Numerical Predictions of Natural Convection in a Uniformly Heated Pool

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In the event of a core meltdown accident, one of the accident progression paths is fuel relocation to the lower reactor plenum. In the heavy water new production reactor (NPR-HWR) design, the reactor cavity is flooded with water. In such a design, decay heat removal to the water in the reactor cavity and thence to the containment may be adequate to keep the reactor vessel temperature below failure limits. If this is the case, the accident progression can be arrested by retaining a coolable corium configuration in the lower reactor plenum. The strategy of reactor cavity flooding to prevent reactor vessel failure from molten corium relocation to the reactor vessel lower head has also been considered for commercial pressurized water reactors.

In Ref. 1, the computer code COMMIX-1AR/P was used to determine if the heat removal rate from the molten corium in the lower plenum to the water in the cavity was adequate to keep the reactor vessel temperature in the NPR-HWR design below failure limits. It was found that natural convection in the molten pool resulted in heat removal rates that kept the peak reactor vessel temperature about 400°C below the steel melting point. The objective of the work presented in this paper was to determine whether COMMIX adequately predicts natural convection in a pool heated by a uniform heat source. For this purpose, the experiments of free convection in a semicircular cavity of Jahn and Reineke were analyzed with COMMIX and code predictions were compared with experimental measurements. COMMIX is a general purpose thermalhydraulics code based on finite differencing by the first order upwind scheme.

Jahn and Reineke performed a series of natural convection experiments in a two-dimensional (rθ) 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 (Ra) from 10^7

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to $10^{12}$. In this work, four numerical experiments were performed for $Ra = 1.33 \times 10^9$, $3.37 \times 10^{10}$, $1.42 \times 10^{11}$ and $8.69 \times 10^{11}$. A uniform grid of $50 \times 50$ (rθ) was used in this analysis. Reference 4 presents average Nusselt number values, $Nu$, for the circular boundary of the cavity as a function of Rayleigh number at steady state conditions. The average $Nu$ was defined by

$$Nu = \frac{q_a L}{\lambda (T_M - T_w)}$$

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; and $T_w =$ boundary temperature.

The attempt to solve the steady state form of the related Navier-Stokes equations using a pseudo-transient approach lead to a transient where the average fluid temperature was nearly constant, but local fluid temperatures and velocities, as well as the average $Nu$ number exhibited an oscillatory behavior. Temperature and velocity distributions from a point of this pseudo-transient were used as initial conditions to solve the time dependent form of the Navier-Stokes equations. The transient solutions gave a nearly constant average fluid temperature (to the first or second decimal point depending on the Ra number) but the local temperatures, the velocities and the average $Nu$ number oscillated continuously.

Figure 1a shows the average $Nu$ number as a function of time for $Ra = 1.33 \times 10^9$. It oscillates with a period of ~330 s. As the Ra number increased, the oscillations became non-periodic. This is illustrated in Fig. 1b which shows the average $Nu$ number for $Ra = 8.69 \times 10^{11}$. Figure 2 shows the temperature field for $Ra = 8.69 \times 10^{11}$ at a peak $Nu$ value and at the local minimum $Nu$ value immediately following the peak. The lower part of the water pool is well stratified, while the upper part is characterized by time-varying convection eddies.

Heat removal from the top of the pool cools the top layer of the fluid. This cooling is the source of the instability that leads to the oscillations. As cooling at the top proceeds, a tongue of cold fluid starts to move downwards into the mass of the underlying hot fluid. This reduces heat removal from the curved surface of the pool and increases the local heatup rate.
As hotter fluid moves to the top the heat removal rate at the top increases. The enhanced heat removal rate at the top cools the top layer to the degree that another tongue of cold fluid from the top starts to move downwards again. The repetition of this cycle leads to the observed oscillations.

In Reference 4, it was found that the experimental values for the average Nu number of the circular boundary were well represented by the function

$$\text{Nu} = 0.6 \, \text{Ra}^{0.2}$$

(1)

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

$$\text{Nu} = 0.455 \, \text{Ra}^{0.2}$$

(2)

These predictions are 24% lower than the values given by Eq. (1), but as Fig. 2b shows, they are within the spread of the experimental measurements.

In conclusion, this work shows that COMMIX predicts reasonably well the natural convection in an internally heated pool that is bounded by a curved bottom. This analysis also supports previous experience showing that although first order upwind differencing suffers from numerical diffusion, adequate predictions can be obtained for many engineering problems with grids that do not impose excessive computation times.

References


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Figure 1. Nu as a function of time
Figure 2. (a) Isotherms, (b) Nu as a function of Ra
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