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# CORE-DEBRIS QUENCHING-HEAT-TRANSFER RATES UNDER TOP- AND BOTTOM-REFLOOD CONDITIONS*

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## Abstract

This paper presents recent experimental data for the quench-heat-transfer characteristics of superheated packed beds of spheres which were cooled, in separate experiments, by top- and bottom-flooding modes. Experiments were carried out with beds of 3-mm steel spheres of 330-mm height. The initial bed temperature was 810 K. The observed heat-transfer rates are strongly dependent on the mode of water injection. The results suggest that top-flood bed quench heat transfer is limited by the rate at which water can penetrate the bed under two-phase countercurrent-flow conditions. With bottom-reflood the heat-transfer rate is an order-of-magnitude greater than under top-flood conditions and appears to be limited by particle-to-fluid film boiling heat transfer.

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## Summary

Light water reactor degraded core accident sequence studies have been performed which consider the existence of high-temperature core-debris beds, either within the reactor vessel [1] (in-vessel), or in the reactor cavity [2] (ex-vessel). Steam generated as a consequence of quenching of the debris beds by available cooling water would impose pressure loadings on the primary system or on the containment building which must be quantified for reactor safety evaluations. In-vessel debris beds would be cooled by either top- or bottom-injection of emergency cooling water depending on the availability of flow paths. Ex-vessel debris beds would be cooled by top-flood by an overlying pool of water. The objective of this paper is to present recent data for the quench heat transfer characteristics of superheated packed beds of spheres which were cooled, in separate experiments, by top- and bottom-flooding modes. The heat transfer rates are compared and limiting physical mechanisms are discussed.

The experiments were performed in a cylindrical quartz vessel to allow photographic observation of the quench process. The experimental parameters for both the top-flood and bottom-flood experiments are presented in Table 1.

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Table 1 - Experimental Parameters

| | |
|---|---|
| Particle Material | Stainless Steel 302 |
| Particle Diameter | 3 mm |
| Bed Height | 330 mm |
| Bed Porosity | 0.4 |
| Vessel Diameter | 88.9 mm |
| Initial Bed Temperature | 810 K |
| System Pressure | 0.1 MPa |

| | Top Flood | Bottom-Flood |
|---|---|---|
| Water Supply | Pool Above Bed | External Vessel with Downcomer |
| Bed Configuration [see Fig. 1] | C1 | C1, C2, C3, C4 |
| Driving Head | ------ | 2.44 m |

Figure 1 presents the bed configurations and "constraints" for the experiments. In both series of experiments the spheres were heated in an oven and were subsequently transferred to the test vessel. At the desired time, water was dropped onto the bed in the top-flood experiments or a valve was opened to permit flow of water to the bed from below in the bottom-flood experiments. Motion pictures of the quench processes were taken and the time to quench the particles in both series of experiments was determined by observation of the duration of two-phase flow within the test apparatus.

The results of the experiments are summarized in Table 2. The two top-injection experiments were characterized by steady steam generation and by average heat fluxes of approximately $10^6$ W/m$^2$. These observations agree with those of Ginsberg [3] and Cho [4]. Run No. 3, the first bottom-injection experiment with no constraint on the particle bed, led to fluidization and intense mixing of the particles, water and steam, and an average heat flux of $3.5 \times 10^7$ W/m$^2$.

The high heat flux observed in Run No. 3 was attributed to fluidization and the forced one-dimensionality of the test vessel. The apparatus was then modified to (i) axially constrain the bed and thus avoid fluidization and (ii) permit diversion of liquid around the bed through the annular gap, thereby simulating availability of alternate low-resistance liquid flow paths. Run Nos. 4-8 were carried out with several combinations of axial constraint, annular gap and water temperature. The observed average heat fluxes in all these experiments were lower by a factor of two or more than the result for the unconstrained bed with bottom injection. Run Nos. 4, 5 and 7 were all conducted with subcooled water. In all cases the water penetrated the bed and resulted

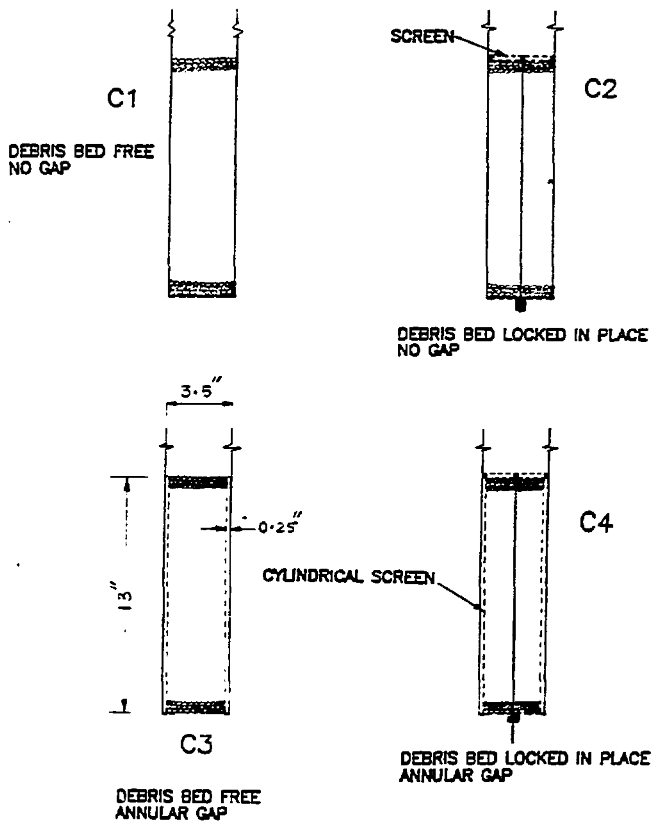


Figure 1. Bed Configurations

Table 2 - Experiment Summary

| RUN NO. | BED CONFIGURATION | WATER INJECTION METHOD | WATER SUPPLY TEMP, K | QUENCH TIME SECONDS | HEAT FLUX $W/m^2$ | REMARKS |
|---|---|---|---|---|---|---|
| 1 | C1 | Top Injection | 373 | 402 | $0.965 \times 10^6$ | Constant Steam Flow |
| 2 | C1 | Top Injection | 298 | 376 | $1.03 \times 10^6$ | Constant Steam Flow |
| 3 | C1 | Bottom Injection | 300 | 11 | $35.3 \times 10^6$ | Entire Bed Fluidized, Mixed |
| 4 | C2 | Bottom Injection | 311 | 30 | $12.9 \times 10^6$ | Intermittent Steam Generation |
| 5 | C3 | Bottom Injection | 311 | 21 | $18.5 \times 10^6$ | Boiling Intermittent, Violent |
| 6 | C3 | Bottom Injection | 366 | 120 | $3.23 \times 10^6$ | Continuous Boiling. No Fluidization. Water Supply Depleted. |
| 7 | C4 | Bottom Injection | 311 | 24 | $16.2 \times 10^6$ | Periodic Steam Generation |
| 8 | C4 | Bottom Injection | 366 | 120 | $3.23 \times 10^6$ | Continuous Boiling. No Fluidization. Water Supply Depleted. |

in rapid, intermittent steam generation with heat fluxes approximately 12-19 times higher than for the case of top flooding. In Run Nos. 6 and 8, carried out with small subcooling, water bypassed the bed through the annular gap and led to depletion of water in the supply vessel. The bed then subsequently cooled by top-flooding and led to heat fluxes closer to that characteristic of the top-injection mode.

Table 3 compares the heat flux data from the top- and bottom-flood experiments with calculations based upon two limiting models. The Lipinski debris bed model [5] assumes that the heat removal rate from a debris bed is limited by the availability of water to the bed. The water supply is assumed controlled by two-phase countercurrent flow within the bed. The film-boiling model [6] assumes that each sphere is surrounded by an infinite sea of water and that the heat transfer rate is limited by the film-boiling dynamics. The results suggest that:

(i) Packed bed quench heat transfer rates are dependent on the mode of flooding.

(ii) Top-flood bed quench heat transfer is limited by the rate at which water can penetrate into the bed. The Lipinski model predicts this reasonably well for the conditions of this experiment.

(iii) The bed quench heat transfer rate with constant-head bottom-reflood is more than an order of magnitude greater than that observed for top-flooding. The observed average heat transfer rate is consistent with the assumption of film-boiling controlling heat transfer resistance.

Table 3 - Comparison of Data and Limiting Heat Transfer Models

**Experimental**

| Condition | Heat Flux ($W/m^2$) |
|---|---|
| Top-Flood | $0.97 - 1.03 \times 10^6$ |
| Bottom Flood | |
| Fluidized | $3.53 \times 10^7$ |
| Constrained/ No Bypass | $1.29 - 1.85 \times 10^7$ |

**Theoretical**

| Model | Heat Flux ($W/m^2$) |
|---|---|
| Lipinski Hydrodynamic [5] | $1.0 \times 10^6$ |
| Film Boiling Heat Transfer [6]* | |
| $\Delta T_{SAT} = 438$ K | $5.94 \times 10^7$ |
| $\Delta T_{SAT} = 100$ K | $1.36 \times 10^7$ |

*10 kg of 3 mm spheres

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