Preliminary Study on Liquid Natural Convection by Temperature Differences

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Abstract - Natural convection is very interesting phenomena on fluid movement especially for liquid convection. Natural convection is believed occur by differences of fluid density, which is happened because of temperature differences. In this paper we have studied on this phenomenon using finite element-based simulation and conduct an experiment to observe the natural convection. Both methods show the liquid could move in a closed-loop pipe. The possibility of temperature effect will be discussed too.

Index Terms- finite element, fluid flow, heat transport, natural convection, temperature distribution.

1. Introduction

Natural convection is the movement of the fluid that caused by density differences of the fluid. This density differences could be caused by temperature differences on the fluid. Usually, the heat source of the system is placed on lower position than heat sink, so the heat and the fluid will be convected [1]. Some examples of the applications of the natural convection are on solar water heater [2], nuclear reactor's coolant system [1], and in geophysics and geothermal process [3].

Finite element-based simulation has been widely used on many types of simulations. One type of simulation that could use finite element method is the simulation of temperature distribution. Previously we have simulated the temperature distribution in a rectangular cavity using finite element method [4].

In this paper we propose two methods to show natural convection phenomenon using finite element-based simulation and a simple experiment combined with infrared camera to observe its temperature distribution.

2. Governing Equations

There are three equations that governing fluid dynamics and heat transfer of the fluid. The first equation is the mass conservation equation. This equation could be written as [5]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{v} \right) = 0 \qquad (1)$$

on the Eulerian frame, or:

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{v} = 0 \qquad (2)$$

on the Lagrangian frame, with:

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \vec{v} \cdot \nabla \qquad (3)$$

is called substantial derivative or material derivative operator.

The second equation is the momentum equation of the fluid. In three-dimensional space coordinate system, for each frame, momentum equation could be described as a set of equations consists of three equations, one for each axis. In Eulerian frame, the set of momentum equations could be written as [5]:

$$\frac{\partial \left(\rho v^{\alpha} \right)}{\partial t} + \nabla \cdot \left(\rho v^{\alpha} \vec{v} \right) = -\frac{\partial p}{\partial x^{\alpha}} + \frac{\partial \tau^{\beta\alpha}}{\partial x^{\beta}} + \rho f^{\alpha} \qquad (4)$$

with α and β index on vector represents components of the vector in each axis and notation $\tau^{\beta\alpha}$ denotes a stress in an α direction exerted on a plane perpendicular to the β-axis. And for Lagrangian frame, the set of momentum could be written as:

$$\rho \frac{Dv^{\alpha}}{Dt} = -\frac{\partial p}{\partial x^{\alpha}} + \frac{\partial \tau^{\beta\alpha}}{\partial x^{\beta}} + \rho f^{\alpha} \qquad (5)$$

The third equation is energy equation for the fluid. From the energy equation, we could get differential heat transfer equation and write it as follows [6]:

$$\rho c_v \frac{\partial T}{\partial t} = \nabla \cdot \left(k \nabla T \right) + \dot{q} \qquad (6)$$

where c_v is heat capacity constant, T is temperature, and $\dot{q}$ is volumetric heat addition per unit mass.

Natural convection happened caused by buoyancy force due by density difference of the fluid. The relation between fluid's density and its temperature could be expressed by following equation [7]:

$$\rho = \rho_0 \left(1 - \beta \Delta T \right) \qquad (7)$$

where ρ_0 is an initial density of the fluid, β is thermal expansion coefficient, and ΔT is a temperature difference between initial fluid and fluid that already heated. The equation of buoyancy force per unit volume could be written as:

$$\vec{f_b} = (\rho_0 - \rho)\vec{g} \quad (8)$$

By substituting heat equation into buoyancy force equation, we got:

$$\vec{f_b} = \rho_0 \beta \Delta T \vec{g} \quad (9)$$

3. Methodology

In this paper, we have used two methods: finite element-based simulation and real simple experiment. Figure 1 gives the illustration of initial set up for both methods.

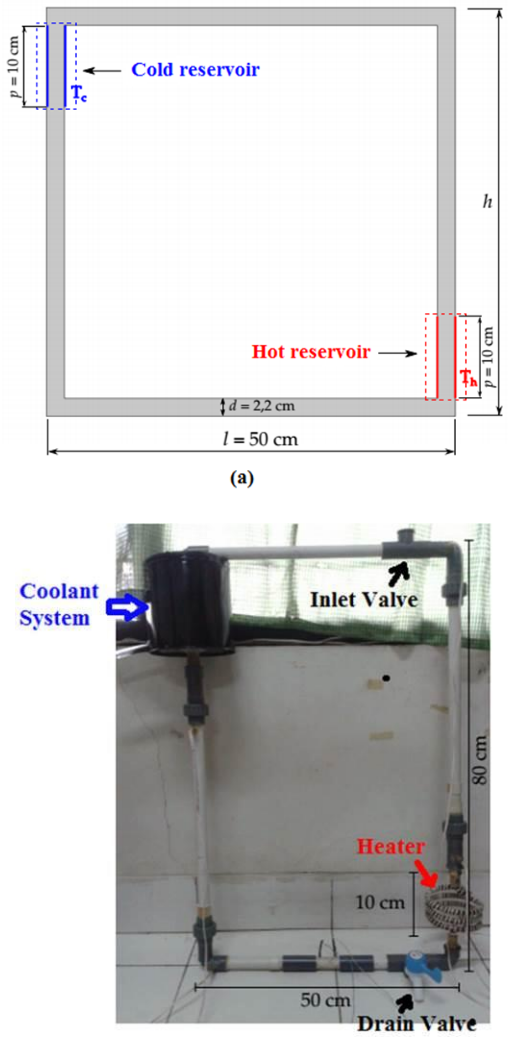

Fig. 1: Initial set up for (a) finite element-based simulation, and (b) real experiment apparatus.

For the simulation, we used several assumptions. The assumptions were that the wall of the loop made from adiabatic material, so there is no heat transfer between system and its environment. Another assumption was the temperature of both reservoirs is made constant. Cold reservoir located on top-left edge of the loop, and hot reservoir located at bottom-right of the loop. We used water as a fluid on the system, so all fluid's parameters were water's characteristic parameters. We have chosen thermal expansion coefficient as thermal expansion coefficient of water which is $\beta = 1.8 \times 10^{-4}$ K^{-1}. We could vary height of the simulation's system and the temperature of both cold reservoir and hot reservoir to observe the dependency of the flow to height or temperature differences.

For the real experiment apparatus, we used PVC pipe as a closed system loop to prevent heat exchange between system and environment. The loop has one drain valve on the bottom and one inlet valve at the top of the loop. To mimic cold reservoir, we used plastic holder located at top-left of the loop. Inside this plastic holder we put ice cube that acts as heat sink for the loop. Then, for the hot reservoir we used coiled filament wire that wraps coiled hose which is connecting PVC loop. We used coiled hose rather than just straight PVC to make contact time between fluids inside loop with heated part of the loop longer, so there is more time for heat to be transferred to the fluid. To measure temperature distribution of the system, we used infrared camera FLIR T425. That camera has IR resolution 320 x 240 pixels with temperature measurement range from -20°C to +1200°C with measurement resolution 0.05°C.

4. Results and Discussion

For the simulation, we set the height at 80 cm, and we varied the temperature of both reservoirs. We have done three simulations with different temperature differences as tabulated in Table 1.

Table 1 : Simulation parameters' configuration.

Simulation #	T_{cold} (°C)	T_{hot} (°C)	ΔT (°C)
1	40	15	25
2	55	10	45
3	70	5	65

By using different temperature differences, we got different curves for the velocity of the flow through time. Figure 2 shows the graphs that show the velocity of the flow through time for different temperature differences.

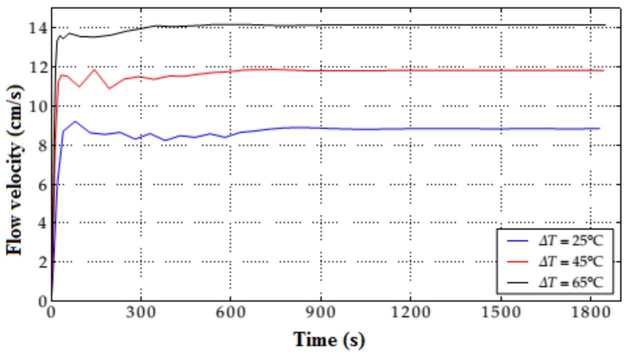

Fig. 2 : Curve of velocity of the flow through time for several different temperature differences.

From that graph we could see that as the temperature differences became larger, the flow also become faster. And as the time goes by, the velocity of the flow will be convergence to some value. Figure 3 gives some snapshots for the simulation with $T_{cold} = 15^{o}C$ and $T_{hot} = 40\,^{o}C$.

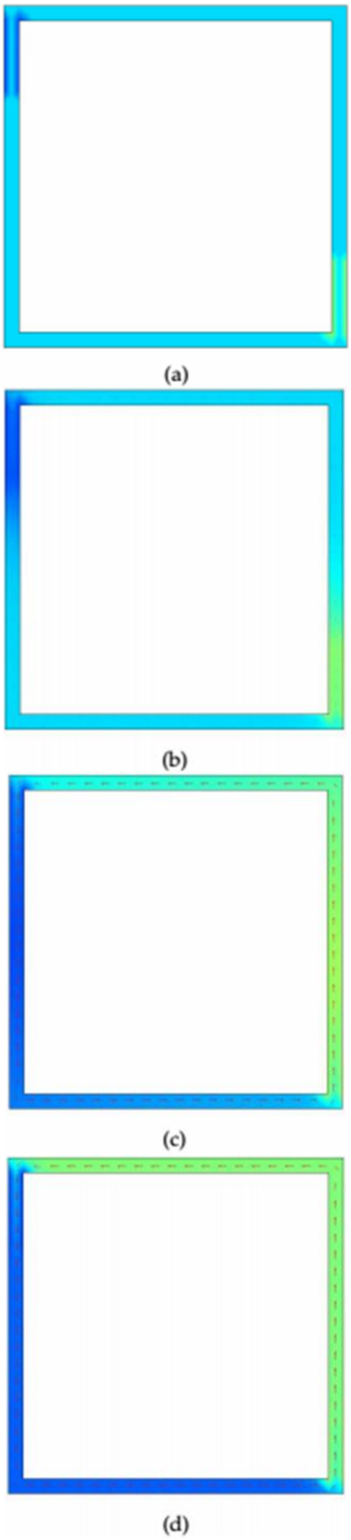

Fig. 3 : Simulation result with $T_{cold} = 15^{o}C$ and $T_{hot} = 40^{o}C$ at (a) $t = 0$ s, (b) $t = 5$ s, (c) $t = 20$ s, and (d) $t = 100$ s.

In those snapshots, we could see that starting from t = 20 s the fluid starts to move and have some velocity (velocity vector shown by small red arrow on the picture).

For the experiment result, we have the infrared photo that represents the temperature distribution of the system. Figure 4 demonstrates the temperature distributions of the system from the experiment result.

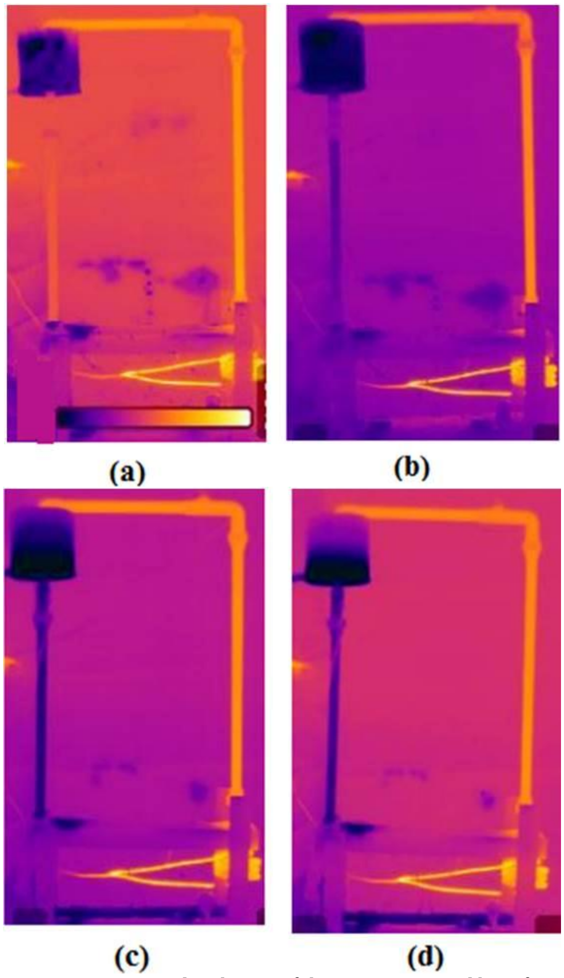

Fig. 4 : Temperature distribution of the system captured by infrared camera.

By that experiment result also we could observe that the natural convection occurred caused only by temperature differences. We cannot measure the velocity of the flow because it is too slow for the flow meter to be measured.

5. Conclusions

From this research, we could conclude that natural convection could happen on the closed loop system depending only to temperature differences. Our proposed finite element-based simulation model has showed successfully the natural convection phenomena. As the temperature difference gets larger, the flow becomes faster. Also, by using simple experiment apparatus that we have made, the natural convection could be observed by using its thermal distribution data from infrared camera.

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