Int. J. Heat Mass Transfer. Vol. 17, pp. 957–959. Pergamon Press 1974. Printed in Great Britain

SATURATION OF A LIQUID METAL WITH INERT GAS IN FORCED CONVECTION FACILITIES*

D. M. FRANCE and R. D. CARLSON
Argonne National Laboratory, Argonne, Illinois 60439, U.S.A.

(*Received* 12 *December* 1973)

NOMENCLATURE

- A_s, surface area of inert gas–liquid interface;
- d, depth of liquid with velocity V;
- D, mass diffusion coefficient of inert gas in liquid;
- k, saturation mass concentration of inert gas in liquid;
- m, mass flowrate of liquid;
- ρ, liquid density;
- V, liquid velocity;
- W_A, mass concentration of inert gas in liquid;
- $\overline{W}_A$, average mass concentration of inert gas in liquid;
- x, coordinate in flow direction;
- z, coordinate transverse to direction of flow;
- ψ, system time constant.

INTRODUCTION

ABNORMAL conditions during the operation of a liquid metal fast breeder reactor (LMFBR) may lead to boiling of the coolant. Since the initial stage of core voiding is highly dependent upon the system superheat at the time of boiling inception, the problem of superheat prediction has received attention. It was demonstrated [1–3] that the presence of inert gas in a liquid metal system could have a significant, if not dominant effect on incipient boiling superheat. In a LMFBR type system the inert gas in the liquid metal coolant originates from the gas–liquid interface in the system plenum. Applying this concept to LMFBR loop type facilities, it was predicted [4] that if boiling was approached after sufficient steady state operating time to allow inert gas mass equilibrium, the incipient boiling superheat would be near zero. This condition was substantiated by recent experiments [5] performed in a facility simulating LMFBR system parameters and using sodium and argon gas working fluids. However, the superheat is not expected to be near zero if the inert gas concentration in the liquid metal is not close to its saturation condition. This situation occurs in a reactor when it is filled with coolant *after every fuel cycle.* It may occur in experimental facilities under a variety of conditions. The purpose of this study was to predict the steady state operational time from coolant fill required to insure that the coolant in a LMFBR type system would be near saturated with inert gas in the plenum. Under this saturated condition, it is expected that the incipient boiling superheat in a subsequent abnormal event would be zero as discussed above.

The analytical model employed produced a family of curves from which the time to saturation could be predicted for any reactor type system provided the plenum flow pattern resembled the analytical model. This prediction requires knowledge of the plenum geometry, liquid metal mass flowrate, and total system coolant inventory. The family of curves are presented and were applied to the Fast Flux Test Facility (FFTF) Reactor and to the LMFBR Heat Transfer Simulation Loop at Argonne National Laboratory for which some data were available. Sodium and argon gas are employed in both systems. The results presented are also applicable to other experimental sodium loops used for superheat experimentation. Estimation of the steady state loop operational time required to control and maintain the inert gas concentration in the liquid metal is an important part of such test programs.

ANALYTICAL MODEL

The diffusion of inert gas from the plenum to surface cavities in a stagnant liquid metal system has been studied in [1] and [6]. In [1] the condition of mass equilibrium was assumed to exist prior to a transient leading to boiling. The present work involved diffusion of inert gas into a liquid metal in the system plenum under conditions of forced convection prior to any system transient. This process leads to the condition of mass equilibrium. The analysis and general results presented are not restricted to liquid metals. Applications were made for sodium–argon systems.

The flow pattern in the plenum was idealized as shown in Fig. 1(a). Using the control volume shown in Fig. 1(b),

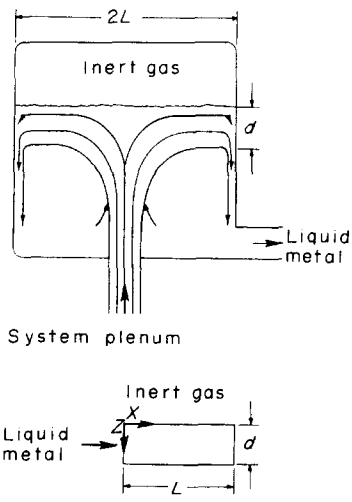

FIG. 1. Plenum model.

*This work was performed under the auspices of the U.S. Atomic Energy Commission.

it was assumed that the liquid metal flows with constant velocity, V, at a depth, d, under the free surface. Argon gas will diffuse into the liquid metal as it passes from $x = 0$ to $x = L$, and the diffusion equation may be written as

$$\frac{\partial W_A(t,z)}{\partial t} = D\frac{\partial^2 W_A(t,z)}{\partial z^2} \tag{1}$$

where

$$t = x/V \tag{2}$$

and diffusion in the x direction is neglected.

The boundary conditions at the free surface, $z = 0$, and at $z = d$ are

$$W_A(t,0) = k \tag{3}$$

$$\left.\frac{\partial W_A}{\partial z}\right|_{z=d} = 0 \tag{4}$$

where k is a constant equal to the saturation concentration. Immediately after the system is filled with coolant, it is assumed that the argon concentration in the liquid is uniform. The initial condition for the problem becomes

$$W_A(0,z) = \text{constant}. \tag{5}$$

Defining variable

$$y \equiv \frac{k - W_A(t,z)}{k - W_A(0,z)} \tag{6}$$

yields the following equation with related boundary and initial conditions.

$$\frac{\partial y(t,z)}{\partial t} = D\frac{\partial^2 y(t,z)}{\partial z^2} \tag{7}$$

$$y(t,0) = 0 \tag{8}$$

$$\left.\frac{\partial y}{\partial z}\right|_{z=d} = 0 \tag{9}$$

$$y(0,z) = 1. \tag{10}$$

The solution evaluated at $t = L/V$ and averaged over depth, d, is given by

$$\bar{y} = 2\sum_{n=0}^{\infty}\frac{1}{\alpha_n^2}\exp(-\alpha_n^2\beta) \tag{11}$$

where

$$\bar{y} \equiv \frac{1}{d}\int_0^d y(L/V,z)\,dz \tag{12}$$

and

$$\alpha_n = (2n+1)\pi/2 \tag{13}$$

$$\beta = \frac{D\rho A_s}{md}. \tag{14}$$

The following relation was employed in obtaining equations (11)–(14).

$$m = \frac{\rho A_s d}{L/V}. \tag{15}$$

The result obtained for $\bar{y}$ in equation 11 is related to the average gas concentration, $\overline{W}_A(L/V)$, in an element of liquid after it has traversed the plenum from $x = 0$ to $x = L$.

$$\bar{y} = \frac{k - \overline{W}_A(L/V)}{k - W_A(0,z)}. \tag{16}$$

The result, equation (11), for a constant value of the concentration entering the control volume, $W_A(0,z)$, was utilized in obtaining a solution applicable to a large experimental loop type facility or reactor system. The solution was broken into discrete time periods of length ψ defined as the time required for the entire liquid metal inventory to pass through the control volume.

$$\psi = I\rho/m \tag{17}$$

where I is the liquid volume inventory. Then the average concentration of gas in the liquid inventory will equal $\overline{W}_A(L/V)$ after the first time period of duration ψ subsequent to system fill with sodium. This average concentration is assumed to exist in the liquid entering the control volume at $x = 0$ during the second time period of duration ψ. In general if p denotes the number of time periods (or number of time constants, ψ) subsequent to the system fill then

$$W_A(0,z)_p = \overline{W}_A(L/V)_{p-1} \qquad p \geqslant 1 \tag{18}$$

where the subscript refers to the time period. Combining equations (16) and (18) yields

$$\bar{y} = \frac{k - \overline{W}_A(L/V)_p}{k - \overline{W}_A(L/V)_{p-1}} \qquad p \geqslant 1. \tag{19}$$

The percentage concentration of inert gas in the liquid relative to the saturation concentration is defined as

$$\xi(p) = \frac{\overline{W}_A(L/V)_p}{k}. \tag{20}$$

Combining relations (19) and (20) yields

$$\xi(p) = 1 - [1 - \xi(p-1)]\bar{y} \qquad p \geqslant 1. \tag{21}$$

Under typical fill conditions where the liquid metal was stored in a relatively cold dump tank it is reasonable to assume that the initial gas concentration is zero, i.e. $W_A(0,z)_{p=1} = 0$. Then equation (21) becomes

$$\xi(p) = 1 - (\bar{y})^p \tag{22}$$

or

$$p = \frac{\ln[1 - \xi(p)]}{\ln \bar{y}} \qquad p \geqslant 1. \tag{23}$$

From the results presented in equations (11) and (23) the number of time constants, p, required to reach a specified percentage of saturated gas concentration, $\xi(p)$, can be calculated using the value of a single parameter, β, as input.

APPLICATION

The results of calculations from equations (11) and (23) are presented in Fig. 2 for a large range of the system parameter, β. The calculational procedure involved evaluation of $\bar{y}$ from equation (11) for a particular value of β. Then the number of time constants, p, necessary to achieve a specified percent concentration, $\xi(p)$, was calculated via equation (23) and the results presented in Fig. 2. The actual time required to reach $\xi(p)$ is ψp. These results were applied to two systems.

Recently, sodium boiling experiments were performed in a test facility simulating a reactor environment [5]. An argon cover gas was employed in the plenum and the flow distribution was estimated to be of the general nature shown in Fig. 1(a). This distribution was promoted by baffels employed for mixing purposes. The experimental facility was initially filled with sodium from a relatively cold dump tank maintained at a pressure slightly above atmospheric. The system was brought to LMFBR simulation conditions and maintained in steady state operation at those conditions prior to initiation of flow coast down tests leading to sodium boiling. It was important to maintain the steady

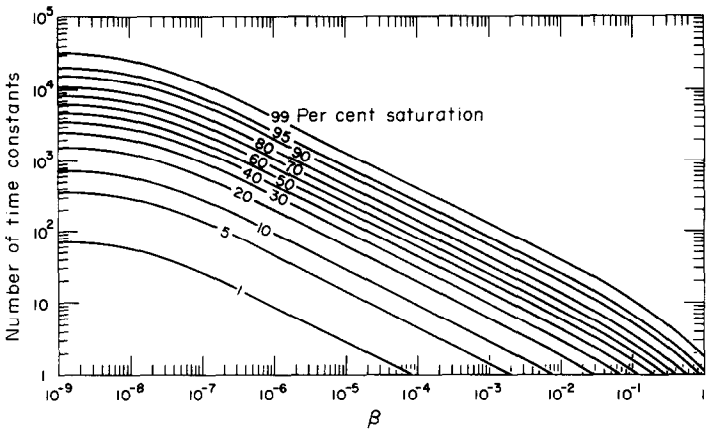

FIG. 2. Time constants required for gas diffusion.

state operation for a period of time sufficient to achieve equilibrium concentration of argon gas in the sodium. The present analysis was applied to this system in loop type reactor operation with a plenum temperature of 755°K. The system parameter, β, was estimated to be in the range of $2 \times 10^{-4} \leqslant \beta \leqslant 5 \times 10^{-4}$ and the time constant, ψ, was 10 min. Using the results presented in Fig. 2, the time required for the sodium to reach 95 per cent of the argon saturation concentration in the plenum was calculated as 20–30 h. Although the inert gas concentration was not directly measured, the results of tests run after 30·5 h of steady state operation consistently produced zero system superheat at boiling inception. These results are indicative of relatively high gas concentrations. In addition, relatively large inert gas bubbles were occasionally detected in the loop subsequent to this time. Alternatively, large superheats (80°K) were obtained when the loop operational time prior to testing was decreased to 1·5 h. These results are indicative of relatively low inert gas concentration in the sodium. Further experimental refinement of the saturation time requirement was not attempted. However, the results of the comparison with the available data indicate that the predictions are in the correct range.

The results of the present analysis were applied to the FFTF reactor presently under construction [7]. The physical characteristics of the plenum in this case were similar in many respects to the plenum of the experimental facility discussed above. The most important exception was the existence of a vortex suppression plate located 0·152 m below the argon–sodium interface in the FFTF reactor. Due to the position of this plate, the estimated range of β was larger than in the previous case, $10^{-6} \leqslant \beta \leqslant 6 \times 10^{-6}$; the time constant, ψ, was 3·2 min. The system operation time (ψp) corresponding to 95 per cent saturation with argon gas was computed as 60–140 h.

REFERENCES

1. R. M. Singer and R. E. Holtz, On the role of inert gas in incipient boiling liquid metal experiments, *Int. J. Heat Mass Transfer* **12**(9), 1045–1060 (1969).
2. J. C. Chen, Incipient boiling superheats in liquid metals, *J. Heat Transfer* **90**(3), 303–312 (1968).
3. O. E. Dwyer, On incipient-boiling wall superheats in liquid metals, *Int. J. Heat Mass Transfer* **12**, 1403–1419 (1969).
4. R. E. Holtz, H. K. Fauske and D. T. Eggen, The prediction of incipient boiling superheats in liquid metal cooled reactor systems, *Nucl. Engng Design* **16**, 253–265 (1971).
5. D. M. France, R. D. Carlson, R. R. Rohde and G. T. Charmoli, Experimental determination of sodium superheat employing LMFBR simulation parameters, *J. Heat Transfer*, to be published.
6. R. E. Holtz, H. K. Fauske and D. T. Eggen, Inert-gas transport in liquid metals during boiling experiments, *Int. J. Heat Mass Transfer* **16**, 520–524 (1973).
7. J. E. Werle, C. B. McGough, P. A. Edwards and A. Selz, The FFTF reactor and coolant system, *Nucl. Engng* **17**(195), 619–623 (1972).