_I}{\Delta t_F}\right)_W \cong \left(\frac{\Delta t_I}{\Delta t_F}\right)_{\text{R-22}} \cong 0{\cdot}96 \quad V < 0{\cdot}45\,\text{m/s}. \tag{8}$$

It follows from equations (7) and (8) that the dimensionless number of the r.h.s. of equation (5), $(\Delta t_I/\Delta t_F)$, is a constant depending only on one particular value of velocity, $V = 0{\cdot}45$ m/s, regardless of the type of liquid, channel geometry and operating conditions in a channel. Therefore, $h_I\Theta_I/q_I$, and consequently the subcooling at the IPNVG during the forced convection motion of any liquid in a channel for which the operating conditions are known can be predicted by the use of equation (5), equation (7) or equation (8), provided the pool boiling or fully developed boiling equation of the liquid is known.

EXPERIMENTAL DATA

The IPNVG has also been determined at high pressures by using a high-speed photographic technique. The results are given in the table below:

Table 2. Experimental data for the IPNVG

Pressure (MN/m^2)	Mass velocity (kg/m^{2}s)	Heat flux at the IPNVG (MW/m^2)	Subcooling at the IPNVG (K)
13·9	2121	0·38	4·3
15·8	2121	0·45	4·1

The experimental set-up is described elsewhere in detail by De Munk [30]. The photographical test section was an adiabatic, cylindrical sapphire of 8 mm I.D. and 20 mm height, mounted just at the end of a 10 m long, sodium heated steam generator pipe. The pictures of subcooled nucleate flow boiling have been taken through the sapphire test section with a framing camera (Dynafax, model 350) at a frequency of 5000 frames/s for different values of heat flux, subcooling and pressure. The developed films have been enlarged 18 times and the void fractions have been determined by counting the bubbles appearing on the films. The velocities of the bubbles taken randomly from the bubble populations have also been determined from the developed films by the use of a Boscar motion analyzer.

From the analysis the following conclusions have been drawn:

(i) For the conditions given in Table 2, the void fraction is very low, i.e. less than 0·5 per cent.

(ii) The experimental determination of the IPNVG has been carried out in a manner different from that given in the literature. Per definition, void fraction increases sharply at the IPNVG. Therefore, the numbers of bubbles appearing on the developed films have been counted for different subcoolings at a constant heat flux, pressure and mass velocity. When the number of bubbles was found to increase suddenly, the conditions at which the film was taken were specified as those of the IPNVG.

For instance there were about 30 bubbles on the film at $\Theta = 5{\cdot}9$ K, $q = 0{\cdot}38$ MW/m^2, $P = 13{\cdot}9$ MN/m^2 and $G = 2121$ kg/m^{2}s. When the subcooling was decreased to 4·3 K, with heat flux, pressure and mass velocity kept constant, the number of bubbles on the film was 170. Therefore, the conditions at which this film was taken were specified as those of the IPNVG. When the subcooling was decreased further, the number of bubbles increased steadily.

(iii) Before the IPNVG was reached, for the case of very small numbers of bubbles present in the test section (say, about 30), not all the bubbles were attached to the wall of the test section, but some were already in the bulk of the water. This is contradictory to the assumption of Levy [4] and of Staub [5] that the IPNVG is situated at the location where the first bubble departs from the heated surface. At present we assume that the IPNVG can be predicted theoretically from the balance between the number of bubbles condensed and the number of bubbles generated in a subcooled nucleate flow regime.

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DETERMINATION DU POINT DE DEBUT DE FORMATION DE LA VAPEUR DANS LES SYSTEMES D'ECOULEMENT EN EBULLITION

Résumé—On présente une corrélation pour déterminer le point de début de formation de vapeur pour l'eau et le réfrigérant-22. La gamme de données corrélées est la suivante: géométrie: tubes circulaires, canaux rectangulaires et annulaires; pression: 0,1–15,8 MN/m²; diamètre hydraulique: 0,004–0,020 m; sous-refroidissement: 3,2–42 K; flux de chaleur: 0,02–1,92 MW/m²; vitesse de masse: 132–2818 kg/m²s; précision: 30 pour cent.

Une formule de proportionnalité pour la prévision de ce point pour d'autres liquides a été également établie.

La détermination expérimentale du point de début de formation de la vapeur d'eau a été effectuée au moyen de photographie ultra-rapide à 13,9 et 15,8 MN/m².

BESTIMMUNG DER STELLE ERSTER DAMPFBILDUNG IN SIEDESTRÖMUNGSSYSTEMEN

Zusammenfassung—Es wird eine Beziehung zur Bestimmung der Stelle erster Dampfbildung für Wasser und R 22 angegeben. Die Daten liegen im folgenden Bereich: Geometrie: kreisförmige Rohre, rechteckige Kanäle und Kreisringe Druck: 0,1–15,8 MN/m²; hydraulischer Durchmesser: 0,004–0,020 m; Unterkühlung: 3,2–42 K; Wärmestromdichte: 0,02–1,92 MW/m²; Massenstromdichte: 132–2818 kg/m² s; Genauigkeit: 30 Prozent.

Es wurde ein Ähnlichkeitsgesetz aufgestellt, das für andere als die obenerwähnten Flüssigkeiten Voraussagen ermöglicht. Die experimentelle Bestimmung für Wasser ist mit einer ultraschnellen fotografischen Methode bei 13,9 und 15,8 MN/m² durchgeführt worden.

ОПРЕДЕЛЕНИЕ НАЧАЛЬНОЙ ТОЧКИ ЧИСТОГО ПАРООБРАЗОВАНИЯ В СИСТЕМАХ КИПЯЩИХ ПОТОКОВ

Аннотация — Дается соотношение для определения начальной точки чистого парообразования для воды и хладагента-22. Коррелированные данные изменялись в следующем диапазоне: конфигурация; трубы круглого сечения, прямоугольные каналы и кольца; давление: 0,1–15,8 Мн/м²; гидравлический диаметр: 0,004–0,020 м; переохлаждение: 3,2–42 К; тепловой поток: 0,02–1,92 Мвт/м²; массовый расход: 132–2818 кг/м² сек; точность: 30%.

Был установлен также закон подобия для расчета этой точки у других жидкостей.

Экспериментальное определение начальной точки чистого парообразования для воды проводилось с помощью высокоскоростного фотографирования при 13,9 и 15,8 Мн/м².