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SHORTER COMMUNICATIONS

A SIMPLIFIED MODEL OF INERT GAS BUBBLE DYNAMICS IN LIQUID METALS

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NOMENCLATURE

$p_{B,v}$,	liquid vapor pressure inside bubble;
$p_{B,g}$,	inert gas pressure inside bubble;
R,	bubble radius;
p_L,	liquid solution pressure;
p_0,	liquid solution pressure at $t = 0$ (equivalent to $p_{L,0}$);
Δp_L,	pressure drop from reactor core inlet to upper plenum;
σ,	surface tension;
T,	core temperature at any axial position;
t,	time ($\equiv$ heated length/liquid velocity);
V,	liquid solution velocity.

Subscript

0,	initial condition at $t = 0$ corresponding to core inlet.

INTRODUCTION

AN ANALYTICAL model of the dynamic behavior of an inert gas bubble flowing with a dilute solution of the gas in a liquid metal was developed in [1]. Included in the model were many processes normally neglected under steady-state or quasi-steady conditions but which may become important during rapid transients. As a result, only the following primary assumptions were invoked: (1) spherical symmetry, (2) negligible convective transport of inert gas caused by bubble expansion or contraction relative to molecular transport, (3) sufficiently small concentration of inert gas in the solution so that the density of the liquid–gas solution and the diffusion coefficient are constant and Fick's law of diffusion may be used, (4) sufficiently large boundaries of the liquid–gas solution relative to the bubble size so that no interaction between the bubble and these boundaries occurs, (5) mass and thermal equilibrium at the bubble-solution interface exists at all times, and (6) the heat of solution is negligible.

The completeness of the mathematical model required for the accurate analysis of bubble dynamics is strongly dependent upon the severity of the thermal-hydraulic transient to which the bubble is subjected. In the model developed in [1], many terms were retained that represent physical phenomena which can be shown to be negligible under steady-state, quasisteady state and mild transient conditions. These terms would normally be eliminated from the mathematical model at the outset for application to such cases. However, extensive numerical calculations were performed using this complete model for cases that include both severe and mild thermal/hydraulic transients.

An analysis of the results revealed that a number of the physical processes included in the analytical model still represented second order effects on the calculated bubble dynamics during many of the transients applicable to liquid metal fast breeder reactors (LMFBR). Based on this observation, the model was simplified by systematically eliminating second order effects in order to arrive at the least complex formulation producing good agreement with the more complete model when applied to cases representing all normal and some severe abnormal LMFBR operating conditions. This procedure resulted in the modification of the original analytical model by the addition of the following assumptions:

1. Negligible magnitude (with respect to unity) and time derivative of the ratio of vapor–gas mixture density in the bubble to liquid solution density.
2. Inviscid liquid solution.
3. Negligible rate of mass transfer of inert gas between the bubble and the liquid solution.
4. Negligible inertia in the liquid solution.

ANALYSIS

These four sweeping assumptions resulted in a major simplification of the conservation equations yielding the following mathematical description:

$$p_{B,v}(T) + p_{B,g} - p_L(t) - \frac{2\sigma}{R} = 0 \tag{1}$$

$$p_{B,g} R^3/T = \text{constant} \tag{2}$$

which may be combined to give the following implicit equation for the bubble radius:

$$\left(\frac{R}{R_0}\right)^3 + f(t)\left(\frac{R}{R_0}\right)^2 - [1+f(0)]\left(\frac{T}{T_0}\right)\left(\frac{p_0 - p_{B,v}(T_0)}{p_L - p_{B,v}(T)}\right) = 0 \tag{3}$$

where

$$f(t) = 2\sigma/R_0[p_L - p_{B,v}(T)]. \tag{4}$$

The functions $T(t)$ and $p_L(t)$ are specified according to the temperature and pressure transients desired, and the nomenclature followed here is identical to that in [1]. It should be noted that the mathematical model has been reduced to the statement that pressure forces due to gas and vapor inside the bubble are equal to the liquid solution pressure force plus the surface tension force, while the mass of inert gas in the bubble remains constant.

Equation (3) was evaluated for a variety of pressure and temperature transients of significance to LMFBR technology. The specific cases studied encompassed those reported in [1].

RESULTS

For nominal LMFBR operating conditions (core channel hydraulic diameter of 3.07 mm, core heated length of 914.4 mm, upper plenum cover gas pressure of 101.3 kPa, core inlet and outlet temperatures of 316 and 471°C, respectively, and core liquid velocity of 5.18 m/s), the calculated dimensionless bubble radius from the simplified model agreed with that from the complete model in [1] to four significant figures for all initial bubble sizes studied (1–1000 μm). This result is not surprising since as mentioned previously, some simplification of the complete analytical model is justified for steady or mild transient conditions, and the parameters representative of normal LMFBR operating conditions are included in this class of problem. However,

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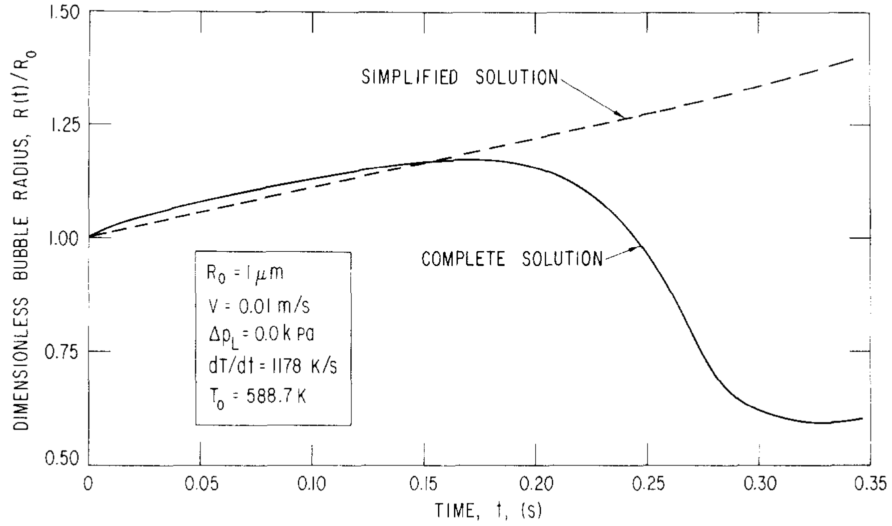

FIG. 1. Comparison of simple and complete models for the case of a core inlet blockage with small R_0.

the usefulness of the simplified model is also dependent on its range of applicability. Thus, comparisons between the predictions of the simplified and complete models were made for more severe transient conditions corresponding to abnormal LMFBR operation of the overpower and core blockage types. In the case of a mild overpower condition (exit liquid temperature of 686°C), similar excellent agreement was obtained between the two models for all values of initial bubble radius studied (1–1000 μm). The results of the core blockage transients, however, were found to be strongly dependent upon the initial bubble radius, R_0. In this case (liquid velocity of 0.01 m/s with continued full power heating) agreement was again excellent for $R_0 > 100\,\mu m$. The results of the two models began to diverge for values of initial radius less than 100 μm where differences of the order of 5% were observed in the predicted bubble radii for $R_0 = 10\,\mu m$, and at $R_0 = 1\,\mu m$ the differences were an order of magnitude larger. The results for bubble radii as predicted by the two models are shown in Fig. 1 for the last condition, $R_0 = 1\,\mu m$. The large differences between the two solutions are evident in Fig. 1 where the diffusion mechanism neglected in the simplified model is a contributing factor to the complete model solution. For initial bubble radii of 100 and 1000 μm, the maximum differences in computed bubble radii were 0.4 and 0.1%, respectively.

CONCLUSION

From these observations, an important conclusion was reached regarding application of the simplified analytical model to LMFBR situations. The dynamics of entrained inert gas bubbles can be described by a very simple model [equations (3)–(4)] with a high degree of accuracy for a wide variety of situations encompassing both normal and some abnormal LMFBR behavior. The applicability to abnormal LMFBR transient situations is limited, and the model must be used cautiously. However, the successful application of the simplified model to some relatively severe LMFBR transient conditions provides assurance of the accuracy of the model when applied to the range of LMFBR operational conditions generally considered to be near nominal.

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THE EFFECT OF TRANSVERSE OSCILLATIONS ON HEAT TRANSFER FROM A HORIZONTAL HOT-WIRE TO A LIQUID. HOLOGRAPHIC VISUALIZATION

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NOMENCLATURE

a,	amplitude of oscillation from center position to extreme position of oscillation;
ω,	pulsation of oscillation;
χ,	heat diffusivity coefficient;
β,	coefficient of thermal expansion;
g,	acceleration of gravity;
ΔT,	temperature difference between the wire and the liquid;
d,	wire diameter;
ν,	kinematic viscosity;