NATURAL CONVECTION IN A UNIFORMLY HEATED POOL*

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In the event of a core meltdown accident, to prevent reactor vessel failure from molten corium relocation to the reactor vessel lower head, the establishment of a coolable configuration has been proposed by flooding with water the reactor cavity.\textsuperscript{1,2} In Reference 3, it was shown that for the heavy-water new production reactor (NPW-HWR) design, this strategy, e.g., the rejection of decay heat to a containment decay heat removal system by boiling of water in the reactor cavity, could keep the reactor vessel temperature below failure limits. The analysis of Ref. 3 was performed with the computer code COMMIX-1AP/P, and showed that natural convection in the molten-corium pool was the dominant mechanism of heat transfer from the pool to the wall of the reactor vessel lower head. To determine whether COMMIX adequately predicts natural convection in a pool heated by a uniform heat source, in Ref. 4, the experiments of free convection in a semicircular cavity of Jahn and Reineke\textsuperscript{5} were analyzed with COMMIX. It was found that the Nusselt (Nu) number predicted by COMMIX was within the spread of the experimental measurements. In the COMMIX analysis of Ref. 4, the semicircular cavity was treated as symmetric. The objective of the work presented in this paper was to extend the COMMIX validation analysis of Ref. 4 by removing the assumption of symmetry and expanding the analysis up to the highest Rayleigh (Ra) number that leads to a steady state.

Jahn and Reineke performed a series of natural convection experiments in a two-dimensional (r-θ) semicircular cavity filled with water and heated by a uniform internal heat source. Heat was removed from the boundaries of the cavity, which were kept at a constant temperature. The heat source was varied to cover a range of Rayleigh numbers from $10^9$ to $10^{12}$. Reference 5 presents average and local Nusselt number values for the circular boundary of the cavity as a function of Rayleigh number.

The average Nusselt number was defined by

\begin{equation}
\text{Nu}_{avg} = \frac{h L}{\kappa}
\end{equation}

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\[ \text{Nu} = \frac{q_a L}{\lambda (T_M - T_W)}, \]

where: \( q_a \) = average heat flux at the circular boundary, \( L \) = diameter of the cavity, \( \lambda \) = conductivity of the fluid, \( T_M \) = average fluid temperature, \( T_W \) = boundary temperature.

Figure 1 shows the average Nusselt number as a function of time for \( \text{Ra} = 1.33 \times 10^9 \). The assumption of a symmetric pool leads to a Nu number that oscillates periodically (Fig. 1a). With the same assumption and larger Ra values the oscillations are chaotic. When the assumption of pool symmetry was removed, for \( \text{Ra} = 1.33 \times 10^9 \) the oscillations became chaotic (Fig. 1b), the amplitude of the oscillations was reduced, but the time average value of the Nu number remained nearly the same (0.1% variation). With no assumption of symmetry, the periodic behavior was exhibited at significantly lower Ra values (Fig 1c).

Figure 2a shows the distribution of the relative local Nu number (local/average) along the bottom of the cavity for \( \text{Ra} = 1.33 \times 10^9 \). The numerical predictions are well within the band of the experimental measurements. In Ref. 5 the experimental values for the average Nusselt number of the circular boundary were fitted by the function

\[ \text{Nu} = 0.6 \text{Ra}^{0.2} \] (1)

As Fig. 2b shows, the COMMIX predictions are very well fitted by the function

\[ \text{Nu} = 0.46 \text{Ra}^{0.2} \] (2)

These predictions are 23% lower than the values given by Eq. (1), but as Fig 2b shows, they are within the spread of the experimental measurements. The predicted oscillatory behavior of the pool is also in agreement with experimental observations. The numerical experiments predicted a steady-state non-oscillatory pool behavior for Ra about \( \leq 2.62 \times 10^7 \). There is no experimental information to compare this prediction.
In this analysis, a 50 x 99 (r - θ) mesh was used. The computation time was very long, for example, to generate the data of Fig. 1c (one Ra value) 940 hr were used in a sun SPARC20 machine.

Figure 2c shows pool temperature distributions for Ra = 2.62E7 (steady-state) and Ra = 7.21E7 (periodic oscillations). The steady-state, although it was converged to a very tight convergence criterion, it exhibits a small assymetry (temperature, heat fluxes). For Ra = 7.21E7 (periodic oscillations) the long term behavior of the pool also exhibited some assymetry.

In conclusion, this work shows that the numerical predictions of natural convection in an internally heated pool bounded by a curved bottom are in reasonably good agreement with experimental measurements. At low Ra values the system reached a steady state. As the Ra number increased, it exhibited a periodic oscillatory behavior, and at higher Ra values the oscillations became chaotic. The assumption of symmetry did not affect significantly the time averaged Nu values, but it affected the transition values of the Ra number.

References


Figure 1. Nusselt number as a function of time.
Figure 2. Nu number as a function of Ra number and pool temperature distributions.

\[ Nu = 0.6 \, Ra^{0.2} \]

\[ Nu = 0.46 \, Ra^{0.2} \]