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FLASHING INCEPTION IN FLOWING LIQUIDS

by

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ABSTRACT

The inception of net vaporization in flashing flows is examined. It is suggested that the flashing inception can be expressed as two additive effects. One is due to the static decompression which is a function of the spinodal limit and also of the expansion rate. The other effect which is a function of Reynolds number and flashing index, is due to the turbulent fluctuations of the flowing liquid. It is shown that by taking a three standard deviation band on the turbulent velocity fluctuations, an adequate representation of the inverse mass flux effect on flashing inception for existing data is obtained.

NOMENCLATURE

English

d =diameter
F_i=flashing index
G =mass flux
p =pressure
T =temperature
u',v',w'=velocity fluctuation components
U_o=Channel mass-averaged velocity

Greek

Δ =difference
μ =viscosity
ρ =density
Σ' =rate of pressure decrease (expansion rate)

Subscripts

Fi =flashing inception
Fio=flashing inception under static conditions
l =liquid
max=maximum
min=minimum
rm=reduced minimum

Superscripts

*=dimensionless
'=fluctuation
‾=averaged

INTRODUCTION

In the unlikely event of a cold leg pipe rupture in a pressurized water reactor, subcooled water at high pressure enters the pipe and undergoes a pressure reduction as it flows toward the break. At some point in the pipe the pressure is reduced below the saturation pressure according to the existing liquid temperature. At some later point, nucleation begins and the resulting nonequilibrium vapor generation causes the flow to be choked at the break location. The discharge flow rate, which is especially sensitive to the actual vapor content, directly affects the subsequent course of events and especially the heat transfer characteristics of the core prior to quenching by emergency cooling. At present there is no general model for the nonequilibrium vapor generation rates or for any of the three major factors which affect the void development under such conditions: flashing inception point, interfacial area available for vaporization, and rate of mass exchange per unit interfacial area. It is the purpose of this paper to address the question of flashing inception as affected by velocity effects. It will be shown that a model based on turbulent fluctuation intensity does a reasonably acceptable job of accounting for these effects when applied to the few data available.

BACKGROUND

It is well known that the mass flow rates in critical flow conditions are highly dependent on the vapor content of the flow. Saha[1] has reviewed and evaluated critical flow research concluding that currently accepted equilibrium models underpredict critical flows for "short" pipes especially for subcooled or nearly saturated sources. While thermal nonequilibrium must be taken into account for "short" pipes, it is not clear how the combination of length and diameter enters the picture. Wu et al.[2] have shown that a model based on spherical bubble growth in fields of variable superheat adequately predicts the data of Reocreux[3] for void fractions less than 0.3. These predictions require accurate knowledge of both the voiding inception point and an initial nucleation density parameter. It is well known[4] that the initial degree of superheat markedly affects bubble growth in both constant and variable pressure fields. The degree of superheat has also been shown to play a strong role in void development in flashing critical flows[2]. Since the point at which flashing inception occurs directly affects the initial superheat, the flashing inception can also be expected to play a strong role in the critical mass flow rates under flashing conditions.

Little work has been accomplished examining the point of flashing inception. Seynhaeve, Giot. and Fritte[5] ran experiments with inlet temperatures between 111°C and 167°C and at mass fluxes between 10 and 20 Mg/m²-s. They determined the superheat at flashing inception to behave inversely with mass flux. Although their data were quite scattered, the superheat apparently decreased to almost zero at the higher mass fluxes, and even became negative in a few cases. In their evaluation of Reocreux's 1.74 bar data, Wu et al.[2] found similar results as shown in Figure 1. In this figure the superheat is expressed in terms of the overexpansion at the inception point denoted by Δp_{FI}. (Note that throughout this paper the terms overexpansion and superheat are used interchangably and are, of course, coupled along the saturation line.) Apparently no other experiment appears to have been here-to-fore undertaken allowing suitable definition for determination of flashing inception superheats.

The boiling inception and onset of net vapor generation in flowing liquids has been the subject of much scrutiny in the case of heating, having been the subject of such well known works as those of Hsu[6], and of Saha and Zuber[7], among others. Unfortunately, flashing inception does not appear to be charactarized by models applicable to heated liquids where the superheat is generally confined to the wall layer in bulk subcooled liquids. Instead, bulk superheating occurs prior to flashing inception while the initial voiding still seems generally relegated to the wall layer.

In the case of static liquids undergoing rapid decompression, the situation appears quite similar. The work of Lienhard, Alamgir, and Trela[8] appears clearly applicable where the very early stages of blowdown were observed starting with pressures up to the 150 bar range and temperatures up to nearly 330°C. They found that the limit of overexpansion depends on the rate of decompression prior to nucleation up to a value of about 65% of the spinodal limit. This limit itself depends on the initial fluid temperature. They further suggest that various imperfections in cleaning and preparation of a given system as well as history of preparation may play a role. On the other hand, the correspondence between their data and the data of Edwards and O'Brien[9] makes this seem somewhat unlikely.

The data of Edwards and O'Brien[9] and of Lienhard, Alamgire, and Trela[8] occur with decompression rates of 0.05 - 1.5 Mbar/s while the data of Reocreux[3] and of Seynhaeve, Giot, and Fritte[5] decompress at rates three orders of magnitude slower. Decompression times in the static systems of References [8] and [9] data are generally less than a millisecond. Decompression times in the flowing systems of [3] and [5] range up to several tens or hundreds of milliseconds. The only other differences between the static and dynamic flashing systems seem to be those of fluid motion. Of the factors influenced by these motions, the turbulent pressure fluctuations appear to be those most likely to have an effect. Indeed, Chen[12] offered a similar suggestion to explain sodium boiling superheat behavior.

It thus seems that decompressive flashing inception might be characterized by at least three considerations: initial temperature; decompression rate; degree of liquid turbulence. Based on these considerations, the balance of this paper will be devoted to attempting to characterize flashing inception in flowing systems to the extent possible in view of the limited data available. Indeed, it will be shown that the inverse mass flux effects of both References [3] and [5] may be explained due to effects of turbulent fluctuations.

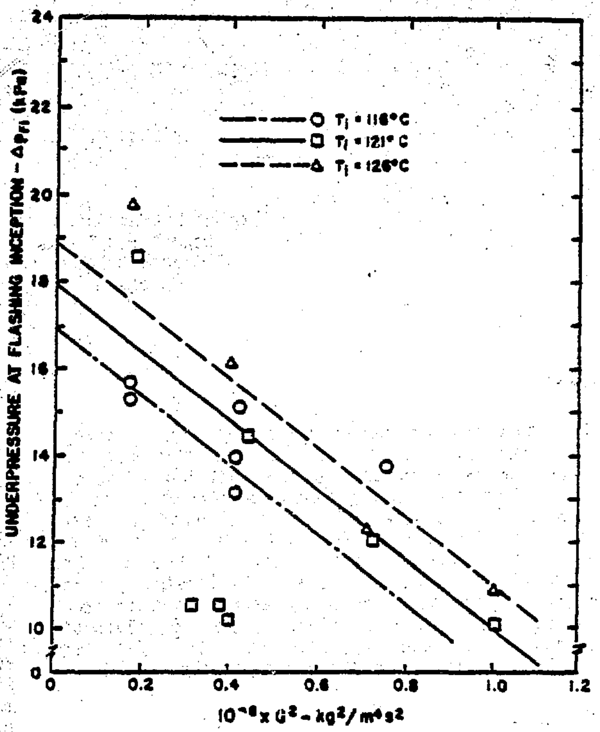

Figure 1 Observed mass flux effect on overexpansion (underpressure) at flashing inception for the data of Reocreux[3]. (BNL Neg.No 3-237-79)

ANALYSIS

In view of the preceeding remarks, it appears that the condition of the fluid at the onset of flashing, either static or flowing, might be characterized in terms of the turbulent pressure fluctuations. In the static systems of References [8] and [9], it is not likely that turbulence had time to develop. In the flowing systems of References [3] and [5], fully developed turbulence was most certainly present at the high Reynolds numbers encountered (order of 10^5). The following hypotheses thus seem reasonable:

1. static flashing overexpansion is a function only of initial temperature and expansion rate, and represents the true inception potential, (Lienhard's hypothesis[8]);

2. dynamic flashing overexpansion at inception is subject to the additive effects of turbulence giving an apparent alteration in the inception potential.

It is suggested that the overexpansion at flashing inception may be expressed as

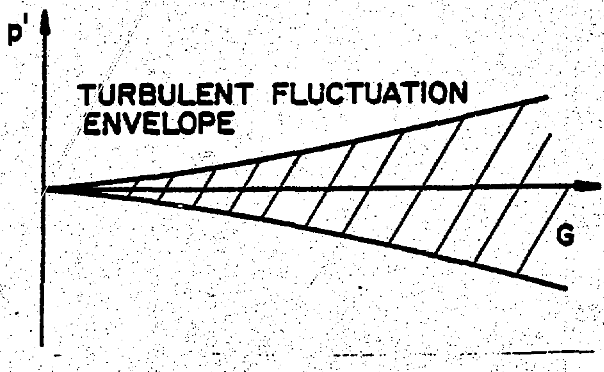

Figure 2 Sketch of pressure fluctuation envelope with varying mass flux. (BNL Neg.No 3-239-79)

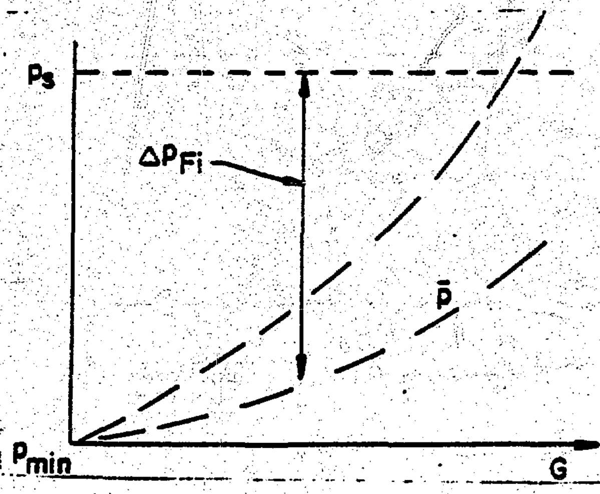

Figure 3 Qualitative Effects of pressure fluctuations on observed overexpansion at flashing inception (BNL Neg.No 3-239-79)

$$\Delta p_{Fi} = f(\Delta p_{Fio}(T_i,\Sigma'), p') \quad (1)$$

where $\Delta p_{Fio}(T_i,\Sigma')$ is the overexpansion under zero flow conditions as dependent on initial temperature, T_i, and expansion rate, Σ'. and p' is the pressure fluctuation. Note that T_i may be replaced with the spinodal limit T_m after Lienhard et al.[8] without loss of generality.

To see how the pressure fluctuations might enter into the picture, the fluctuation envelope may be envisioned as sketched in Figure 2 depending on the mass flux. As the flux increases, so does the turbulence intensity. According to the hypotheses, the bottom of the envelope would represent the true minimum pressure at any mass flux. If this minimum pressure is taken as identical to the static value at inception represented by hypothesis (1), then the average pressure at the inception point would have to increase with increasing mass flux as shown in Figure 3. Since the overexpansion at inception is the difference between the saturation pressure and the observed average pressure, this value, Δp_{Fi}, is seen to decrease in accordance with observation. If we define the apparent overexpansion at flashing inception as

$$\Delta p_{Fi} \equiv p_s - \bar{p}_{Fi} \quad (2)$$

and the true value is taken to be identical with the static value as

$$\Delta p_{Fio} \equiv p_s - p_{min} \quad (3)$$

then the relationship between the two, in view of Figures 2 and 3 is simply

$$\Delta p_{Fi} = \Delta p_{Fio} - \text{Max}\,|p'| \quad (4)$$

Note that the importance of turbulent pressure fluctuations in cavitation has been previously recognized by Daily and Johnson [10]. They, in fact, point out that the effects of dissolved gas or pre-existing gas nuclei will be to reduce the cavitation or flashing inception superheat.

The maximum in the pressure fluctuation envelope is assumed to coincide with the maximum kinetic fluctuations so that

$$\text{Max}\,|p'| = \frac{1}{2}\rho_\ell\,(u'^2_{max} + v'^2_{max} + w'^2_{max}) \quad (5)$$

The nucleation density monotonically increases with increasing superheat while the probability density of the kinetic energy fluctuations first increases then decreases. The product of nucleation density and superheat probability density is expected to yield a maximum with increasing superheat. This maximum would probably represent the inception point and is expected to fall within the 99% probability band. If the maximum fluctuation in each velocity component is thus assumed to be represented by the three sigma value, (three standard deviations), then

$$\text{Max}\,|p'| = \frac{1}{2}\rho_\ell\,[(3\sqrt{\overline{u'^2}})^2 + (3\sqrt{\overline{v'^2}})^2 + (3\sqrt{\overline{w'^2}})^2] \quad (6)$$

so that, for the case of isotropic turbulence (4) becomes

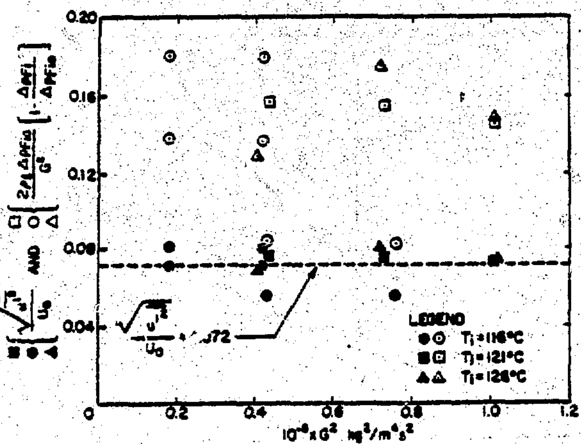

Figure 4 Velocity and scaled kinetic energy fluctuation intensities calculated from the overexpansion data of Reocreux[3] at flashing inception. (BNL Neg.No 3-235-79)

$$\Delta p_{Fi}^{*} \equiv \frac{\Delta p_{Fi}}{\Delta p_{Fio}} = 1 - 27\left(\frac{\overline{u'^2}}{U_0^2}\right)\frac{G^2}{2\rho_\ell \Delta p_{Fio}} \tag{7}$$

It is thus seen that the apparent superheat at flashing inception in flowing systems may be expected to scale with the reduced limit of superheat, the expansion rate, the flashing index (reciprocal of the cavitation index), and the Reynolds number through the turbulent fluctuation intensity. Thus,

$$\Delta p_{Fi} = f(\Delta T_{rm}, \Sigma'^{*}, Re, F_i) \tag{8}$$

where

ΔT_{rm}=difference between the nucleation temperature and the saturation temperature at the same pressure, reduced to the critical temperature,

Σ'^{*}=dimensionless expansion rate (decompression rate).

R_e=Reynolds number given by $R_e = U_0 d\rho_\ell/\mu$

F_i=flashing index given by $F_i = 1/2\rho_\ell U_0^2/\Delta p_{Fio}$.

There does not seem to be a readily apparent reference to nondimensionalize the expansion rate.

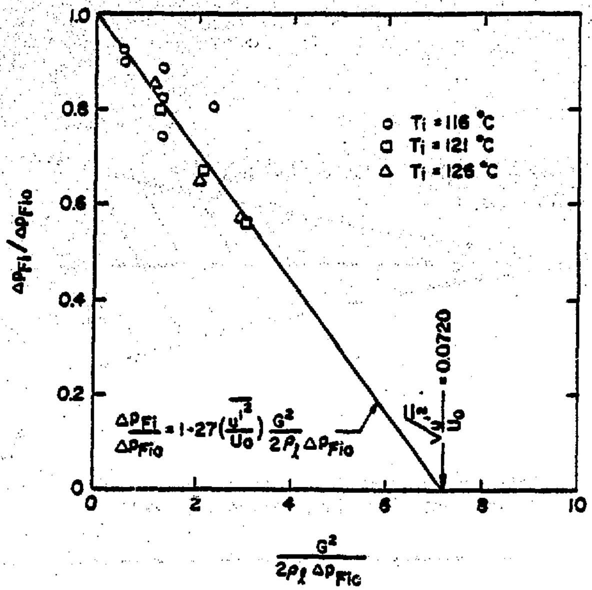

Figure 5 Dimensionless correlation of Reocreux's[3] overexpansion data at flashing inception. (BNL Neg.No 3-240-79)

RESULTS AND DISCUSSION

Equation (7) shows that the apparent overexpansion at flashing inception should be linear in the square of the mass flux with an intercept of the static inception value, Δp_{Fio}. If the ideas previously expressed are at all valid, then using extrapolated values of Δp_{Fio}, turbulent fluctuation intensities obtained at known inception points should match those found, for instance by Laufer[11], of 0.07-0.08.

Figure 1 shows the data of Reocreux[3]. The straight lines in the figure represent an attempt to correlate the three sets of data in a consistant fashion and in a way that allows extrapolation to zero mass flux. The values of Δp_{Fio} thus obtained were 17, 18, and 19 kPa, representative of actual superheats of approximately 3.5°C. Note that 1.0 kPa represents about 0.18°C at the conditions tested.

Using the values of Δp_{Fio} obtained from Figure 1, the mean fluctuation intensities may be computed from the data. These are shown in Figure 4, (solid symbols). Also shown in this figure are the kinetic energy fluctuation intensities scaled appropriately for convenience of plotting, (open symbols). The average of the velocity fluctuation intensities obtained is 0.072 in good agreement with the measurements of Daily and Johnson[10] based on their measurements of bubble motion and also of Laufer[11]. No observable trend with mass flux is noticed. Also, there is surprisingly little scatter in the results so obtained.

Reocreux's data are replotted in Figure 5 on dimensionless coordinates suggested by Equation (7). Since the fluctuation effects are subtractive, Equation (7) suggests the possibility of negative superheats. This is shown by the x-intercept at a flashing index, F_i, of 7.2. While there is nothing actually prohibiting the turbulent pressure fluctuations from exceeding the values required to overcome the zero-flow incipient superheat, bubbles thus generated would probably collapse almost immediately in the bulk subcooled liquid unless carried to lower pressure regions before this could happen. An envelope of Δp_{Fi}^* is thus suggested as

$$\Delta p_{Fi}^* = \text{Max} \begin{cases} 0 \\ 1\text{-}27 \left(\dfrac{\overline{u'^2}}{U_o^2} \right) F_i \end{cases} \qquad (9)$$

Finally, extrapolative determination of Δp_{Fio} for the data of Seynhaeve. Giot, and Fritte[5] would negate the validity of any other comparison. Thus, it is not possible to obtain a meaningful comparison of the majority of these data with the results of Equation (9). However if there is any validity in the preceeding concepts, it might be expected that the Reference [5] data in the same temperature range as the Reocreux[3] data may exhibit the same behavior. Both sets of data are plotted in Figure 6. Also shown in this figure is the prediction based on a static inception underpressure of 18 kPa. The trends observed appear to support the conclusions previously stated. Note that the lower limit of zero superheat also appears reasonable and tentatively supported by the relatively meager amount of data available.

CONCLUSIONS AND RECOMMENDATIONS

1. Flashing inception superheat in flowing systems appears to be described by the effects of turbulent fluctuations, (Equation 9). This suggests that the flowing and static superheats at inception are identical once turbulent fluctuations are accounted for.

2. It is suggested that the limit of flashing inception with vanishing mass flux in flowing systems coincides with that value that would be obtained by static decompression at the same expansion rates.

3. The scaling parameters for flashing inception appear to be the reduced limit of superheat, ΔT_{rm}, the Reynolds number, the flashing index (reciprocal of the cavitation number), and a dimensionless expansion rate. It is not clear, however, what reference quantities are reasonable to render the expansion rate dimensionless.

4. Additional data are needed for flashing inception at higher pressures. Sufficient detail are required to accurately determine the inception point due to the sensitivity of void development to small changes in superheat at inception. Sufficient range in mass flux is required to allow extrapolative determination of the case of vanishing turbulence.

5. Analysis is needed to determine the behavior of the static flashing inception with expansion rate. The reasons for the observed behavior are not clear at this time.

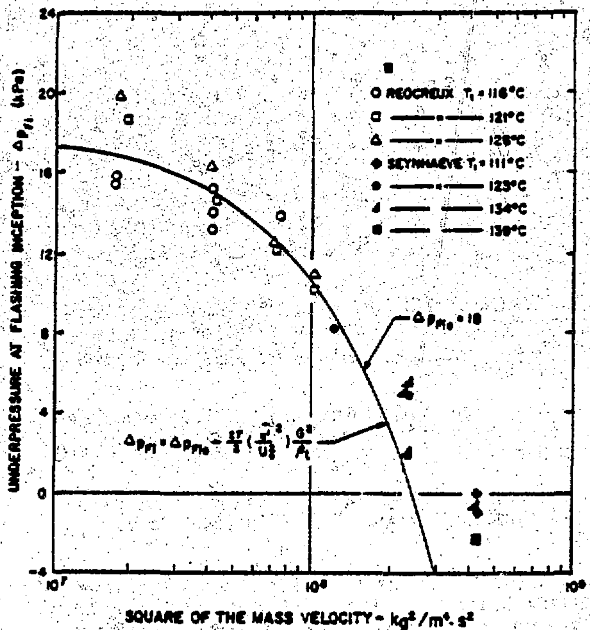

Figure 6 Comparison of the flashing inception data of Reocreux[3] and of Seynhaeve, Giot, and Fritte[5] with the theory developed herein using the approximate static flashing overexpansion value of 18 kPa for the computation. (BNL Neg.No 3-238-79)

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REFERENCES

[1] P. Saha, "A Review of Two-Phase Steam-Water Critical Flow Models with Emphasis on Thermal Nonequilibrium," BNL-NUREG-50907, September, 1978.

[2] B.J.C. Wu, P. Saha, N. Abuaf, and O.C. Jones, Jr., "A One Dimensional Model of Vapor Generation in Steady Flashing Flow," Interim Milestone Report, BNL-NUREG-25709, October, 1978.

[3] M. Reocreux, "Contribution a l'Etude des Debits Critiques en Ecoulement Diphasique Eau-Vapeur," PhD Thesis, Universite Scientifique et Medicale de Grenoble, France, 1974.

[4] O.C. Jones, Jr., and N. Zuber, "Bubble Growth in Variable Pressure Fields," Trans. ASME, J. Heat Trans., 100C, 453-459, 1978.

[5] J.M. Seynhaeve, M.M. Giot, and A.A. Fritte, "Non-Equilibrium Effects on Critical Flow Rates at Low Qualities," Proc. of the CSNI Specialists Meeting on Transient Two-Phase Flow - Toronto, Canada, August 3-4, 1976.

[6] Y.Y. Hsu, "On the Size Range of Active Nucleation Cavities on a Heating Surface," Trans. ASME, J. Heat Trans., 84C, 207-216, 1962.

[7] P. Saha, and N. Zuber, "Point of Net Vapor Generation and Vapor Void Fraction in Subcooled Boiling," in Heat Transfer 1974, Proc 5th Int. Heat Trans. Conf., Vol IV, 175-179, 1974.

[8] J.H. Lienhard, Md. Alamgir, and M. Trela, "Early Response of Hot Water to Sudden Release from High Pressure," Trans. ASME, J. Heat Trans., 100C, 473-479, 1978.

[9] A.R. Edwards, and T.P. O'Brien, "Studies of Phenomena Connected with Depressurization of Water Reactors," J. Brit. Nucl. Ener. Soc., 9, 125-135, April, 1970.

[10] J.W. Daily, and V.E. Johnson, Jr. "Turbulence and Boundary Layer Effects on Cavitation Inception from Gas Nuclei," Trans. ASME, 78 1695-1706, 1956.

[11] J. Laufer, "Investigation of Turbulent Flow in a Two-Dimensional Channel," NACA TN 2123, July, 1950.

[12] J.C. Chen, "Effect of Turbulent Flow on Incipient Boiling Superheat," Proc. 1st Mtg. of Technology Grp. on Liq. Metl. Thermal Sci., Brookhaven National Laboratory, May, 1969.