CONVECTIVE HEAT TRANSFER CORRELATIONS FOR MOLTEN
CORE DEBRIS POOLS GROWING IN CONCRETE*

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The heat and mass transfer processes taking place in volumetrically-heated pools are of interest because of their relevance in post accident heat removal analyses for fast reactors. Earlier studies on volumetrically-heated pools have focused on natural convection phenomena. These, however, do not apply for molten core debris pools growing in concrete since large amounts of gas will be released by the concrete. These gases will vigorously mix the pool. Knowledge of the heat transfer rates at the pool boundaries is necessary in order to assess the passive core retention capability of the concrete support structure below the reactor vessel. Hence, the main objectives of this investigation have been to experimentally simulate the gas evolution process at the pool boundaries and determine the effect of gas release on the heat transfer rates along the boundaries. Nusselt-type correlations have been obtained for the downward, sideward, and upward heat transfer rates.

The experimental apparatus consists of a rectangular test cell bounded from the sides and bottom by nearly-isothermal porous brass plates through which a non-condensable gas is injected at controlled rates. Joule heating of an electrolyte solution contained within the test cell provides the volumetric heat source and simulates the core debris pool. The upper pool boundary is either a free surface or an isothermal copper plate with holes to allow passage of the injected gas out of the pool. Measurements of the pool temperature distribution along with the downward, sideward, and upward heat transfer rates have been made. A wide range of internal Rayleigh number, gas injection rate, and pool aspect ratio have been investigated. A total of 400 experiments have been conducted.

The results indicate that pool maximum temperatures are considerably reduced with gas injection compared to natural convection values. The pools are well stirred by the gas and show nearly isothermal temperature distributions. Natural convection effects are found to be negligible in the gas mixed pool; the downward, sideward, and upward Nusselt numbers are independent of the internal Rayleigh number. The Nusselt numbers are found to depend on the product of Reynolds and Froude numbers; $(Re \times Fr) \equiv (\rho V^3 / \mu g)$, where ρ and μ are the density and viscosity of the pool, g is gravitational acceleration, and V is the superficial gas velocity. Small gas injections rates are found to result in large increases in Nusselt numbers from the natural convection values. Typical results for pools with a free surface upper boundary are shown in Fig. 1.

The following Nusselt-type correlations have been obtained. For pools with a solid upper boundary, the downward Nusselt number is given by:

$$(Nu_0)(W/L) = 204[Re \times Fr]^{0.05} \quad (5 \times 10^{-10} \leq (ReFr) \leq 5 \times 10^{-3}) \quad (1)$$

where $Nu_0 \equiv h_0 L / k$, h_0 is the average heat transfer coefficient along the bottom surface of the pool, L is the pool depth, W is the pool width, and k is the thermal conductivity of the pool. For pools with a free upper surface, the downward Nusselt number is given by:

$$(Nu_0)(W/L) = 231[Re \times Fr]^{0.074} \quad (10^{-10} \leq (ReFr) \leq 10^{-2}) \quad (2)$$

The sideward Nusselt number for pools with a solid upper boundary is given by:

$$(Nu_s)(W/L) = 194[Re \times Fr]^{0.043} \quad (5 \times 10^{-10} \leq (ReFr) \leq 5 \times 10^{-3}) \quad (3)$$

The upward Nusselt number for pools with a solid upper boundary is given by:

$$(Nu_1)(W/L) = 565[Re \times Fr]^{0.048} \quad (5 \times 10^{-10} \leq (ReFr) \leq 5 \times 10^{-2}) \quad (4)$$

The above relations are the main result of this work. They can be used to predict the heat transfer rates along the surfaces of a volumetrically-heated pool with gas release at the boundaries over a wide range of the independent variable (ReFr). These results show that for pools with gas injection, the downward and sideward Nusselt numbers are comparable in contrast to the natural convection case where the sideward Nusselt numbers are significantly higher than those for the downward direction. The downward Nusselt number in a free upper surface model shows a higher dependence on the superficial gas velocity than models with a solid upper boundary. This underscores the importance of proper modelling of the boundary conditions in actual systems.

Figure 1 : Variation of the Downward Nusselt Number with the Product of Reynolds and Froude Numbers for a Volumetrically-Heated Pool with Gas Injection at the Boundaries.