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AN ANALYTICAL MODEL FOR STUDYING EFFECTS OF GAS RELEASE FROM A FAILED FUEL PIN OF A LIQUID-METAL REACTOR

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ABSTRACT

An analytical model for describing dynamics of a gas bubble in the liquid sodium of a liquid-metal reactor as the result of failed fuel pins is discussed. A model to describe the coupled response of the liquid sodium surrounding the gas bubble is also discussed. The analysis method is programmed in a computer code and used to analyze some available experimental data, and the results are discussed.

1 INTRODUCTION

A sudden release of fission gas from failed fuel pins in the liquid sodium environment of a liquid-metal reactor (LMR) fuel channel can produce large pressure pulses which can damage the fuel system hardware; particularly, the hexagonal can containing fuel pins. An analytical method to adequately predict the effects of such an event is needed in order to design the fuel system hardware to withstand or mitigate the pressure pulses. The need is especially true for the advanced LMR fuel concept currently being developed where a high degree of fuel burn-up is being sought.

A number of studies have been performed in the past to describe such an event analytically (Chang et al, 1974; Kazimi, 1976; Srinivas et al, 1977). Common in these studies and other similar works in the past was that the response of the fluid surrounding the gas bubble was simply modeled. Also, a simplified analytical approach was adopted for describing the gas dynamics and blowdown of gas from the fuel pins. The simplifications employed in these studies are such that the applicability of the method as a whole to an actual complex system may be significantly limited.

In this paper, an analytical method is presented by which the event in a complex system may be realistically modeled and analyzed. The phenomenon under consideration here is similar to that of a sodium/water reaction (SWR) in an LMR steam generator system. Also, the analytical models presented here can be regarded as special cases of the analytical models published earlier for the analysis of SWRs (Shin et al, 1975).

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2 ANALYTICAL METHOD

2.1 Bubble Dynamics Model

Release of gas from failed fuel pins is assumed to take place rapidly to form a single, stationary bubble of a spherical shape in the liquid sodium environment. Dynamics of growth or contraction of such a bubble is governed by the energy equation, and the equation of state of the gas involved, which may be as

$$\frac{d}{dt}(me) = h\frac{dm}{dt} - p\frac{dV}{dt} - Q_L; \tag{1}$$

$$pV = (k-1)me, \tag{2}$$

where m is the mass, e the internal energy, h the enthalpy, p the pressure, V the total volume, k the ratio of specific heats of the gas, Q_L the heat loss to the surrounding fluid, and t the time. An ideal gas is assumed for the bubble gas.

Ideal gas relations need to be used to express variables in Eq. (1) in terms of the dependent variables, e and V. In an actual calculation, Eq. (1) is rewritten in terms of the dependent variables, p and T. Here T is the temperature of gas. Further, a complete thermal and pressure equilibrium is assumed to exist in the bubble at all times.

2.2 Surrounding Fluid Response

Equation (1) above involves the variable, V, which depends on the fluid response surrounding the bubble. The method used to model the coupling is described here. Figure 1 shows a concentric spherical region enclosing the spherical bubble and adjoining the fluid on the outside in the cylindrical confinement. The concentric spherical region, for which an incompressible flow is assumed, provides a geometrical transition from the spherical growth of bubble to the one-dimensional, pancake-shape response of fluid in the cylinder.

A potential flow equation applies to this intermediate spherical region, and the integrated form as published earlier (Shin et al, 1988) is used:

$$\frac{p - p_R}{\rho_N} = \left(1 - \frac{a}{R}\right)\left[a\frac{d^2a}{dt^2} + 2\left(\frac{da}{dt}\right)^2\right] - \frac{1}{2}\left(\frac{da}{dt}\right)^2\left[1 - \left(\frac{a}{R}\right)^4\right], \tag{3}$$

where p_R is the fluid pressure at radius R of the spherical region, a the radius of the bubble, and ρ_N the fluid density. p is the bubble pressure as defined earlier. This equation provides the coupling of the bubble growth to the fluid response in the cylinder.

The fluid in the cylindrical confinement (and whatever network of piping may be connected to the ends of the cylinder) is modeled by one-dimensional waterhammer equations (Shin et al, 1975). The waterhammer calculations are coupled to the bubble growth dynamics through the following characteristic equation written for the fluid/bubble interface:

$$p_R - (\rho_N c_N)_i u_i = \bar{p}_i - \overline{(\rho_N c_N)}_i \bar{u}_i + \left[\overline{G}dt + \overline{GSA}\right]_i, \tag{4}$$

where u_i is the fluid velocity at the fluid/bubble interface corresponding to p_R, c_N the sonic speed of fluid, and the quantities with an upper bar the quantities at neighboring states in the cylinder. Gdt and GSA are gravity and friction terms, respectively. p_R and u_i are the boundary conditions at the fluid/bubble interface used in the waterhammer calculations.

Initially, the shape of the bubble is assumed to be spherical. As the bubble grows, it is converted to a pancake shape, at which time the intermediate spherical region no longer exists in the model. A criterion to determine when the shape conversion should take place is an important consideration since an arbitrary criterion may introduce unphysical oscillations in the solution. A criterion is adopted here in such a way to preserve continuity of physical variables. This was achieved by preserving the bubble volume and the bubble/fluid interface area at the shape conversion. The corresponding bubble sizes before and after shape conversion, are

$$a^* = \frac{1}{\sqrt{2}}R; \quad x^* = \frac{\sqrt{2}}{3}R,$$

where x is width of the pancake-shape bubble.

2.3 One-Dimensional Gas Dynamics

One-dimensional analysis is used to solve the gas dynamics in the ruptured tube, and the rate at which the gas is blown out into the fluid through the rupture opening. A method in which finite difference is used for the interior nodes and the method of characteristics for boundary nodes was used in the calculation. (Shin et al, 1981). The bubble gas pressure, p, serves as the back-pressure for the gas outflow at the rupture opening.

3 CALCULATION PROCEDURE

Equations (1) through (4), containing four dependent variables, e, V (or a or x), p_R, and u_i, are solved using an ordinary differential equation solver. The dependent variable, u_i, is solved in conjunction with the waterhammer equations for the compressible fluid region (Shin et al, 1975). m is a quantity provided by the gas dynamics equations.

4 ANALYSIS OF EXPERIMENTAL DATA

The set of equations as discussed above are programmed in a computer code and then linked to a second computer code to calculate the one-dimensional waterhammer, and a third computer code to calculate the one-dimensional gas dynamics. The combined code is used to analyze experimental data (Koenig, 1970).

The experimental data are from a pressurized aluminum tube (0.18 in. ID, with reduced thickness and slot cut into the reduced thickness) ruptured inside a hexagonal can (2.21 in. ID and 16.5 in. long) submerged in a water-filled 55-gallon drum. The tube was pressurized with helium gas at room temperature and placed centrally in the hexagonal can. Gas pressure histories were measured at one end of the tube . Hexagonal can wall pressure histories were also recorded on the inside wall opposite the rupture point. These measurements, from two experimental runs, are used for comparison with analysis results.

In the Run 1 Experiment, the tube was filled with 5.3 cm^3 of gas at 2080 psig. The analysis results are shown in Figs. 2 and 3. Since the history of the rupture opening area was not measured but needed in the analysis as input, it was assumed that the opening area increased linearly with time. The analysis results show that an opening time of 2 ms to a full rupture gives the best agreement with the experimental data. The agreement is good. Some discrepancy is noted, however, in the hexagonal wall pressure after it reached the peak. The early bubble pressure as calculated is considerably higher than the hexagonal wall pressure as indicated in Fig. 2.

In modeling of the waterhammer, there exists no proven method to represent the general two-dimensional geometry one-dimensionally. A parametric study was performed to examine its effects on the results. As shown in Fig. 4, where the results of the parametric study are given, flow restrictions varied at the ends of the hexagonal can affect the wall pressure significantly; in particular, the peak pressure and the pressure after the peak is reached.

A second suspicion for the noted discrepancy was the unknown rupture opening history. The opening history, therefore, was generated via the analysis by matching calculation results and measured pressure histories. The tube opening history thus generated is shown in Fig. 5, and the corresponding pressure histories in Fig. 6. The discrepancy noted above is still present.

In the Run 2 Experiment, the tube was filled with a larger volume of gas, 27 cm^3, at a lower pressure, 1600 psig. Here again, three different tube opening times were calculated: 0.1, 1.0, and 2.0 ms. Figure 7 shows the results as compared with the experimental data. In this case, the best agreement is shown for the tube opening time of 0.1 (much shorter than 1.0 ms observed for Run 1). The hexagonal can wall pressure, as predicted, shows a slightly higher peak than the experimental data. The discrepancy noted in the Run 1 Experiment for the hexagonal can wall pressure is also evident in the Run 2 Experiment.

5 CONCLUSIONS

In general, results of the analysis are found to be in good agreement with experimental data. In particular, the agreements observed for gas dynamics in the tube and for initial hexagonal can wall pressures up to the peak pressures are very good. However, despite the good agreements in these aspects, significant discrepancy is evident in another aspect of the waterhammer results. This discrepancy was observed in both of the experiment runs analyzed.

Waterhammer modeling was suspected as the source for the discrepancy and a parametric study was performed. The results indicated that it may be partially attributable to the discrepancy. Heat transfer between the gas, both in the tube and the bubble, and the water is neglected in the analysis here. This is suspected to be the main cause for the observed discrepancy. The gas is cooled significantly during the sudden expansion process, and the heat transfer can help maintain the bubble pressure and, in return, the hexagonal can wall pressure is high, especially during later times.

The overall method discussed here consists of three different analytical models. Success of the overall method depends on the success of each of the three constituent models. Examination of the validity of the overall analytical approach requires detailed experimental data that address all aspects involved in the three models. In particular, the tube rupture opening history needs to be measured. In addition, the gas pressure measurement at rupture point in the tube would be helpful. A simple water system configuration would also be helpful for critical evaluation of the overall analytical method.

ACKNOWLEDGMENT

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REFERENCES

Chang, L. K., Golden, G. H., Judd, A. M., and Koenig, J. F. (1974). Pressure Pulse on a Subassembly Wall Due to Gas Release from a Failed Fuel Pin. Nucl. Eng. and Design 31, pp. 72-76.

Kazimi, M. S. (1976). Analysis of Pressure Pulse Generation Due to Gas Release from Failed Fuel Pins in a Liquid-Metal Fast Breeder Reactor. Nucl. Sci. Eng. 59, pp. 1-11.

Koenig, J. F. (1970). Tube Rupture Test in an EBR-II Hexagonal Can. Unpublished Data, Argonne National Lab., Argonne, IL.

Shin, Y. W. and Chen, W. L. (1975). Numerical Fluid-Hammer Analysis by the Method of Characteristics in Complex Piping Networks. Nucl. Eng. and Design 33, pp. 357-369.

Shin, Y. W. and Wiedermann, A. H. (1981). A Hybrid Numerical Method for Homogeneous Equilibrium Two-Phase Flows in One Space Dimension. ASME J. Press. Vessel Tech. 103, pp. 20-26.

Shin, Y. W., Wiedermann, A. H., Eichler, T. V., Youngdahl, C. K., and Ockert, C. E. (1988). An Analytical Model for Dynamics of a Sodium/Water Reaction Bubble in an LMFBR Steam Generator and the Coupled Response of the Intermediate Heat Transport System. Nucl. Eng. and Design 106, pp. 221-230.

Srinivas, S. and Chopra, P. S. (1977). A Model for Calculation of Pressure in the Duct Due to Discharge of Gas from a Failed Fuel Pin. Nucl. Eng. and Design 44, pp. 201-210.

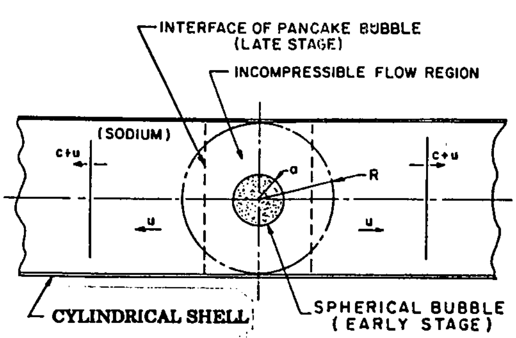

Fig. 1. Bubble Dyanmics/Fluid Response Coupling

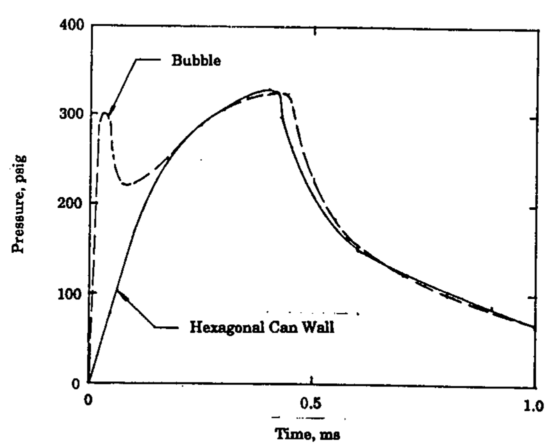

Fig. 2. Early Pressure Histories for Run 1 Experiment

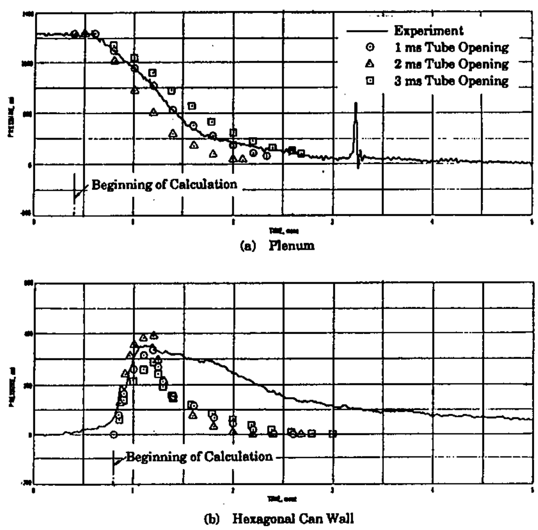

Fig. 3 Analysis Results and Comparison with Run 1 Experiment

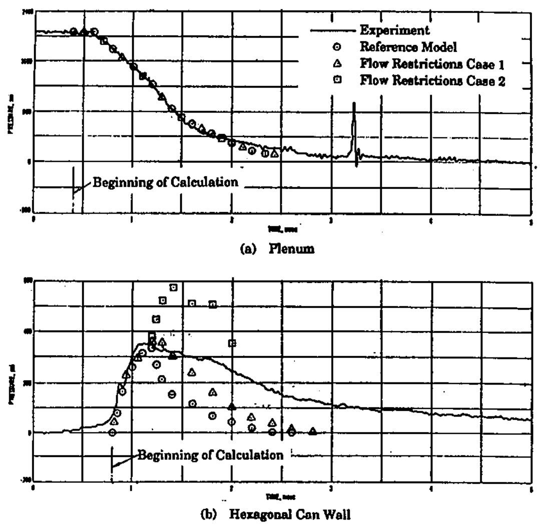

Fig. 4 Effects of Flow Restrictions in Analysis of Run 1 Experiment

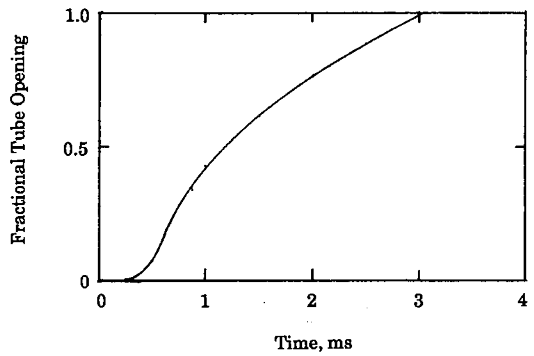

Fig. 5 Tube Opening History Suggested by Analysis for Run 1 Experiment

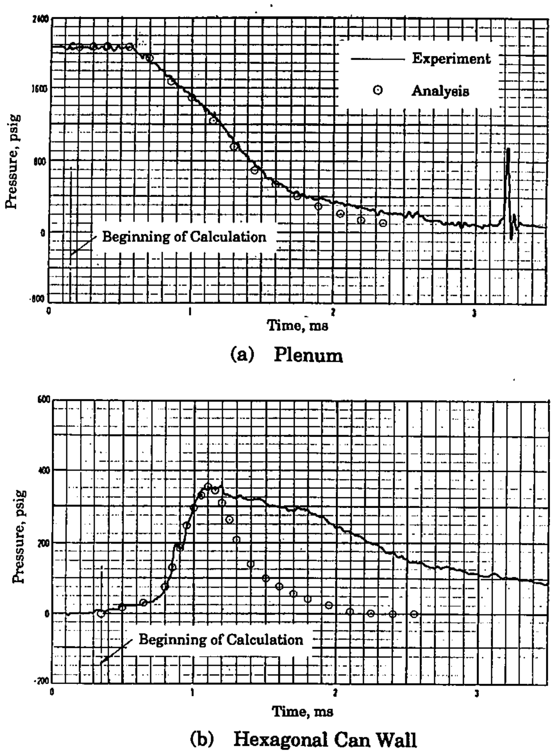

Fig. 6 Analysis Results Corresponding to Tube Opening History Shown in Fig. 5

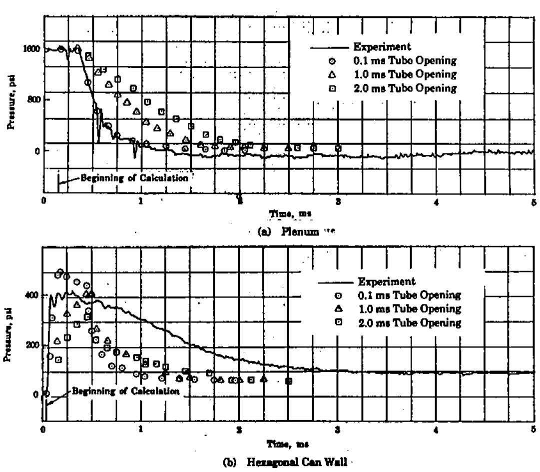

Fig. 7 Analysis Results and Comparison with Run 2 Experiment