Prandtl Number Dependent Natural Convection Heat Transfer in a Rectangular Pool

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1. Introduction

During a severe accident in a nuclear reactor, the core may melt and be relocated to the lower plenum to form a hemispherical pool. Should there be no effective cooling mechanism, the core debris may heat up and the molten pool run into natural convection due to decay heat. Natural convection tests were performed in SIGMA RP (Simulant Internal Gravitated Material Apparatus Rectangular Pool). The SIGMA RP apparatus comprises the test section, heat-exchanger, cartridge heaters, thermocouples and the data acquisition system. The internal heater heating method was used to simulate uniform heat source which is related to the modified Rayleigh number (*Ra'*). The test procedure started with air and water, the working fluid, filling the test section. The working fluid Prandtl number (*Pr*) ranged from 4 to 8 for water, and 0.7 for air. Particular attentions were paid to the *Pr* influence on natural convection heat transfer in the pool. There were two boundary conditions: one dealt with both walls being cooled isothermally, while the other had to with only the upper wall being cooled isothermally. The heat exchanger was used to maintain the isothermal boundary condition. Four side walls were surrounded by the insulating material to maintain the adiabatic condition and to minimize the heat loss. In the top and bottom boundary cooling condition, the upward Nusselt number (Nu_{up}) was greater than the downward Nusselt number (Nu_{dn}). For a lower *Pr* fluid, the thermal boundary layer at the upper wall is greater than for a larger *Pr* fluid. Note that the heat transfer is inversely proportional to the thermal boundary layer thickness. This implies that high *Pr* increased the upward heat transfer Nu_{up}. The influence of *Pr* on the fluid behavior grows with the increase in *Ra'*.

2. Experiment

2.1 Experimental Apparatus

SIGMA RP (Simulant Internal Gravitated Material Apparatus Rectangular Pool) is a rectangular pool 500 mm long, 160 mm wide, and 500 mm high as portrayed in Fig. 1. The width-to-height ratio, *W/L*, of the rectangular pool was greater than 0.25 avoid wall effects according to Dinh et al. (1997). Walls of the test apparatus were made of acrylic. The upper and lower plates were made of copper to maximize the heat transfer. The distance between the upper and lower plates was defined as the pool height, *L*, whose tolerance was ±0.2 mm. Forty thin cartridge heaters, 4.2 mm in diameter and 500 mm long, were inserted to simulate volumetric heat generation in the pool. The heater average resistance was 210 Ω within ±5 %. The heaters were uniformly distributed to supply a maximum power of 2.5 kW to the rectangular pool.

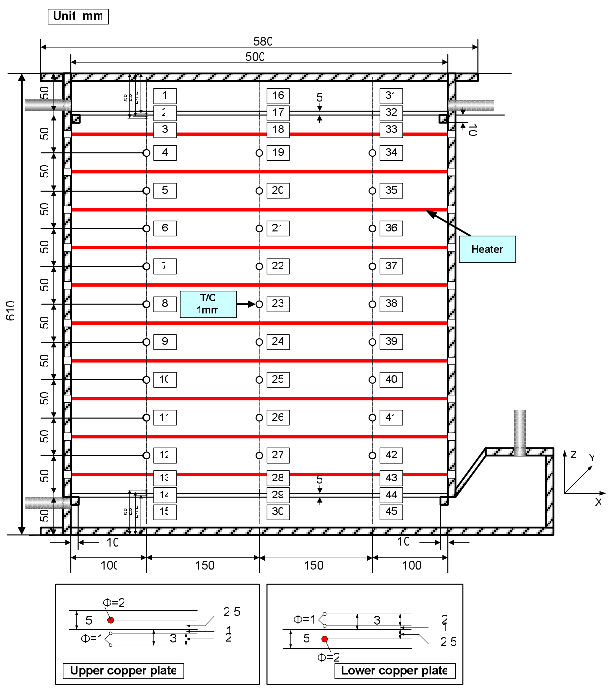

Figure 1. SIGMA RP heater and thermocouple locations.

Fig. 2 is a schematic diagram of the SIGMA RP test loop. The loop consisted of a demineralized water system, test section, heat exchanger, power controller and a data acquisition system (DAS) to read temperatures from the thermocouples.

2.2 Experimental Results

The heat transfer coefficient in a rectangular pool may be expressed as

$$h = f(\alpha, \beta, \nu, k, L, q) \tag{1}$$

$$\frac{hL}{k} = f\left(\frac{g\beta q L^5}{\alpha \nu k}, \frac{hL}{k}\right) \text{ or } Nu = C \cdot Ra'^{m} Pr^{n} \tag{2}$$

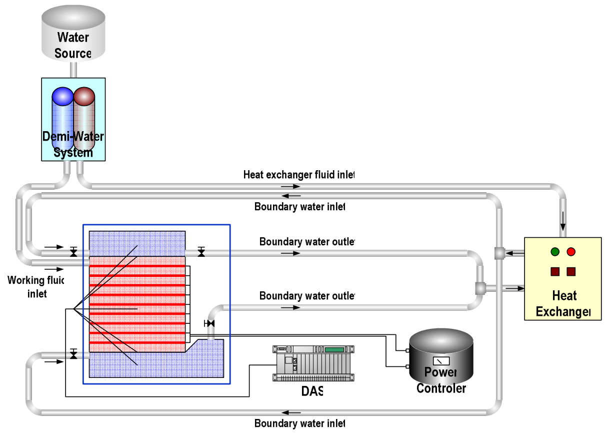

Figure 2. Schematic diagram of SIGMA RP test loop.

Nu is an indicator of how effectively heat is transferred by convection as compared to conduction. The exponent *m* was determined from the plot of *log(Nu)* versus *log(Ra)* at an almost constant *Pr*. All the test data were plotted in terms of $log(Nu/Ra'^m)$ versus *log(Pr)*. The exponent *n* and the constant *C* were found from the fitting.

Fig. 3 illustrates the *Pr* effect on the natural convection heat transfer. The *Pr* dependence in the upward heat transfer is given by $Nu_{up}=0.089Ra'^{0.226}Pr^{0.104}$.

The result shows that high *Pr* led to enhanced heat transfer by as much as 22.4 %.

The *Pr* dependence in the downward heat transfer is expressed by $Nu_{dn}=0.056Ra'^{0.142}Pr^{-0.191}$. Note that low *Pr* led to augmented heat transfer by as much as 59.2 %.

For a lower *Pr* fluid, the thermal boundary layer at the upper wall is greater than for a larger *Pr* fluid. Note that the heat transfer is inversely proportional to the thermal boundary layer thickness. This implies that high *Pr* increased the upward heat transfer Nu_{up}. The influence of *Pr* on the fluid behavior grows with the increase in *Ra'*.

3. Conclusion

This paper has identified the *Pr* effect in naturally convecting fluids. The SIGMA RP tests were conducted in a rectangular pool with volumetrically heated fluids at high *Ra'*. The internal heating method using the cartridge heaters was adopted to simulate volumetric heat sources. When the upper wall was cooled isothermally while the lower wall was kept adiabatic, the results of the experiment showed a dependency of Nu_{up} on *Pr*. When the upper and lower walls were cooled isothermally, the fluid with higher *Pr* enhanced the upward heat transfer, Nu_{up}, through the upper wall. In contrast, low *Pr* fluid led to increased downward heat transfer, Nu_{dn}, through the lower wall.

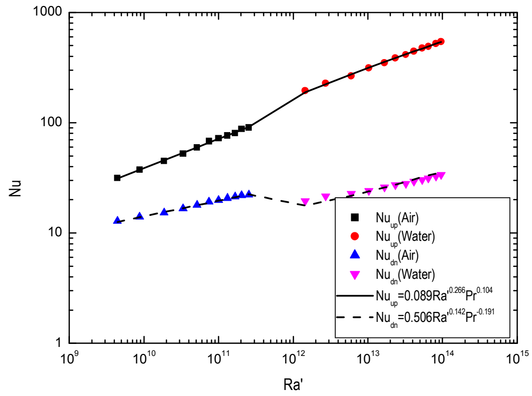

Figure 3. Prandtl number effect on natural convection heat transfer.

ACKNOWLEDGMENTS

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