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Growth of Molten Core Debris Pools in Concrete

Progress Report

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ABSTRACT

Experiments have been conducted using a volumetrically-heated pool with noncondensable gas injection at the boundaries to simulate the heat transfer processes taking place in molten core debris/concrete systems. Measurements of the upward, downward, and sideward heat transfer rates have been made over wide ranges of internal Rayleigh number ($6.0 \times 10^5 < Ra < 2.7 \times 10^9$), superficial gas velocity ($0 < V_g < 2.5$ cm/min), and pool aspect ratio ($1.32 < W/L < 5.16$). Pools with either an isothermal solid upper boundary or a free surface have been examined. Detailed measurements of the temperature distribution within the pools have also been made. The results indicate that the downward heat transfer rates are significantly increased while the sideward heat transfer rates are slightly affected by gas injection. The heat transfer rates at the pool boundaries are sensitive to the upper surface boundary condition.

Efforts are continuing on the second part of the present study where the phase-change and gas evolution processes are combined.

I. Introduction

I.A. Background and Overview of Present Study

An experimental investigation has been undertaken at the University of Wisconsin to examine the different heat and mass transfer processes taking place in molten core debris pools growing in concrete beds. The aim of this investigation is to develop the basic understanding and obtain the data base necessary for predicting the effects of the different physical parameters, viz. gas evolution rates, initial density ratio, and power density on the downward and radial growth rates of molten debris pools. Such information is needed to ascertain the efficacy of the third line of assurance for LMFBR safety [1,2].

The present study involves two types of experiments. The first is concerned mainly with heat transfer to the surfaces of a volumetrically heated pool with gas injection at the boundaries. The second experiment couples the phase-change and gas release processes. The first experiment has been completed and is described in detail in this report. Efforts on the second experiment are continuing.

The purpose of the first experiment is to determine the extent to which gas injection affects the sideward and downward heat transfer rates in volumetrically heated pools. Experiments have been conducted over wide ranges of internal Rayleigh number ($6.0 \times 10^5 < Ra < 2.7 \times 10^9$), superficial gas velocity ($0 < V_g < 2.5$ cm/min), and pool aspect ratio ($1.32 < W/L < 5.16$). Pools with either an isothermal solid upper boundary or a free surface have been examined. Detailed measurements of the temperature distribution within the pool have also been made. The results indicate that the downward heat transfer rates are significantly increased while the sideward heat transfer

rates are slightly affected by gas injection. The heat transfer rates at the pool boundaries are sensitive to the upper surface boundary conditions as evidenced by the large differences between experiments with an isothermal solid upper boundary and those with a free surface.

The second type of experiments will simulate the pool growth phenomenon coupled with the gas evolution process. Earlier pool growth experiments conducted at ANL did not simulate the gas release process [3,4]. These experiments have shown that the horizontal and vertical growth rates of the pool depend on the initial density ratio and power density. Larger vertical penetrations are obtained with higher values of $\rho_{\text{pool}}/\rho_{\text{bed}}$ and low initial power density. It remains to be shown how gas evolution at the pool boundaries will affect the development of pool shape. This phenomenon is expected to play an important role in molten fuel/concrete systems.

I.B. Compliance with Contract Requirements -- Summary of Progress

1. Work on the present contract is on schedule. We anticipate no problems in fulfilling our commitments within the budget and time period of the current contract.
2. The principal investigator, S. I. Abdel-Khalik, has devoted approximately thirty percent of his time to this project since the beginning of the current term of the agreement. He expects to spend the same time fraction during the remainder of the current term.
3. Experiments on the first test cell have been conducted. The results are summarized on this report. These results were presented at the annual PAHR Information Exchange Meeting at Argonne National Laboratory, November 2-4, 1977. Efforts are continuing to correlate the data obtained so far.
4. Work on the second type of experiment is underway.

II. Experimental Apparatus and Procedure

A schematic diagram of the test cell used in the first experiment conducted in this investigation is shown in Fig. 1. The electrically-heated fluid (CuSO_4 solution) is bounded from the bottom and two sides by water-cooled porous bronze plates 0.16 cm thick mounted on 1.25 cm thick plexiglas frames. Air is injected into the test cell through these three porous plates. The porous side plates also serve as electrodes for the passage of alternating current through the fluid. The other two sides are made of 1.25 cm thick plexiglas plates. The top surface of the test cell is a water-cooled copper plate. Both the top and bottom plates are covered with a thin layer of electrically-insulating Mylar film. The Mylar film on the bottom plate contained 0.16 cm diameter holes arranged in a square grid with 1.27 cm pitch to allow air flow through the porous bottom plate.

The injected air leaves the test cell through four plexiglas tubular risers, 1.27 cm OD and 0.64 cm ID, attached to the top plate. In addition, the air leaves the test cell through twenty 0.32 cm diameter holes in the top plate arranged in a square grid with a 1.9 cm pitch. The carry-over liquid is settled in the suppression chamber atop the upper plate.

The fluid cell is 10.0 cm wide and 15.0 cm long with an adjustable height from 1.9 to 8.0 cm. The pool aspect ratio can be modified by lowering the top plate to the desired height and covering the exposed portions of the porous electrodes with plexiglas inserts of the proper dimensions. Three separate compartments surround the porous bottom and side plates so that air can be injected through them at independently controlled rates. The air flow rates are measured by means of calibrated

rotameters. The entire test cell is thermally insulated using a 2.5 cm thick layer of styrofoam.

The temperature distribution within the fluid cell is determined by means of three copper-constantan thermocouple probes mounted on a micro-meter drive assembly. The thermocouple outputs are measured by means of a potentiometer. Four copper-constantan thermocouples are welded onto each of the four water-cooled plates in order to determine their average temperatures. The heat transfer rates to the different sides are determined by measuring their cooling water flow rates and corresponding temperature rises. The flow rates are measured by means of calibrated rotameters while the coolants' inlet and exit temperatures are measured using copper-constantan thermocouple probes. The power input to the test cell is varied by means of a 110 V x 50 A variac.

Two types of experiments have been conducted using this test cell. In the first type of experiments, the top plate is held in contact with the copper sulfate solution, while in the second type the top plate is held at a level 1.9 cm higher than the free surface of the electrically-heated fluid. For both modes of experimentation, the air flow rates through the porous bottom and side plates have been adjusted so that the superficial velocities based on their respective wetted areas are the same.

Experiments have been conducted with different values of power input, pool height, and superficial gas velocity. The ranges of experimental variables and the corresponding non-dimensional parameters are listed in Table 1. For all the 129 experiments conducted so far, the external Rayleigh numbers are one or two orders of magnitude lower than the corresponding internal Rayleigh numbers.

Table 1Ranges of Experimental Variables and Non-dimensional Parameters

Power input (watt)	100 - 600
Pool height (cm)	1.9 - 7.6
Superficial gas velocity (cm/min)	0.0 - 2.5
<hr/>	
Internal Rayleigh number	$6.0 \times 10^5 - 2.7 \times 10^9$
Aspect ratio (W/L)	1.32 - 5.16
$V_g L/\alpha$	0.0 - 200

III. Results, Discussion, and Conclusions Based on the First Experiment

Typical results showing the temperature distribution along the pool centerline for two experiments with and without gas injection are given in Fig. 2. These results demonstrate the considerable mixing effect of gas injection. Values of the maximum pool temperature rise for both modes of experimentation are plotted in Figs. 3 and 4. The pool temperature rise ΔT has been normalized using the corresponding one-dimensional conduction values, namely $(QL^2/8k)$ for pools with an isothermal solid upper boundary and $(QL^2/2k)$ for those with a free surface. Figures 3 and 4 clearly show that for the same power input gas injection will considerably decrease the maximum pool temperatures (i.e. increase M) from the corresponding natural convection values. Reductions by more than a factor of 2 are obtained as the superficial velocity is increased to the upper limit of the examined range. For the same power input, pool dimensions and gas velocity, pools with a free surface will obviously have a higher maximum temperature than those with a cooled upper boundary.

Figure 5 shows variation of the fraction of pool power removed at the lower boundary, f_{down} , with internal Rayleigh number and aspect ratio for pools with a cooled solid upper boundary with and without gas injection. These results show that gas injection causes a marked increase in the downward heat transfer rate. Increases in f_{down} by more than a factor of 2 are observed even at the low superficial velocity (0.45 cm/min) shown in Fig. 5. Coupled with the decrease in maximum pool temperature (Figs. 3 and 4), these results indicate that the average Nusselt number at the lower boundary is greatly increased by gas injection. Figure 5 also shows that at such low gas velocities, natural convection effects are still present as evidenced

by the decrease in f_{down} with the internal Rayleigh number. Similar results for pools with a free upper surface are shown in Fig. 6. Again, air injection significantly affects the downward heat transfer rate. Comparison between Figs. 5 and 6 reveals the large effect of the upper surface boundary condition on the relative heat transfer rates at the different pool boundaries.

As the superficial gas velocity is increased, the downward heat transfer rate increases. However, it seems to level off beyond a gas velocity of about 1.5 cm/min (Fig. 7). Such velocities are lower than those anticipated for early times following an HCDA by more than an order of magnitude [5]. The mixing effect appears to saturate at slightly higher gas velocities for pools with a free upper surface than those with a cooled upper boundary. It should be indicated that even though the downward heat transfer rate approaches a constant value at high gas velocities, the average Nusselt number will continue to increase because of the continued decrease in maximum pool temperature (Figs. 3 and 4).

Figure 8 shows variation of the fraction of pool power removed at one of the side plates, f_{side} , with internal Rayleigh number and gas velocity. These results are typical of all the cases examined. They show that within the range of velocities used, f_{side} is slightly affected by gas injection. Again, the sideward Nusselt number will increase because of the decreased pool temperature.

The results of this investigation clearly show that gas injection at the boundaries of a volumetrically-heated pool will markedly affect the heat transfer rates at the pool surfaces. The downward heat transfer rate is significantly increased with gas injection; however, it seems to

saturate at superficial velocities considerably lower than those anticipated for early times following an HCDA. Values of f_{down} which are more than double the corresponding natural convection values have been observed.

On the other hand, the sideward energy fractions are only slightly affected by gas injection. The injected gas will vigorously mix the pool and reduce the maximum pool temperature rise; reductions by more than a factor of 2 have been observed for the low velocities used in this investigation.

The observed large differences between pools with a free surface and those with a cooled upper boundary emphasizes the importance of accurately modelling the top surface boundary condition. Core debris/concrete pools may have a stratified layer of molten steel on top with, possibly, a crust layer at the interface. However, since concrete is miscible in UO_2 , the debris pool will be continually diluted to the point where its density becomes lower than that of the steel layer above. The inversion process that follows will significantly affect the heat and mass transfer rates at the pool boundaries.

At the low gas velocities examined here natural convection effects are still present as evidenced by the dependence of f_{down} and f_{side} on the internal Rayleigh number. However, it should be apparent from the data presented here that models for describing the growth of molten core debris pools in concrete which are based on pure natural convection correlations and ignore the gas evolution process are clearly in error. Efforts are continuing to obtain correlations for the average Nusselt numbers along the bottom and side walls which would more-closely represent molten debris/concrete systems.

IV. Nomenclature

f_{down}	Fraction of pool power removed at lower boundary
f_{side}	Fraction of pool power removed at one side plate
g	Gravitational acceleration
k	Thermal conductivity
L	Pool height
M	Inverse non-dimensional pool temperature rise
Q	Volumetric heat generation rate
Ra_{int}	Internal Rayleigh number; $Ra_{\text{int}} = g\beta QL^5/64\alpha\nu k$
Ra_{ext}	External Rayleigh number; $Ra_{\text{ext}} = g\beta L^3(T_{\text{bot}} - T_{\text{top}})/8\alpha\nu$
T_{bot}	Bottom surface temperature
T_{top}	Top surface temperature
T_{max}	Maximum pool temperature
ΔT	Pool temperature rise; $\Delta T = T_{\text{max}} - 0.5(T_{\text{top}} + T_{\text{bot}})$
V_g	Superficial gas velocity
W	Pool width
α	Thermal diffusivity
β	Coefficient of thermal expansion
ν	Kinematic viscosity

V. References

1. J. D. Griffith, et al., "Safety Related Design Considerations for Large Fast Breeder Plants", Proc. International Meeting on Fast Reactor Safety and Related Physics, Chicago (Oct. 1976).
2. E. L. Gluekler, "Status of Post-Accident Core Retention Concepts and Models", GEAP-14048, General Electric Company (1975).
3. L. Baker, Jr., et al., "Post-Accident Heat Removal in Fast Reactors", ANL/RAS 75-44, Argonne National Laboratory (Nov. 1975).
4. R. Farhadieh and L. Baker, Jr., "Simulation Experiments of the Growth of a Hot Fuel Pool in a Sacrificial Bed", ANL/RAS 76-27, Argonne National Laboratory (Sept. 1976).
5. A. Dayan, "Dehydration of Concrete Due to Heating", presented at Safety Technology Meeting on Inherent Retention, Bethesda, Maryland (Sept. 1976).

VI. Earlier Publications

- (1) S. I. Abdel-Khalik, "Growth of Molten Core Debris Pools in Concrete", Progress Report April 1 - May 31, 1977, C00-4261-1.
- (2) S. I. Abdel-Khalik, "Growth of Molten Core Debris Pools in Concrete", Progress Report June 1 - August 31, 1977, C00-4261-2.
- (3) S. I. Abdel-Khalik and D. K. Felde, "Heat Transfer in Volumetrically-Heated Pools with Gas Injection at the Boundaries", Presented at Annual PAHR Information Exchange Meeting, Argonne, Nov. 2-4 (1977), C00-4261-3.

Figure 1. Schematic diagram of the test cell used in this investigation.

Figure 2. Temperature distribution along the pool centerline for two experiments with and without gas injection.

Figure 3. Variation of the inverse non-dimensional pool temperature rise with superficial gas velocity for pools with a cooled solid upper boundary at different values of Ra_{int} and W/L .

Figure 4. Variation of the inverse non-dimensional pool temperature rise with superficial gas velocity for pools with a free upper surface at different values of Ra_{int} and W/L .

Figure 5. Variation of the fraction of pool power removed at the lower boundary with internal Rayleigh number and aspect ratio for pools with a cooled solid upper boundary with and without gas injection.

Figure 6. Variation of the fraction of pool power removed at the lower boundary with internal Rayleigh number and aspect ratio for pools with a free upper surface with and without gas injection.

Figure 7. Variation of the fraction of pool power removed at the lower boundary with superficial gas velocity.

Figure 8. Variation of the fraction of pool power removed at one of the side plates with internal Rayleigh number and superficial gas velocity.