VOLUME-HEATED BOILING POOL FLOW BEHAVIOR AND APPLICATION TO TRANSITION PHASE ACCIDENT CONDITIONS

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ABSTRACT

Observations of two-phase flow fields in volume-heated boiling pools are reported. Photographic observations, together with pool-average void fraction measurements are presented. Flow regime transition criteria derived from the measurements are discussed. The churn-turbulent flow regime was the dominant regime for superficial vapor velocities up to nearly five times the Kutateladze dispersal velocity. Within this range of conditions, a churn-turbulent drift flux model provides a reasonable prediction of the pool-average void fraction data. The results of the experiment and analyses are extrapolated to transition phase conditions. It is shown that intense pool boil-up could occur where the pool-average void fraction would be greater than 0.6 for steel vaporization rates equivalent to power levels greater than one percent of nominal LMFBR power density.

INTRODUCTION

The transition phase of the (hypothetical) loss-of-flow core disruptive accident in an LMFBR may be characterized by the temporary entrapment of pools of molten-oxide fuel and boiling steel within the confines of the original core volume (Bohl, et al., 1975). It has been argued (Fauske, 1975) that the molten fuel would be in a boiled-up configuration and would be dispersive. These arguments are based, to a considerable extent, on flow regime transition criteria which are extrapolated from existing data (Kutateladze, et al., 1960) to molten fuel systems. These criteria have played a vital role in support of the contention that fuel dispersal would prevent phase recriticality events at power levels down to one percent of nominal LMFBR power density (Fauske, 1977a).

The extent of fuel dispersal by boiling steel depends on the magnitude of steel vaporization and upon the vapor-liquid void dynamics. Assessment of the extent of fuel dispersal requires analytical models for prediction of the spatial distribution of molten fuel. Models which couple the material distributions to the thermodynamic, heat transfer and neutronic characteristics of transition phase molten pool configuration are currently under development (Bell, et al., 1977).

In the absence of such detailed mechanistic models, it has been assumed (Fauske, 1977b) that the oxide fuel-steel system acts as a saturated, homogeneous mixture of heat source (molten fuel) and vapor source (boiling steel), subject to volumetrically distributed heating. Predictions of the extent of fuel dispersal have been based upon flow regime transition criteria, and associated vapor-liquid void dynamics models, available in the two-phase flow literature. These criteria and models had been developed in conjunction with experimental data from systems characterized by either surface heating or surface gas injection. Experimental data with molten fuel-steel mixtures with volumetric heating have not been developed. In this sense, therefore, fuel dispersal by boiling-steel vapor generation has not been demonstrated.

Two-component volume-heated experiments with simulant fluids are also not available. Several single-component volume-heated boiling experiments have been reported (Gustavson, et al., 1976; Gabor, et al., 1976; Stein, et al., 1974). The vapor generation rates, however, are much too low for application to transition phase conditions (see Fig. 2.1).

In only one prior experimental study was the boiling behavior observed in a volume-heated boiling pool system, in which the vapor velocities generated approached that of interest in transition phase conditions. Farahat, et al., (1976) used microwave heating to study the two-phase flow behavior of open boiling pools of water of various geometries. The water was doped with red, neutrally bouyant, plastic particulate, in order to promote volumetrically-distributed nucleation. Visual observations of the boiling behavior were made, together with measurements of the pool-average void fraction ($\bar{\alpha}$, see below). The power available for vaporization was deduced from a calorimetric power calibration with single-phase water. The test results revealed the following significant departures from prior notions based upon the previous two-phase flow literature:

(i) A transition from the bubbly-flow regime to the churn-turbulent flow regime was not observed, even at superficial vapor velocities, $j_{g\infty}$, up to 50 times the transition velocity given by (Wallis, 1969)

$$\frac{j_{gb}\sqrt{\rho_\ell}}{\sqrt[4]{g\sigma(\rho_\ell - \rho_g)}} = 0.3 \qquad (1)$$

(Note: for later reference, this is equivalent to $j_{gb}/U_\infty = 0.25$).

(ii) A transition to the dispersed flow regime was not observed, even at superficial vapor velocities up to three times the Kutateladze (1960) dispersal velocity, given by

$$\frac{j_{gk}\sqrt{\rho_g}}{\sqrt[4]{g\sigma(\rho_\ell - \rho_g)}} = 0.14 \qquad (2)$$

(iii) A stable, high void fraction, bubbly flow regime, characterized as a "foam" regime (Henry, 1977), was observed at vapor velocities exceeding that represented by Eq. (1). The range of observed void fraction is presented in Fig. 2.1.

The above behavior has not yet been rationalized with respect to prior two-phase flow experience. It is known, however, that both chemical and particulate impurities present in liquids may enhance foam development and stability (Bikerman, 1973). It is possible, therefore, that the particulate additives, with its associated red, water-soluble coloring agent, enhanced the stability of bubbles against coalescence and, hence, led to a foam regime.

The study reported here was performed to evaluate the applicability of existing flow regime criteria, and of two-phase drift flux formulations, to prediction of volume-heated boiling pool void dynamics. This paper summarizes the results of the study and discusses the implications with respect to the transition phase accident sequence.

ANALYTICAL BACKGROUND

The steady state, one-dimensional vapor mass balance equation for a single-component volumetrically heated boiling pool of constant cross-section is (Greene, et al., 1977)

$$\frac{dj_g}{dx} = \frac{Q'''(1 - \alpha)}{\rho_g h_{fg}} \tag{3}$$

In terms of area-averaged quantities, the drift velocity, V_{gj}, is related to the superficial velocities, through the relationship

$$j_g = \alpha[V_{gj} + (C_o - 1)j] + \alpha j \tag{4}$$

where C_o is the *"distribution parameter"* (*Zuber, et al., 1965*). *For a boiling* pool, j_ℓ is nearly zero. Then Eq. (4) becomes

$$j_g = \frac{\alpha}{1 - C_o\alpha} V_{gj} \tag{5}$$

and, therefore, Eq. (3) may be written

$$\frac{d}{dx}\left(\frac{\alpha V_{gj}}{1 - C_o\alpha}\right) = \frac{Q'''(1 - \alpha)}{\rho_g h_{fg}} \tag{6}$$

Eq. (6) may be written in the dimensionless form

$$\frac{d}{d\eta}\left(\frac{\alpha F}{1 - C_o\alpha}\right) = \frac{j_{g\infty}}{U_\infty} (1 - \alpha) \tag{7}$$

where H_o is used to scale the distance and U_∞ to scale the drift velocity. The quantity $j_{g\infty}$ is the superficial vapor velocity at the top of the pool.

The void distribution $\alpha(\eta)$ is a function of $j_{g\infty}/U_\infty$, the form of the drift velocity function ,F, and the distribution parameter, C_o. It is usually assumed that F is a function only of α and material properties. Furthermore, $F(\alpha)$ and C_o are flow regime dependent (Ishii, 1977).

For the bubbly-flow regime, it has been suggested that (Wallis, 1969)

$$F(\alpha) = (1 - \alpha)^2 \tag{8}$$

For the churn-turbulent regime, Zuber, et al. (1962) proposed that F is constant, i.e.,

$$F(\alpha) = 1 \tag{9}$$

For a given flow regime, the void distribution is a function only of $j_{g\infty}/U_\infty$ and C_o. Flow regime transition criteria must, of course, be specified in order to choose the appropriate forms for F(α).

The above formulation is compared with the experimental results described below. The pool-average void fraction is computed based upon the solution to Eq. (7) and compared with the experimental data.

EXPERIMENTAL SYSTEM

Observations of two-phase, single-component volume-heated boiling pool behavior were made in an electrically heated water-zinc sulfate (14 weight percent) system. The pool, described by Ginsberg, et al., (1977), was 120 cm high and was 8.89 cm x 6.35 cm in cross-section. Two electrodes penetrated the length of the pool. In operation, the pool was filled with liquid to a given depth, power was applied and volume boiling ensued. Photographic observations of pool behavior were made, together with measurements of the applied power and the pool-average void fraction, $\bar{\alpha}$, defined by

$$\bar{\alpha} = \frac{H - H_o}{H} \tag{10}$$

Representative results are presented below.

RESULTS

Figure 1 shows the non-foaming behavior of the boiling pool over the range of conditions covered in this work. The results are characterized in terms of the dimensionless superficial vapor velocity $j_{g\infty}/U_\infty$. The pool-average void fractions, $\bar{\alpha}$, are also presented with the photographic observations. Figure 2.1 summarizes the average void fraction data measured in several series of measurements in this investigation. It also shows the results of Farahat, et al., (1976), Gabor, et al., (1970), and Gustavson, et al., (1970).

The photographs presented in Fig. 1 display the general features of the boiling pool behavior observed during most of the test series. At superficial vapor velocities up to approximately $j_{g\infty}/U_\infty$ = 1-2, a bubbly flow regime was always observed, as shown in Fig. 1, Run No. 402. For $j_{g\infty}/U_\infty$ greater than approximately 4, a churn-turbulent flow regime was observed. This flow regime was observed for $j_{g\infty}/U_\infty$ up to 19. As shown in in Fig. 1, Run Nos. 413, 424, and 523, this regime was an extremely dynamic one, characterized by a chugging, highly turbulent behavior. The pool-average void fraction data are shown bounded in Fig. 2.1, for both Series 400 and 500 in one band. Figure 2.2 shows predictions based upon the void dynamic model described above. The churn-turbulent drift velocity model, with C_o between 1.2 and 1.35 provides a reasonably good prediction of the data of Series 400 and 500 for the range of $j_{g\infty}/U_\infty$ from 1 to 19.

While the above two-phase flow behavior was observed during most of the tests, under some conditions a "foam" flow regime was observed. For $j_{g\infty}/U_\infty$ between 1 and 4, sometimes a bubbly flow regime, and other times a churn-turbulent flow regime was observed. This range of conditions appeared to be markedly influenced by the presence of contaminants. A foam flow regime was observed in instances where system contamination by particulate impurities (probably copper sulfate) was observed. In all cases, however, the foam regime was observed to collapse to the churn-turbulent regime beyond $j_{g\infty}/U_\infty = 4$. This behavior is reflected in Fig. 2.1, in the Series 600 data. The void fractions observed are significantly greater than observed in the Series 400 and 500 experiments, up to $j_{g\infty}/U_\infty \approx 4$. Thereafter, the data do not differ dramatically. Figure 2.2 indicates the bubbly flow drift velocity model, with $C_o = 1.2$, is an upper bound prediction for the Series 600 data.

SUMMARY

Table 1 summarizes the flow regime observations made in this investigation. The associated ranges of observed pool-average void fractions are also presented.

A bubbly flow regime was always observed for $j_{g\infty}/U_\infty$ up to approximately unity. In most of the experimental runs, a transition from bubbly to churn-turbulent flow was observed at this point. The void fraction data i this regime are characterized reasonably well by the bubbly flow drift velocity formulation.

In the range of $j_{g\infty}/U_\infty$ between 1 and 4, the flow regime appeared to be markedly influenced by the presence of contaminants. A foam flow regime was observed in instances where system contamination by particulate impurities (probably copper sulfate) was observed. This regime always gave way to the churn-turbulent flow regime for $j_{g\infty}/U_\infty$ greater than 4. The void fraction data in the churn flow regime are also described reasonably well by the churn-turbulent drift velocity model.

The churn-turbulent regime was observed at vapor velocities up to nearly five times the Kutateladze dispersal limit (Kutateladze, 1960). This observed stability of the churn-turbulent regime is consistent with the dispersal limit proposed by Dukler (1977).

The results of this experiment differ from those of Farahat, et al., (1976). The major difference is the apparent persistence, in Farahat's experiments, of the foam regime to relatively large vapor fluxes. The consequence of this is that for comparable vapor fluxes, the average void fraction was greater than 0.9 in Farahat's experiment's, and approximately 0.6-0.7 in the present work. A major unresolved issue is the question of the reasons for the observed persistence of bubbly flow, and the influence of system contamination on the observed behavior.

APPLICATION TO TRANSITION PHASE CONDITIONS

The results described above have been extrapolated to transition phase pools of molten fuel and boiling steel (with spatially uniform ratio of fuel mass to steel mass). Table 2 shows the flow regime and average void fraction characteristics of transition phase pools, as extrapolated from results of the experiment reported here. Results are shown for steel vapor generation rates equivalent to one percent and eight percent of nominal LMFBR power density. As shown in Table 2, the results of this experiment suggest that the churn-turbulent regime is dominant under these conditions. As such, the churn-turbulent drift flux model was applied to the pool. The results indicate that the pool-average steel vapor volume fraction would be in the range 0.6-0.7 at one percent, and in the range 0.7-0.8 at eight percent, of nominal fuel power density (applied to steel porization).

In a typical LMFBR core, the fuel and steel occupy approximately 60 percent of the available volume. Only 40 percent of the core volume, therefore, is ava te for boil-up by steel vapor if all the fuel and steel are confined to the pool. Table 2, however, indicates that the pool-average void fraction would be greater than 0.6 for power levels greater than one percent of nominal LMFBR conditions. If the pool is open at the top, the mixture of molten fuel and steel could potentially boil up considerably beyond the original core volume (where it would encounter upper fuel assembly structure). This intense pool boil-up, predicted by the churn-turbulent drift flux model, may serve as a mechanism which would reduce the potential for transition phase recriticality events.

It has been shown (Ludewig, et al., 1976) that the reactivity of the disrupted (CRBR) molten core depends upon the radial and axial extent of the molten region, on the extent of intermixing of enrichment zones, the quantity of fuel displaced from the core zone, and upon the average void fraction of the molten fluid within the disrupted core. It is expected that the reactivity will depend not only on the average void fraction, but also upon the detailed spatial distribution of molten fuel within the disrupted core configuration. The neutronics response of large LMFBR's to molten fuel distributions predicted by the churn-turbulent void dynamics model needs to be evaluated.

NOMENCLATURE

C_o	two-phase flow distribution parameter
$F(\alpha)$	dimensionless drift velocity fraction
g	acceleration of gravity
h_{fg}	heat of vaporization
H	boiled-up pool height
H_o	non-boiling pool height
j	superficial velocity (liquid plus vapor)
j_g	superficial vapor velocity
j_{gb}	superficial vapor velocity for bubbly-flow to churn-trubulent flow regime transition
j_{gk}	superficial vapor velocity for transition to dispersed flow regime

Nomenclature (Cont'd)

$j_{g\infty}$ superficial vapor velocity at top of pool

Q''' volumetric heat generation rate

U_∞ bubble rise velocity $\left(\equiv 1.53 \frac{\sqrt[4]{g\sigma(\rho_\ell - \rho_g)}}{\sqrt{\rho_\ell}}\right)$

x distance from bottom of pool

α local void fraction

$\bar{\alpha}$ pool-average void fraction

η dimensionless pool height ($\equiv x/H_o$)

ρ_g vapor specific gravity

ρ_ℓ liquid specific gravity

σ surface tension

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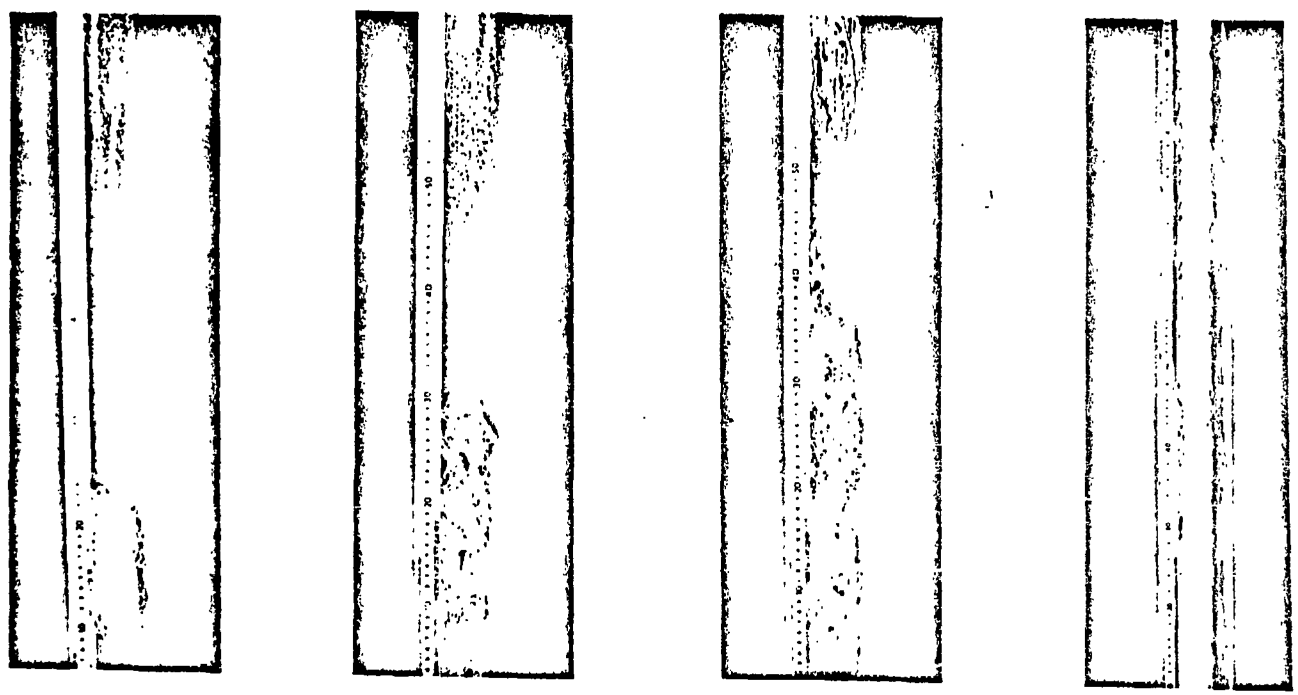

Run No.	402	413	424	523
$j_{g\infty}/U_{\infty}$	.67	4.63	8.95	19.1
$\bar{\alpha}$	.37-.40	.52-.57	.61-.65	.68
H_o(cm)	15	15	15	30

Figure 1 - Photographic Observations of Boiling Pool Flow Behavior.

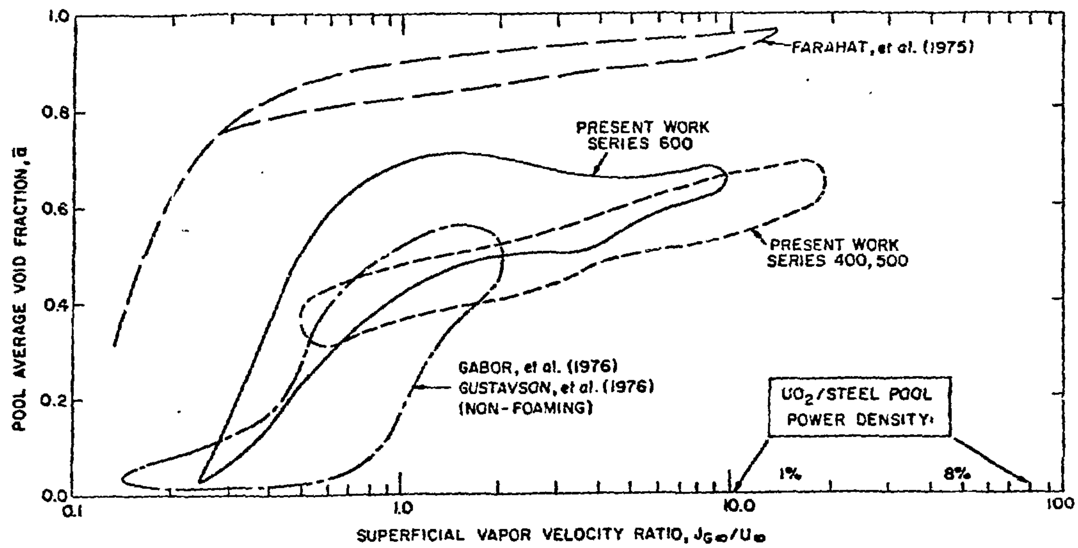

Figure 2.1 - Pool-Average Void Fraction Measurements

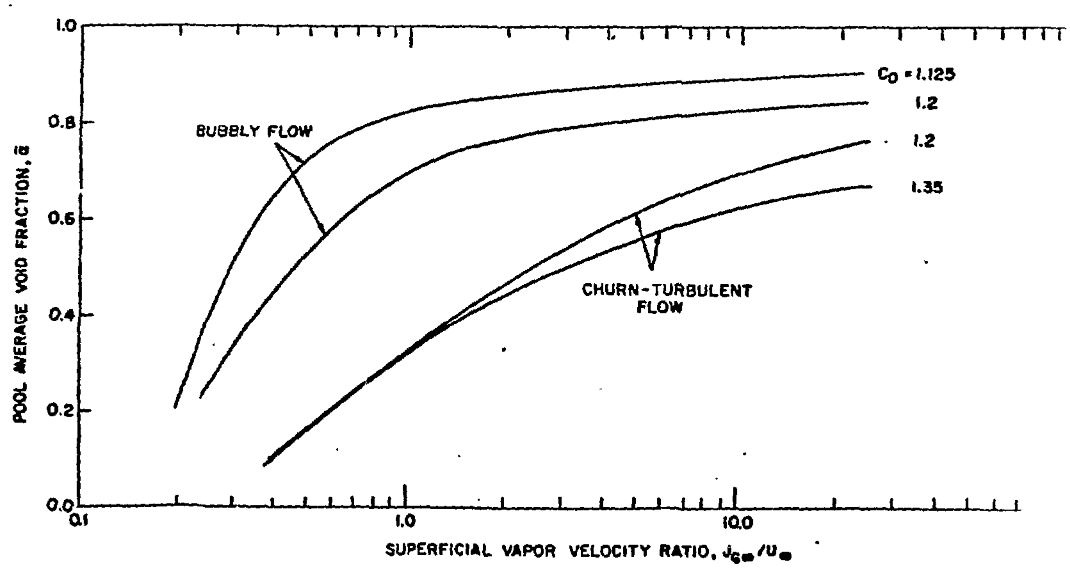

Figure 2.2 - Predictions of Pool-Average Void Fraction.

TABLE 1 - SUMMARY OF FLOW REGIME OBSERVATIONS

$j_{g\infty}/U_\infty$	$j_{g\infty}/j_{gk}$	FLOW REGIME	VOID FRACTION $\bar{\alpha}$
0 - 1*	0 - 0.25	Bubbly	0 - 0.35
1 - 4	0.25 - 1.0	Bubbly (Foam)-Churn-Turbulent	0.25 - 0.75
4 - 19	1.0 - 4.8**	Churn Turbulent	0.4 - 0.7

* The transition from bubbly flow to churn-turbulent flow has been previously observed to occur at $j_{g\infty}/U_\infty \sim 0.25$[6]

** The Kutateladze relationship[3] predicts to transition to the dispersed flow regime to occur for $j_{g\infty}/j_{gk} = 1$

TABLE 2 - EXTRAPOLATED TRANSITION PHASE CHARACTERISTICS

Power Available for Steel Vaporization (percent of LMFBR nominal power density)	$\frac{j_{g\infty}}{U_\infty}$	$\frac{j_{g\infty}}{j_{gk}}$	FLOW REGIME	Pool-Average Void Fraction* $\bar{\alpha}$
1	10.6	0.56	Churn-Turbulent	0.59 - 0.66
8	85	4.5	Churn-Turbulent	0.7 - 0.8

*Predicted using churn-turbulent drift flux model with distribution parameter C_o between 1.2 and 1.35.