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DEBRIS-BED COOLING
FOLLOWING AN HCDA IN A FAST REACTOR

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ABSTRACT

Natural convection within simulated core debris beds has been investigated experimentally and numerically. The objectives of this research have been: (1) to develop a three-dimensional transient model for analyzing single-phase cooling of debris beds, (2) to validate the model using out-of-pile simulant experiments which measure the detailed structure of the convection cells within the bed as well as integral heat transfer rates, and (3) to apply the model to typical core debris beds over a wide range of parameters in order to determine the relative importance of conduction and convection in sodium-cooled debris beds.

The bed has been simulated using directly-heated two-dimensional packed tube bundles of different "particle" diameters, bed loadings, porosities, heat generation rates, and overlaying fluid layer heights. Detailed velocity and temperature profiles within the bed and overlaying fluid have been measured using particle tracing techniques and Mach-Zehnder interferometry. Measurements of the downward and upward power fractions and Nusselt numbers over a wide range of experimental variables have been made. The data have been compared with predictions of the transient three-dimensional natural convection computer code COMMIX-1A with the aim of validating the code for debris bed applications.

1. INTRODUCTION

During a hypothetical core disruptive accident in a sodium-cooled fast reactor, fuel and steel particles may be formed as a result of the rapid quenching, freezing, and fragmentation of the molten core debris upon contact with liquid sodium. These particles may settle on various horizontal surfaces within the reactor vessel to form "debris beds." The particles will be volumetrically heated by the radioactive decay of the retained fission products and actinides. The debris bed may be adequately cooled by conduction, convection, or local boiling of the sodium so that it can be stably retained within the vessel. On the other hand, if the heat generation rate exceeds the cooling limits of the bed, the bed will dry out and may then remelt causing the support structure to fail.

The behavior of debris beds depends on numerous variables including decay heat level, bed loading, particle size distribution, bed permeability and stratification, amount and distribution of steel particles, sodium subcooling and contamination, and bed boundary conditions. Numerous investigations [1-13] have been conducted to examine the behavior of these volumetrically-heated beds so that the course and consequences of the HCDA can be assessed. The investigations conducted so far consist of both in-pile and out-of-pile experiments as well as theoretical model development. Most of these investigations are "integral" in nature focussing primarily on the evaluation of the dryout limit and its dependence on the different variables. Such information is quite valuable, however, it is necessary to have a basic understanding

of the phenomena involved so that the behavior of debris beds under "realistic" conditions can be accurately predicted. In particular, without such understanding it would be difficult to utilize the results of out-of-pile experiments in a quantitative fashion especially those conducted with nonmetallic coolants. To this end, this research program has been undertaken. The primary objectives of this research have been: (1) to develop a three-dimensional transient model for single-phase cooling of debris beds, (2) to validate the theoretical model using out-of-pile simulant experiments which measure the detailed structure of the convective cells within the bed as well as integral heat transfer rates, and (3) to apply the model for typical core-debris beds over a wide range of parameters in order to determine the relative importance of conduction and convection in sodium-cooled debris beds.

The remainder of this report is organized as follows. Section II provides an overview of the investigations undertaken and the significant results obtained so far. Section III summarizes the research accomplishments and the level of compliance with the agreement requirements. Section IV is a list of the personnel supported through this research and their contributions.

II. OVERVIEW OF RESEARCH PROGRAM

II.1 Experimental Procedures and Results

An experiment has been designed to simulate single-phase-cooled debris beds. The aim is to obtain detailed data for the velocity and temperature distributions within the bed as well as integral heat transfer rates for a wide range of bed geometries and operational parameters. These data are to be used to validate the theoretical model to be developed in this investigation which, in turn, can be used to predict the behavior of "actual" debris beds.

The debris bed is simulated using two-dimensional packed tube bundles (Figure 1). Different beds 14 cm wide and 10 cm long with heights ranging from 2.86 to 10.0 cm have been examined. Four tube diameters are used, namely, 3.2, 6.4, 9.5, and 11.1 mm. The tubes are arranged in either a square or triangular grid with porosities varying between 0.31 and 0.95.

The tubular bed is placed horizontally in a test cell with double glass walls on all four sides to allow flow visualization (Figure 2). The cell bottom is a nearly-isothermal, water-cooled brass plate. Water is used as the bed coolant; the water height in the test cell is varied so that the ratio η between the overlying coolant layer height and the bed height would vary between 0.1 and 1.0. Values of 0.1, 0.2, 0.5, and 1.0 have been examined for all the beds tested. The top surface of the coolant is either free or in contact with a nearly-isothermal, water-cooled brass plate.

Direct heating of the bed has been accomplished by passing DC current from a regulated supply through the thin stainless steel tube walls from which the bed is constructed. The power input is varied between 25 and 400 Watts. The outside surface of the tubes is coated with a thin layer of electrically-insulating paint to avoid electrical leakage. For Joule-heated experiments, an extremely dilute electrolyte solution (CuSO_4) is used as the coolant. AC current from a variac is passed through the coolant between the bottom plate and a wide-mesh screen placed immediately atop the bed. For all Joule-heated experiments, the bed is constructed from electrically-insulating polyvinyl rods to prevent electrical leakage. For bottom heated experiments, a 0.5 mm thick sheet-type electric heater with dimensions equal to those of the bed is attached to the bottom plate immediately below the bed. For these experiments, the bottom plate is thermally insulated. A summary of the different experimental variables is given in Table 1.

Flow visualization within the bed and overlying fluid layer is achieved by adding a small amount of aluminum particles 10-15 μm in diameter to the bed coolant. A light source producing a thin sheet of light is used to illuminate the mid vertical plane along the tubular bed. After steady state has been reached (about 4 hours), direct photography is used to record the flow pattern made visible by the particle traces within the bed and overlying fluid. An exposure time of one second is used. Figure 3 is an overall view of the experimental apparatus.

Typical flow patterns for the three different heating methods are shown in Figure 4; these correspond to a 5.4 cm high bed with 3.2 mm

diameter tubes and a 5.4 cm thick overlying fluid layer with a solid upper surface. Similar results have been obtained for other experimental parameters. These results clearly show that the heating method has a significant effect on the convective flow patterns within the bed and overlying fluid.

The particle trace photographs for directly-heated beds have been analyzed using a computer-controlled digitizer which measures the length and orientation of particle traces at selected points within the bed and overlying fluid. Knowledge of the exposure time allows the two velocity components in the illuminated plane to be determined. The velocity components at grid points spaced 12.7 mm in the horizontal and vertical directions have been determined for comparison with predictions of the transient three dimensional natural convection computer code COMMIX-1A [14] to be used for debris bed modelling.

The steady-state downward and upward power fractions for the different experiments have been determined by measuring the steady state coolant flow rates and temperature rises for the bottom and top isothermal plates. For a given experiment, variation of the maximum coolant temperature and downward and upward power fractions with time has been determined (Fig. 5). When steady state conditions are reached, the corresponding values are recorded. Steady state conditions are reached when the error in the steady state energy balance is minimized (Fig. 6). Typically, the error in the energy balance is about 5%.

Typical results showing variations of the downward power fraction, f_{down} , with the heat generation rate and overlying fluid layer height

ratio η are shown in Figure 7 for experiments with a free upper surface. The results for experiments with a solid isothermal upper boundary are qualitatively similar, however, the change in f_{down} with power input is considerably less steep than that in Fig. 7. The power fractions and maximum temperature difference between the coolant and the boundaries have been used to determine the corresponding average Nusselt numbers (Figure 8). These results extend the Rayleigh number range covered by previous investigators by nearly two orders of magnitude [15-17]. These "integral" data will also be compared with the predictions of the COMMIX-1A Code as described in the following section.

11.2 Numerical Modelling of Debris-Beds Cooling

As indicated earlier, one of the primary objectives of this research has been the development of an experimentally-validated transient three-dimensional model describing the different heat transfer processes taking place within volumetrically-heated particle beds. The validated model will then be applied to typical core debris beds over a wide range of parameters in order to determine the relative importance of conduction and convection in sodium-cooled debris beds and examine the applicability of out-of-pile simulant experiments.

The computer code COMMIX-1A developed at Argonne National Laboratory [14] for analyzing transient three dimensional natural/forced convection in tube bundles provided the starting point for this work. The code is based on a porous medium formulation and can, therefore, be easily modified for application to debris beds. Prior to doing so, however, we

have attempted to validate the code by comparing its predictions with the data obtained in our simulant experiments. The code is used in a completely apriori fashion to model the different simulant experiments presented in the previous section. Typically, the bed and overlaying fluid are divided using a rectangular mesh with 17 nodes in the vertical direction, 13 nodes in the horizontal direction perpendicular to the tubes axes and 5 nodes in the horizontal direction along the tube axes. A smaller number of nodes is used in the last direction since the flow is nearly two-dimensional (Figure 9).

A typical steady-state flow map produced by COMMIX-1A is shown in Figure 9 for the flow pattern in the mid vertical plane of a bed 10.0 cm high with an overlaying fluid layer height of 10.0 cm, a tube diameter of 11.1 mm, a bed porosity of 0.40, power input of 200 watts, and an isothermal solid upper boundary. For such cases there is little coupling between the flow fields within the bed and the overlying fluid. However, strong coupling is obtained for beds of high porosity as shown in Fig. 10 which corresponds to a bed 10 cm high with an overlaying fluid layer height of 10.0 cm, a tube diameter of 6.4 mm, a bed porosity of 0.80, power input of 50 Watts, and an isothermal solid upper boundary.

For a given simulation, transient variation of the upward and downward power fractions, energy balance error, maximum coolant temperature, Rayleigh number, upward and downward heat transfer coefficients, and Nusselt numbers have been obtained (Figures 11 through 14). Steady state conditions are reached when the energy balance error is less than 0.01% and the

change in maximum pool temperature between two consecutive time steps is less than a user-specified value. At that point the velocity and temperature profiles are recorded.

The COMMIX-1A code has been used to model all the simulant experiments conducted in this investigation over a wide range of parameters, viz., bed height, heat generation rate, bed porosity, particle size, overlaying fluid layer height and top surface boundary conditions. Preliminary comparison between the experimental velocity profiles and those obtained using COMMIX-1A shows good agreement. However, comparison between the integral quantities, namely, power fractions, Nusselt numbers, and maximum coolant temperature did not yield satisfactory agreement as can be seen in Table 2. The reason for this surprising discrepancy is currently being investigated.

In addition to the above described apriori calculations, a new version of COMMIX-1A applicable for volumetrically-heated particle beds has been developed. This version differs from the original code developed at ANL in that the frictional pressure drop terms in the x, y, z momentum equations [14] have been replaced by appropriate expressions for packed beds; the model of Macdonald, et al. [18] has been used. In order to check the validity of this new version it will be used to predict variations of the Nusselt number with the internal Rayleigh number as well as the critical Rayleigh number for sodium-cooled and water-cooled debris beds. These results will be compared with experimental data.

III. RESEARCH ACCOMPLISHMENTS

The following achievements have been made during the course of this research program:

- (1) An experimental investigation simulating single-phase-cooled debris beds has been completed. This is the first, and only, experiment which allows detailed measurement of the structure of the convection cells within the bed and overlaying fluid in addition to the integral heat transfer quantities commonly measured in simulant experiments.
- (2) The transient three-dimensional computer code COMMIX-1A has been used to model all the simulant experiments conducted in this investigation in an apriori fashion with the aim of validating the code for debris bed applications. Experiments with a wide range of bed heights, heat generation rates, bed porosities, particle sizes, overlaying fluid layer heights, and top surface boundary conditions have been modelled.
- (3) A new version of the COMMIX-1A code which is applicable for debris bed problems has been created and successfully used to model both sodium-cooled and water-cooled beds. The validity of this version will be checked by comparing the Nusselt-Rayleigh predictions as well as the critical Rayleigh number with experimental data.

IV. PERSONNEL SUPPORTED THROUGH THIS RESEARCH AND THEIR CONTRIBUTIONS

1. S.I. Abdel-Khalik: Principal INvestigator; responsible for overall direction and management of the program; supervises graduate students involved in this research; assists in the design, construction, and operation of the experiments; assists in interpretation of results of numerical modelling; prepares annual report. Approximately 15% of PI's time has been devoted to this project since the beginning of the current term. Nearly 25% of PI's time is expected to be devoted to this project during the remainder of the current term.
2. H.S. Kim: Graduate student; responsible for the design, construction and operation of the experiment; responsible for the development and application of the theoretical model.
3. W.P. Chang: Graduate student; assists in the operation, data collection, data reduction and analysis of experimental data.

V. REFERENCES

1. J.D. Gabor, et al., "Studies and Experiments on Heat Removal from Fuel Debris in Sodium," CONF-740401-P2, 823, Beverly Hills (1974).
2. J.D. Gabor, "Particulate Debris Bed Leveling Experiments in Water," PAHR Information Exchange Meeting, Sandia (Oct. 1974).
3. J.B. Rivard, "Sandia Laboratories Debris Bed Studies Program," *ibid.*, Sandia (Oct. 1974).
4. J.D. Gabor, et al., "Studies of Heat Removal and Bed Leveling of Induction-Heated Materials Simulating Fuel Debris," PAHR Information Exchange Meeting, Sandia (Nov. 1975).
5. V.K. Dhir, et al., "Dryout Heat Fluxes in Volumetrically Heated Particulate Beds," *ibid.*, Sandia (Nov. 1975).
6. J.B. Rivard, "Status of Sandia Laboratories Debris Bed Studies Program," *ibid.*, Sandia (Nov. 1975).
7. V.K. Dhir, and I. Catton, "Prediction of Dryout Heat Fluxes in Beds of Volumetrically Heated Particles," CONF-761001, Vol IV, Chicago (1976).
8. E.S. Sowa, et al., "Studies of Formation and Cooling of Particulate Fuel Debris Beds in Sodium," *ibid.*, Chicago (1976).
9. J.B. Rivard, "Preliminary Results from Initial In-Pile Debris Bed Experiments," PAHR Information Exchange Meeting, ANL (Nov. 1977).
10. V.K. Dhir, and I. Catton, "The Effect of Particle Size Distribution and Non-Heated Constituents on Debris Bed Dry-Out," *ibid.*, ANL (Nov. 1977).
11. J.D. Gabor, "Particulate Bed Formation and Phenomena," *ibid.*, ANL (Nov. 1977).
12. D.O. Lee, and R.H. Nilson, "Experimental Studies of Heat Generating Porous Beds," *ibid.*, ANL (Nov. 1977).
13. J.B. Rivard, "Cooling of Particulate Debris Beds: Analysis of the Initial D-Series Experiments," PAHR Information Exchange Meeting ISPRA (Oct. 1978).
14. W.T. Sha, et al., "COMMIX-1: A Three-Dimensional Transient Single-Phase Computer Program for Thermal-Hydraulic Analysis," Argonne National Laboratory Report ANL-77-96, NUREG/CR-0785 (September 1978).

15. L. Barleon and H. Werle, "Dependence of Debris Bed Dryout Heat Flux on Particle Diameter," Trans. ANS Meeting, Bal Harbour (June 1981).
16. S.J. Rhee, V.K. Dhir, and I. Catton, "Natural Convection Heat Transfer in Beds of Inductively Heated Particles," J. Heat Transfer, 100, 78-85 (Feb. 1978).
17. H.C. Hardee and R.H. Nilson, "Natural Convection in Porous Media with Heat Generation," Nuc. Sci. and Engineering, 63, 119-132 (1977).
18. J.F. Macdonald, et al., Ind. Eng. Chem. Fundamentals, 18, 199 (1979) (as quated by F.A.L. Dullien, Porous Media -- FLuid Transport and Pore Structure, Academic Press (1979)).

TABLE I EXPERIMENTAL VARIABLES

Heating Method:	Volumetric, Joule, Bottom
Boundary Condition:	Free, Solid Upper Surface
Particle Diameter:	3.2, 6.4, 9.5, 11.1 (mm)
Bed Height:	32, 57, 83, 95 (mm)
Bed Porosity:	0.95, 0.80, 0.56, 0.49*, 0.40, 0.31*
Fluid Height Ratio:	0.1, 0.2, 0.5, 1.0
Power:	25, 50, 100, 200, 300, 400 (W)

* Staggered tube arrangement

TABLE II

COMPARISON BETWEEN EXPERIMENTAL DATA AND COMMIX-1A RESULTS*

	<u>Experimental</u>	<u>COMMIX-1A</u>
Max Pool Temp (°C)	30.7	34.3
Upward Power Loss (W)	33.0	40.1
Downward Power Loss (W)	14.2	10.0
Energy Balance Error (%)	-8.0	-1.0
Upward Power Fraction (%)	69.9	80.1
Downward Power Fraction (%)	30.1	19.9
Upward ht. Trans. Coeff (W/m ² °C)	505	182
Downward ht. Trans. Coeff (W/m ² °C)	179	45
Internal Rayleigh Number	1.91×10^6	2.37×10^6

* Bed height = 10 cm; Overlaying fluid height = 10 cm; Tube diameter = 6.4 cm; Power Input = 50 W; Bed Porosity = 0.80; Solid Upper Boundary

Figure 1: Photograph of One of the Tube Bundles Used in this Investigation to Simulate Debris Beds (Tube Diameter = 11.1 mm; Bed Height = 10.0 cm; Bed Porosity = 0.40)

Figure 2: Photograph of the Test Cell Housing Showing the Simulated Debris Bed and Overlaying Fluid Layer.

Figure 3: Overall View of Experimental Apparatus.

(A) Joule Heating

(B) Bottom Heating

(C) Direct Heating

Figure 4: Comparison Between the Flow Patterns Obtained for Three Different Heating Methods (Solid Isothermal Upper Boundary; Power = 200 W).

Figure 5: Variation of the Maximum Coolant Temperature and Downward Power Fraction with Time.

Figure 6: Variation of Energy Balance Error with Time.

Figure 7: Typical Experimental Data Showing Variation of Downward Power Fraction with Power Input and Overlying Fluid Layer Height

Figure 8: Typical Results Showing Variation of Downward Nusselt Number with Internal Rayleigh Number and Overlying Fluid Layer Height Ratio.

K = 3

— .0121 (METER/SEC)

Figure 9: Typical Flow Map in the Bed and Overlaying Fluid
Produced by COMMIX-1A for a Low-Porosity Bed.

K = 3

— .0043 (METER/SEC)

Figure 10: Typical Flow Map in the Bed and Overlaying Fluid
Produced by COMMIX-1A for a High-Porosity Bed.

Figure 11: Typical Results Showing COMMIX-1A Results for the Upward and Downward Power Fractions and Energy Balance Error as a Function of Real Time.

Ra-int

Tmax

Figure 12: Typical Results Showing COMMIX-1A Results for the Internal Rayleigh Number and Maximum Coolant Temperature as a Function of Real Time.

Figure 13: Typical Results Showing COMMIX-1A Results for the Variations of the Downward and Upward Heat Transfer Coefficients, h_b and h_t , as a Function of Real Time.

Figure 14: Typical Results Showing COMMIX-1A Results for the Downward and Upward Nusselt Numbers, Nu_b and Nu_t , as a Function of Real Time.