Basic analysis on heat transfer phenomena in natural circulation for liquid sodium

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Abstract. Natural convection, the heat transfer on fluid due to density differences that can be caused by differences in fluid temperature. One example application of natural convection is cooling system, such as nuclear reactor cooling system. The purpose of this study is to analysis the basic characteristic heat transfer of sodium liquid in the natural circulation system for steady state analysis and transient characteristic with Finite Element Method. The selected module is the Non-Isothermal Flow (NITF) module. This module is a combination of three basic equations, namely the continuity equation, the Navier-Stokes equation, and the dynamic equation of heat transfer in fluid. The simulation model measures 1.5 x 2 (m) with sodium liquid (Na) as a fluid.

1. Introduction
Convection is a heat transfer phenomenon in fluid medium. In the convection phenomenon, fluid flow occurs together with heat transfer. There are two types of convection, namely forced convection and natural convection. Forced Convection is a transfer of heat due to the help of external forces, such as the force of a pump or fan. In contrast to forced convection, natural convection that occurs due to differences in density in the fluid that can be caused by differences in fluid temperature. The difference in fluid density can cause fluid flow. Fluid with lower density will move up and fluid with higher density will move down[1].

One application of natural convection phenomena is cooling systems, for example in diesel reactor coolers[2]. In nuclear reactors, cooling is a very important part for the need to avoid excess heat in nuclear reactors. Coolers in nuclear reactors Usually use fluid that is flowed using a pump. Damage to the pump in the cooling system can cause excess heat which can be removed by a nuclear reactor accident. To overcome this, use natural circulation fluid which uses the phenomenon of natural convection by using a difference so that the cooling material can be used to prevent damage to the pump[3].

Characteristics of Liquid salt are low melting and high boiling points, even at low pressure, so it possible to design high temperature system without increasing pressure. This is an advantage for nuclear reactor systems which use liquid salt as a coolant. There are many salt compositions which can be considered for use. However, sodium and potassium nitrates are more potential as coolants. The melting point of fluoride is too high. Therefore fluoride is suitable for use in high temperature reactors[4].
Based on this, the study will conduct a heat transfer study on liquid salt in the natural circulation system in a steady and transient state. The used fluid is sodium (Na) in the form of liquid salt with a liquid temperature range of 100-800 °C. The natural circulation model is sized 1.5 x 2 (m) with additional heating and cooling to the system. This research uses COMSOL Multiphysics software to find out how the temperature, pressure and velocity distribution of fluid flow in the system during operation.

2. Research Method
a. Non-Isothermal Flow (NITF) Module

Non-Isothermal Flow (NITF) module is chosen for this study. This module is a combination of three basic equations, those are the continuity equation, the Navier-Stokes equation, and the dynamics equation of heat transfer in the fluid[5]. Those equations, in the COMSOL software, are written as Continuity equation

\[ \nabla \rho \vec{v} + \frac{\partial p}{\partial t} = 0 \]  

(1)

Navier-Stokes equation[6]

\[ \rho \frac{D \vec{v}}{Dt} = -\nabla P + \nabla \cdot \Gamma + F \]  

(2)

The dynamics of heat transfer in the fluid equation[7]

\[ \rho c_v \frac{\partial T}{\partial t} = \nabla \cdot k \nabla T + \dot{q} \]  

(3)

COMSOL software uses finite element methods (FEM) in the calculation process. The natural convection phenomenon is related to fluid lifting force due to temperature difference. In COMSOL software, lifting force can be defined as volume force. The general lifting force equation is explained in the following equation[8]

\[ F = \rho_0 \beta \Delta T g \]  

(4)

where F is the lifting force, \( \rho \) is the density of the fluid, \( \beta \) is the thermal coefficient of liquid sodium valued at 0.0002 / K[9], and \( \Delta T \) is the temperature difference between the heated fluid and the initial fluid temperature. In figure 1, shows the flowchart for calculate the simulation with Finite Element Method (FEM).

![Flowchart for calculate the simulation with Finite Element Method (FEM)](image_url)

Figure1. Flowchart for calculate the simulation with Finite Element Method (FEM)
b. The Description Simulation Model of Natural Circulation Liquid Sodium

The first step of this research was carried out by comparing the simulation results which had a 50 x 50 (cm) model with the results of the experiments by Habibie (2013) [10], [11] and discussed in another paper. The simulation model in this study is shown in Figure 2, with 2-dimensional shape of the model size of 150 x 200 (cm) and placed in the measurement points of temperature and fluid flow velocity. The used fluid is sodium (Na) with the physical properties of the fluid presented in table 1.

| Name          | Sodium (Na) |
|---------------|-------------|
| Melting Point | 97.80°C     |
| Boiling Point | 883°C       |
| Density       | 0.7 g/cm³   |

The built simulation will describe 3 conditions in the natural circulation system, those are[13]:

- Steady state: Constant liquid sodium temperature with heater input \( W = 0.02 \) kg/s.
- Transient I: Heater transformation from 1200 W to 1500 W.
- Transient II: Heater transformation from 1500 W to 1600 W.

For the temperature on the cooler wall (cooler) is set 100°C, the initial condition of the steady state system has a temperature of 25°C, with a flow rate of 0.02 kg/s. The initial inputted pressure in the simulation system is 1 atm.

Figure 2. Simulation model schema of natural liquid sodium circulation and temperature measurement points (5,6,7,8) velocity (1,2,3,4)

After determining the initial conditions and boundary conditions, then meshing. Meshing is dividing the geometry of the system into smaller sizes. After meshing, the system geometry will be shaped as shown in Figure 3.

Figure 3. The geometry of the circulation system after meshing
3. Result and Discussion
Simulation natural circulation study for liquid sodium:
In this study, the simulation of the natural circulation system has initial condition with the presented profile in table 2

Table 2. Simulation Profile of the Study of Natural Circulation Liquid Sodium

| Model | 1.5 x 2 (m) |
|-------|-------------|
| Heat source | 1200 W |
| Cooling Temperature | 100 [°C] |
| The initial temperature system | 25 [°C] |
| Input | 0.02 kg/s |
| v_in | 10 [cm/s] |

a. Simulation steady state condition
Simulation results from the presented input in table 2, can be seen in figures 4 and 5 for the temperature profile, figure 6 and 7 for fluid flow velocity profile in the natural circulation for steady state of sodium liquid, and Figure 8 for pressure distribution in the system.

![Temperature Distribution](image)

Figure 4. Temperature distribution in the simulation when steady state (a) at second 0 s (b) at second 500 s (c) at second 1000 s (d) at second to 2000 s

In figure 4 (b), showing the simulation condition when it runs until the 500th second, the temperature condition of the heater output rises, it is influenced by the temperature conditions on the heater. After passing the 500 second, the output from the cooler temperature profile starts to follow the cooler, which is around 100°C. as time goes by, the output from the cooler to the heater input starts to become
similar, around 125°C. This condition shows the increasing temperature in the overall system. Therefore the system temperature ranges from 125°C around the cooler, to 390°C around the heating area.

![Diagram](image1)

**Figure 5.** (a) The position of temperature measurement points (5,6,7,8) (b) Graph of temperature when simulating natural circulation in the steady state condition

From figure 5 we can see that the temperature increase is faster when compared to experiments conducted by A.K. Srivastava, et al in 2014[13]. This happens because the difference in fluid used, in this simulation, only uses 1 fluid so that the density value affects the fluid movement in the system. In addition, when simulating the system is in a very ideal state so that there is no technical interference from the environment or other systems (such as measurement).

![Diagram](image2)

**Figure 6.** (a) Position of velocity measurement points for fluid flow (1,2,3,4) (b) Graph of fluid flow velocity when simulating natural circulation in the steady state

In this study, the initial fluid velocity was 15 [cm/s], when the initial operation of the system showed instability up to 500 seconds, it was affected by the system as the temperature increased. After the temperature conditions have stabilized, the speed value also shows a stable number which ranges from 15 to 37 [cm/s].
Figure 7 The Distribution of fluid flow on natural circulation simulation of sodium liquid when steady state condition (a) at 0s (b) at 500s (c) at 1000s (d) at 2000s

From Figure 7 it is known that the flow speed near the heater is higher than the flow speed in a system with a relatively low temperature (125°C). This shows that the temperature affects the speed of the flow rate in the system. For the pressure distribution profile, the pressure at the beginning of the simulation condition is 1 [atm]. During the simulation, there is no significant influence on the value of the system pressure, still in the range of 1 [atm].

Figure 8 The distribution pressure on natural circulation simulation of sodium liquid when steady state condition (a) at 0s (b) at 1000s

b. Simulation of Transient I (1500 W)
In this study, a transient I simulation by adding power to the heater is carried out, around 3000 W. So that the heating power becomes 1500 W. Measurements in the simulation are only carried out on the
temperature profile, because the characteristics of the fluid flow velocity in the system and the pressure have the same as in the simulation on steady state. So, transient I here mean change the temperature profile when there is an increase in power in the heater from its normal operation. Figure 9 shows a graph of the temperature distribution in transient study I (1500 W).

![Graph of Temperature (Transient I)](image)

**Figure 9** Graph of temperature change during transient I (1200-1500 W)

In the transient I condition, a significant change occurred in the output heater which increased to 470°C and then stabilized at 455°C. Whereas for the input heater, there was only a slight increase until the temperature stabilized at 140°C.

c. Simulation of Transient II (1600W)

In this study, the power is increased from 100W to 1600W. Changes in temperature can be seen in Figure 10.

![Graph of Temperature (Transient II)](image)

**Figure 10**. Graph of temperature change during transient II (1500-1600 W)

In transient II, the temperature rise in the heater output is not too significant. From the data obtained, the maximum temperature is 497 °C and stable at that value, and the temperature at the input heater has a maximum value of 150 °C and then stable at 143 °C. In the next graph, Figure 11 shows the relationship between changes in power and temperature changes in the heater input and output.
Figure 11. Graph relationship between temperature and heating power of the heater

On the graph, it can be seen that the higher the heating power value will increase the temperature value. This, in line with several experiments that have been conducted by (A.K.Srivastava, 2014) and (S.S.P. Wahnon, 2018). The difference lies in the increase in the temperature of the system, which is caused by differences in the type of fluid used. In addition, in experiments the maximum threshold value of temperature rise is also limited due to the limitations of the material and measuring devices used.

4. Conclusion
Natural system simulation of liquid sodium circulation using the Finite Element Method has also been carried out to determine the characteristics of temperature during steady and transient conditions by calculating many conditions, namely:
1. Steady state, with a 1200W heater input power the temperature rise reaches 390°C around the heater output and 120°C around the heater input
2. Transient condition I, the heating power input rises from 1200 W to 1500 W, which results in an increase in temperature values both around the heater input and around the heater output. Each worth 138°C and 455°C
3. Transient condition II, the heating power input rises from 1500W to 1600 W with the result that the temperature around the heater input becomes 142°C and the temperature around the heater output has a value of 497°C

The results of natural liquid sodium circulation studies during transient I and II conditions indicate that the increase in heating power in the natural circulation system is still within safe limits. The system is still in a stable condition, such as when the steady state distinguishes only the temperature value that increases with temperature.

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