Natural Convection Heat Transfer in a Horizontal Layer Heated from Below and Cooled from Side and Above

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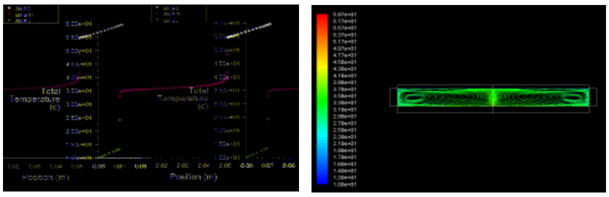
1. Introduction

The thermofluid dynamic characteristics of natural convection flow depend strongly on thermal boundary condition such as the spatial and temporal variation of heat flux on the pool wall boundaries. In general the natural convection heat transfer phenomena involving the bottom heat generation are represented by the Rayleigh number, *Ra*, which quantifies the bottom heat source and hence the strength of the buoyancy force [1, 2]. This work focuses on natural convection in which the density gradient is due to a temperature gradient and the body force is gravitational. The presence of a fluid density gradient in a gravitational field does not ensure the existence of natural convection currents, however, in an apparatus enclosed by two horizontal plates of different temperature. The temperature of the lower plate exceeds that of the upper plate, and the density decreases in the direction of the gravitational force. The LIDO (Liquid Internal Dynamics Operation) tests are conducted in a horizontal circular layer 500 mm in diameter and 220 mm in height using fluid, whose thermophysical properties are typified by the Prandtl number, *Pr*. The tests cover the range of $3\times10^5 < Ra < 1\times10^{10}$ and $0.02 < Pr < 2.22$ Tests are conducted with air, water and Wood's metal (Pb-Bi-Sn-Cd) as simulant to determine the Nusselt number, *Nu*. The upper and side walls are cooled, while the lower wall is heated at uniform temperatures.

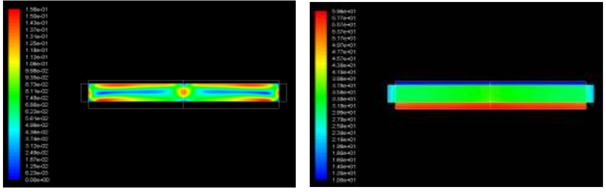
2. Computational Analysis

Prior to experimental testing, a two-dimensional (2D) natural convection model was applied to LIDO. The computational fluid dynamics (CFD) code FLUENT 6.2 was adopted to solve natural convection within two horizontal circular plate layers. The test section was modeled using the Graphic User Interface (GUI) environment of GAMBIT. The test section is 220 mm high and 500 mm long. In the process of modeling, a 2D layout was introduced with 50,000 interior faces in the individual square meshes, which is enough for the static temperature profile. The fluid temperature adjacent to the upper and side walls was set equal to 283 K for air and water, and 347 K for Wood's metal, respectively. The bottom heat flux was varied as $2.5\times10^3 \sim 5.0\times10^4$ W/m^2. Fig. 1 shows 2D computational analysis results. Three-dimensional (3D) computational analysis was also conducted utilizing the design modeler of the CFX®. Fig. 2 describes 3D analysis results.



(a) Total temperature in test section

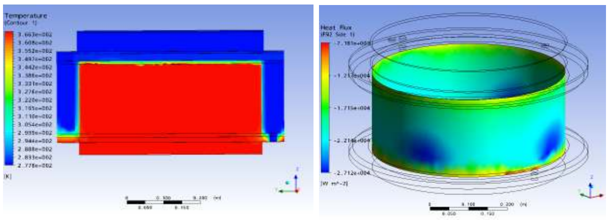
(b) Path line colored by density



(c) Velocity magnitude

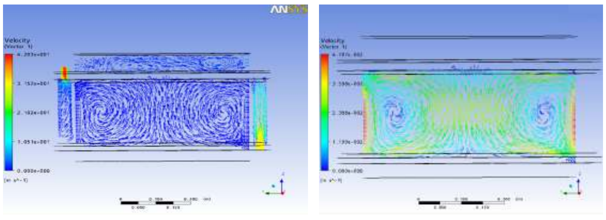
(d) Total temperature

Fig. 1. Natural convection contours of temperature, density and velocity vector of working fluid.



(a) Color of total temperature

(b) Color of sidewall heat flux



(c) Velocity contours

(d) Color of test section velocity

Fig. 2. Natural convection contours of temperature, sidewall heat flux and velocity vector of working fluid.

3. Experimental Apparatus and Procedure

The test section is of a 220 mm × 500 mm cylindrical cavity as portrayed in Fig. 3. Five ring heaters are used to simulate bottom heating in the pool. A 12 kW heater is installed in the bottom horizontal plate of the test section. The test section is made of 10 mm thick 304 stainless steel. 50 mm thick copper plate is installed under the test section. Also, 25 mm thick copper plate is installed between cooling section and inner side of the test section. The pot equipped with a 6 kW heater is used to melt Wood's metal prior to injection to the test section. A coolant supply tank is equipped with a 5 kW heater to control the coolant temperature. Temperatures inside the test section are measured using twenty-four T-type thermocouples of 1.2 mm diameter, which are placed in sidewall cylindrical arrays of thermocouple bundles located at every second position of the length and width of the test section. Also, the temperatures are determined along a vertical line joining the centers of the bottom and top plates. Eighteen thermocouples are aligned in the horizontal direction of upper wall and cooling regions. Two thermocouples are immersed in the heating region, while the other ten are located in the cooling region.

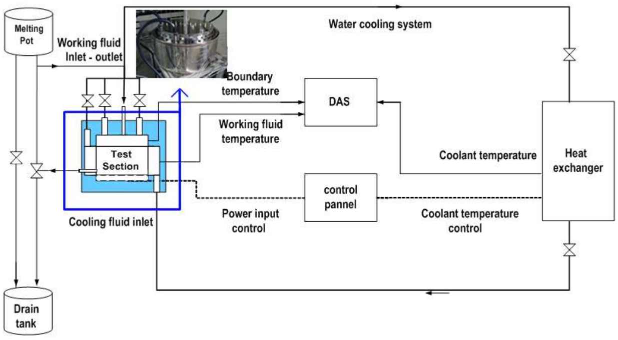


Fig. 3. LIDO apparatus system.

For the constant temperature boundary condition of the bottom heating surface, the test parameters include the bottom surface temperature ranging from 293 K to 523 K, and the injection coolant temperature spanning from 281 K to 348 K. Data acquisition system (DAS) bias error was calibrated to minimize measurement errors. Once properly calibrated, thermocouples were placed at their designated locations. The water-cooling system, or heat exchanger, supplies the well-defined upper boundary conditions. Performance test of this water cooling system showed the temperature difference of ± 0.1℃ ranging from 278 K to 363 K. Table I summarizes specification of the test apparatus.

Table I: Design parameters LIDO apparatus

Working Fluid	Air, Water, Wood's metal
Test section Size [mm] (Height and Length)	220/500
Thermocouple Class	T-Type
Number of Thermocouples	72
Azimuthal Angle [°]	90, 270
Heater Type	Pipe
Number of Pipe Heaters	5
Maximum Power [kW]	12
Heater Diameter [mm]	11

4. Results and Discussion

Nu is obtained by using the heat transfer coefficient and the height of the test section. *Ra* is defined by the temperature difference between the bottom and top surfaces in the test section and the height of the pool. *Nu* and *Ra* are determined as follows:

$$Nu = \frac{hL}{k} \tag{1}$$

$$Ra = \frac{g\beta\Delta TL^3}{\alpha v} \tag{2}$$

$$\alpha = \frac{k}{\rho c_p} \tag{3}$$

$$v = \frac{\mu}{\rho} \tag{4}$$

Assuming the functional relationship to be given by a product of powers one obtains

$$Nu = CRa^m Pr^n \tag{5}$$

The heat flux can be derived from the temperature difference between the top and the bottom surfaces of the copper layer using the heat conduction equation. The actual heat flux is calculated from the temperature measurements from the thermocouples located just underneath the distance between the two points. Values are obtained once a steady state has been accomplished. Fig. 4. illustrates the bottom heated fluid layer. There are three distinct regions: the upper boundary layer, turbulent mixing core, and lower boundary layer. In this test, the boundaries are kept at differing temperatures. The mixing core region moves upward and downward as *Ra* increases. Also, a thin thermal boundary layer is quite rapidly developed at the upper surface as *Ra* increases. Thus, *Nu* has a strong dependency on *Ra*.

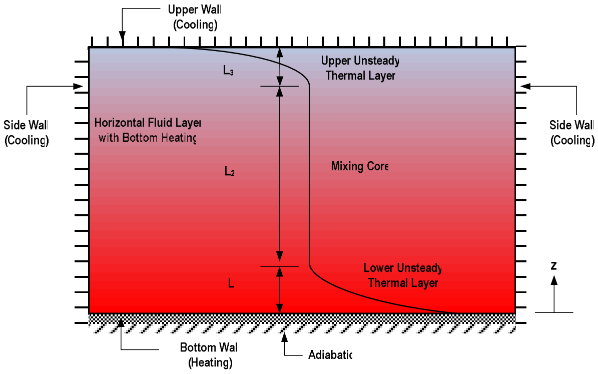


Fig. 4. Schematic of temperature profile with upper cooling and lower heating walls.

ACKNOWLEDGEMENTS

This work was performed under the auspices of Center for Advanced Initiative Reactor Options (CAIRO) as part of the Brain Korea 21 Energy Systems Engineering Program funded by the Korean Ministry of Education, Science & Technology.

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