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Downward Heat Transfer from Heat-Generating Boiling Pools Pertaining to PAHR and Transition Phase*

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The phenomenon of heat transfer from volume heated boiling pools in the downward direction is of considerable interest in nuclear reactor safety analysis. For example, in the post-accident heat removal studies of LMFBRs the downward heat transfer to a boiling steel layer in molten pool penetration of the MgO substrate is of interest. The bubbles rising from the boiling of stainless steel film, lying at the bottom of the heat generating pool consisting of MgO and UO_2 eutectic solution, cause the upward motion of bulk fluid. This buoyancy effect of two-phase bulk fluid generates a negative pressure gradient along the base, resulting in motion of single-phase fluid in a boundary layer over the stainless steel liquid film. The heat transfer from concrete substrate during molten pool penetration or during sodium-concrete reaction also takes place owing to convection that is driven by gas and water vapor bubbles released from the concrete substrate due to its heatup. Similarly, downward heat transfer in the boiling pool of stainless steel and fuel mixture pertaining to the transition phase of hypothetical core disruptive accidents is of considerable interest in predicting the dynamics of the pool. Besides these applications in LMFBR safety, the phenomenon of heat transfer from volume heated boiling pools is of potential interest in chemical reactor engineering in cooling techniques of electronic equipment.

The initial preliminary experimental study of the downward heat transfer from heat generating boiling pools was carried out by Stein et al. [1].

Subsequently, their work was extended with various refinements by Gabor et al. [2]. However, there have been no successful attempts in devising a suitable model to correlate these heat transfer data. The present analytical study proposes a mechanistic model and successfully correlates the heat transfer data of Gabor et al. [2].

The proposed model assumes that owing to the density difference caused by volume boiling or bulk two-phase fluid between the bulk fluid and that near the base of the pool, the lighter two-phase bulk fluid causes upward movement of the fluid and thereby generates a negative pressure gradient along the base of the pool. This in turn causes motion of returning single-phase fluid along the base of the pool in laminar/turbulent boundary layers. The analysis for the laminar case shows that the combined (or opposing) two-phase and thermal expansion driven natural convection along the base of the pool is characterized by the Grashof number, $Gr = (\beta\Delta T_w + 6\alpha)gL^3/\nu^2$, where β is the thermal expansion coefficient, $\Delta T_w = T_w - T_a$, the temperature difference between the base plate and the bulk fluid outside the boundary layer, α the void fraction, g the acceleration due to gravity, L the height of pool, and ν the kinematic viscosity of the liquid. With this definition of Gr, the analysis for the laminar case shows that heat transfer law for the combined two-phase and thermal expansion driven natural convection and that for the temperature difference driven alone are equivalent. The turbulent flow in the boundary layer is analyzed by assuming a two-layer model in which the inner layer is characterized by viscous and conduction terms and the outer by mean convection terms. The similarity analysis of the governing equations yields universal profiles for temperature and velocity and the scaling laws for the inner and the outer layers. An asymptotic matching of the temperature profiles in the overlap region leads to the following heat transfer law: $Nu = hL/K = C\ Ra^{1/3} = C(GrPr)^{1/3}$, where Nu is the Nusselt number, h the heat transfer coefficient, K the thermal conductivity, Pr the Prandtl number, Ra the Rayleigh number, and C a constant. A log-log plot of the data of Gabor et al. [2] is shown in Fig. 1. Maintaining a slope of one-third on this plot as predicted by the above heat transfer law, the least square fit yields $C = 0.0375$. On the average the data does appear to show a slope of one-third, thus signifying a satisfactory agreement of the theory with the data. Also shown in the figure is Long's empirical correlation [3] $Nu = 0.04356\ Ra^{1/3}/[1 - 1.402\ (Ra\ Nu)^{-1/12}]^{4/3}$ obtained by correlating data for the single-phase turbulent thermal convection in horizontal fluid layers. The correlation shows as $Ra \to \infty$, $Nu \propto Ra^{1/3}$, which is in agreement with the present theory and furthermore, the two correlations appear to agree in increasingly closer tolerance as Ra increases in value and in fact as, $Ra \to \infty$, the two correlations differ only by about 14%, which is well within the scatter of data.

These comparisons with the data and the existing "single-phase" correlations (both for laminar and turbulent flows) amply demonstrate the validity of the proposed model for downward heat transfer from volume heated boiling pools.

References

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Figure Caption

Fig. 1. Correlation of downward heat transfer coefficient data of Gabor *et al*. [2]

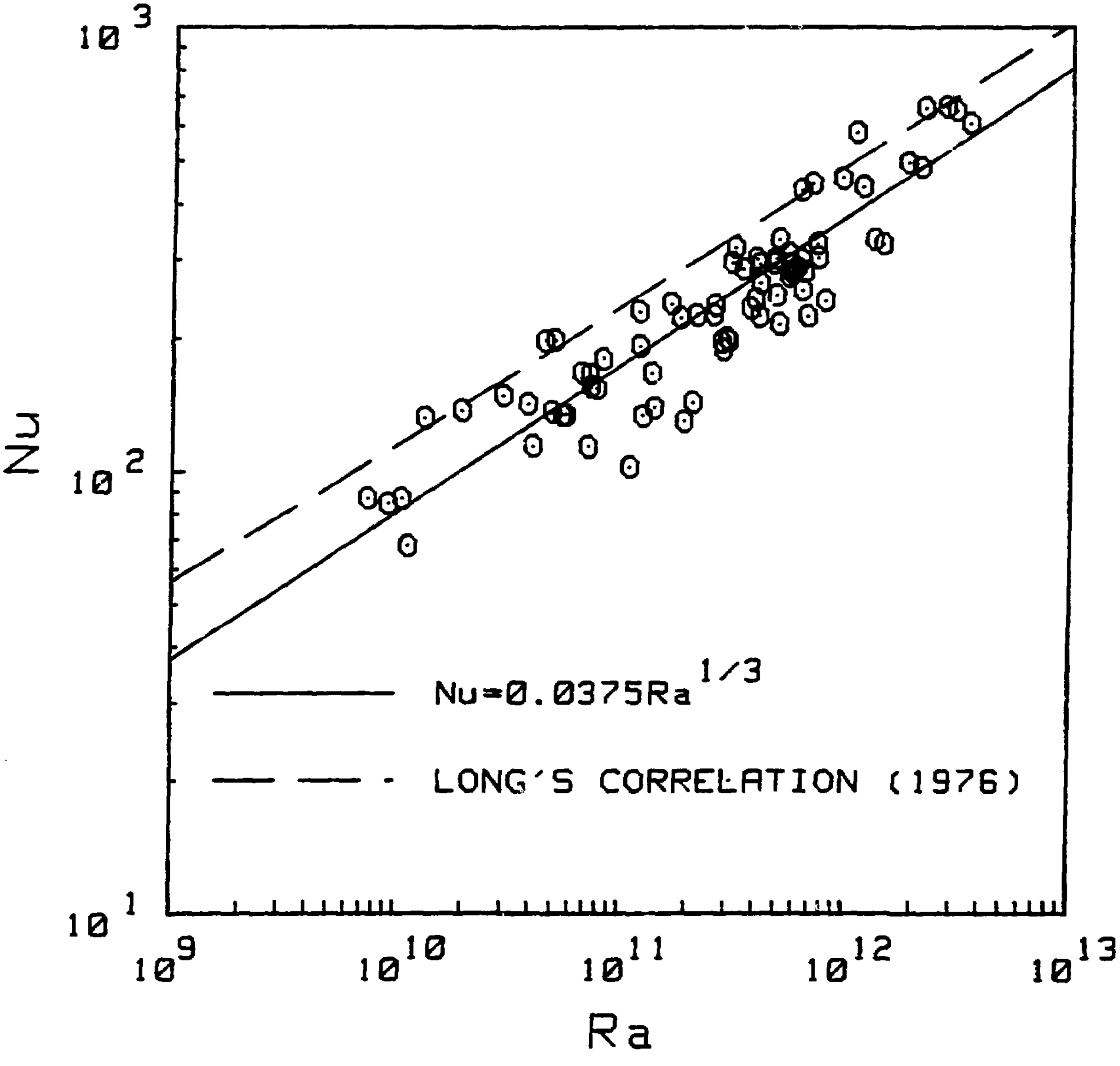

Fig. 1. Correlation of downward heat transfer coefficient data of Gabor *et al.* [2]