

Experimental Study of Natural Circulation Based on Thermal Effect during Steady-State Condition

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Abstract. *Natural circulation flow can passively transfer heat from the heat source to the heat sink without a pump mechanism. For this reason, this system can implement in many thermal engineering applications, such as nuclear power plants. Passive safety systems are one of the alternatives to reactor safety systems. The advantages of this system include simplicity and no need for external power. This study aims to determine the characteristics of temperature difference in the loop, flow velocity, and non-dimensional number correlation. The experimental method is the most relevant method to understand the passive cooling system; then, the results of this study will be compared with theoretical models and research results from previous researchers. The results showed that the higher the T_{HTS} , the more extensive the Reynolds number range. The same pattern also occurs in the Grashof number. In this experiment, the range values for the Reynolds and Grashof numbers were $990 < Re < 2114$ and $1.67 \times 10^{11} < Gr < 1.22 \times 10^{12}$.*

Keywords: *flow velocity, grashof numbers, natural circulation, Reynolds number, passive safety*

1. Introduction

Natural circulation flow can passively transfer heat from the heat source to the heat sink without requiring a pump mechanism. For this reason, this system can implement in many thermal engineering applications, such as nuclear power plants. Passive safety systems are one alternative to reactor safety systems. The advantages of this system include simplicity and no need for external power. Therefore, passive safety systems are increasingly recognized as an essential component in the latest nuclear reactors (Chang et al., 2000; Park et al., 2017; Juarsa et al., 2018). However, its reliability must be more guaranteed than that of other thermal management systems. So, research based on temperature and geometry changes must be carried out to improve the performance and efficiency of passive cooling systems. Research on the Single-Phase Natural Circulation Loop (SPNCL) phenomenon has been widely conducted. Vijayan et al. proposed a non-dimensional correlation between the Reynolds number (Re) and the Gr_m/N_G parameter on the behavior of SPNCL at steady-state conditions (Vijayan & Date 1992). Swapnalee and Vijayan proposed a general flow equation in SPNCL for stability maps that include all three flows, laminar, transition, and turbulent, and conditions where a single friction law does not apply throughout the loop (Swapnalee & Vijayan, 2011). Misale et al. (2007, 2016) studied the thermohydraulic performance of NCL at constant power and variable temperature. Wu et al. (2017) studied the performance of local and friction resistance, the

relationship between natural circulation mass flow rate and heating power, and the heating section's temperature increase. The analysis results stated that the Re number and the ratio of the local resistance loss coefficient and the friction resistance coefficient R_n would decrease with increasing R_n .

Then other studies using computer software-based simulations related to natural circulation phenomena, both for single-phase and two-phase flows, were also carried out, one of which was by Wang et al. and Angelo et al., who focused on investigating the characteristics of flow and heat transfer in rectangular loops using the CFD investigation method. Their research compared experimental data with CFD investigation, and the results showed that the method could be applied to the simulation of natural circulation mechanisms (Wang et al., 2013; Angelo et al., 2012). Antariksawan et al. (2019) conducted experiments on two different heat source powers. The experimental results were analyzed using existing correlations and numerical model simulations. The RELAP5 system code was applied to model natural circulation. The analysis shows the formation of stable natural circulation at all heat power inputs, and calculations using existing correlations show that the experimental Re numbers are lower than those predicted by correlations.

Based on the description above, experimental-based research is the most relevant method to understand passive cooling systems. Several countries have large-scale experimental facilities to study and develop passive cooling systems based on natural circulation (Kim et al., 2014; Kapulla et al., 2018). On the other hand, to study more relevant passive cooling systems based on natural circulation flow, an experimental study was conducted using a medium-scale experimental facility called FASSIP-03 NT loop designed to simulate passive cooling systems. This study aims to determine the characteristics of temperature difference in the loop, flow velocity, and non-dimensional number correlation. The results of this study will be compared with the theoretical model (Vijayan 2002). Moreover, the results of previous researchers proposed a rectangular loop (Swapnalee & Vijayan, 2011; Wang et al., 2013).

2. Method

Experimental apparatus

The FASSIP-03 NT loop used in this study consists of a heating tank section (HTS), a cooling tank section (CTS), and a loop piping system. The loop piping system has copper helical tubes in the HTS and CTS. A sketch of the experimental apparatus is shown in Fig. 1. The geometrical dimensions of the FASSIP-03 NT loop are shown in Fig. 2. The dimensions of each component of the FASSIP-03 NT loop are shown explicitly in Table 1. Where D represents the diameter of the loop, H is the height difference between the HTS and CTS, and L is the total length of the loop. The HTS is installed on a vertical pipe at the bottom of the loop, acting as a heat source. The CTS is installed on a vertical pipe at the top of the loop, acting as a coolant. An expansion tank is installed at the top of the loop to release pressure when the working fluid is heated and ensure no air is trapped.

Table 1. Geometrical dimensions of FASSIP 03 NT.

Item	Geometry	Size/Material
Cooling tank section	Square	1 m x 2 m x 1.5 m (stainless steel 304, $t=5$ mm)
Heating tank section	Cylinder	Dia. 16inch, Sch.40, $h=800$ mm (stainless steel 304)
Pipe	Cylinder	Dia. 1 inch, Sch.40 (stainless steel 304)
Transparent pipe	Cylinder	Dia. 1 inch (Pyrex)

Item	Geometry	Size/Material
The helical tube inside HTS	Cylinder	Outside Dia. 20 mm, t=3 mm, (Cooper)
The helical tube inside the CTS	Cylinder	Outside Dia. 20 mm, t=3 mm, (Cooper)
Expansion tank	Cylinder	Transparent pipe (Dia. 6 inch) with open valve
Heater	-	Length= 30 cm, P=2 kW @ 4 pcs
Height differences (H)	-	3050 mm
Total loop length (L)	-	21000 mm
Total loss coef. (K)	-	10

The loop is equipped with seven K-type thermocouples located in the middle of the pipe, with a diameter of 6 mm and an accuracy of ± 1.5 °C (see Fig. 1). Eight thermocouples are installed on the CTS, marked as T1-CTS to T8-CTS. Three thermocouples are placed on the HTS, also marked as T1-HTS, T2-HTS, and T3-HTS from bottom to top. Experimental data in temperature and natural circulation flow rate are obtained and stored by a high-speed data acquisition system (National Instruments) at an interval of 1 data per second. An electromagnetic flow meter measures the natural circulation flow rate in the loop. The electromagnetic flow meter used has an uncertainty of $\pm 5\%$. This study selected water, HTS, and CTS as the working fluid in the loop. The thermophysical properties of water are shown in Table 2 (Allen Crabtree 1993).

Table 2. The thermo-physical properties of water (Allen Crabtree 1993)

Fluid	temperature	ρ (kg/m ³)	μ (kg/m.s)	C_p (J/kg.K)	β (1/K)
Water	25 °C	996.4975850	0.000892016	4177.794529	0.000254694
	30 °C	994.9112815	0.000797990	4177.857974	0.000301293
	35 °C	993.1958025	0.000718980	4178.242811	0.000344449
	40 °C	991.3511479	0.000651970	4178.958797	0.000384415
	45 °C	989.3773178	0.000594655	4180.016317	0.000421442
	50 °C	987.2743121	0.000545253	4181.426429	0.000455781
	55 °C	985.0421308	0.000502367	4183.200915	0.000487685

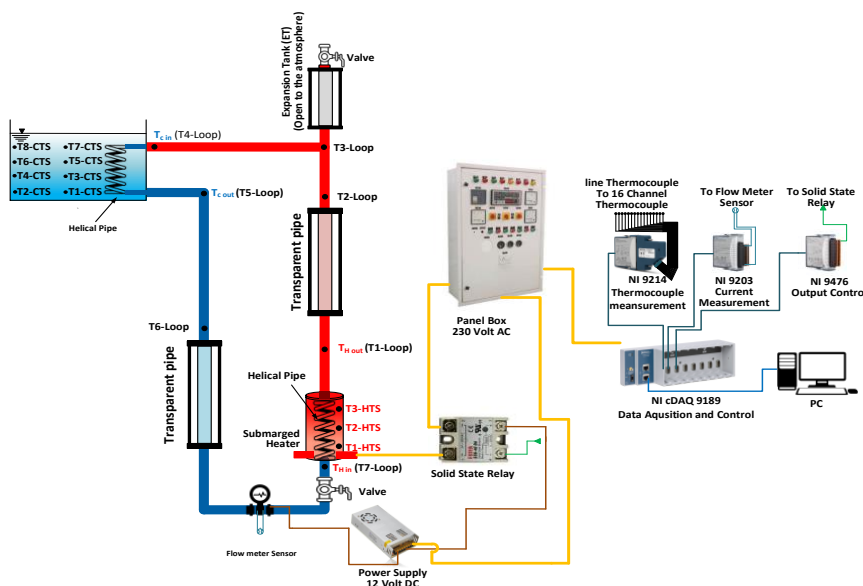


Figure 1. Experimental apparatus

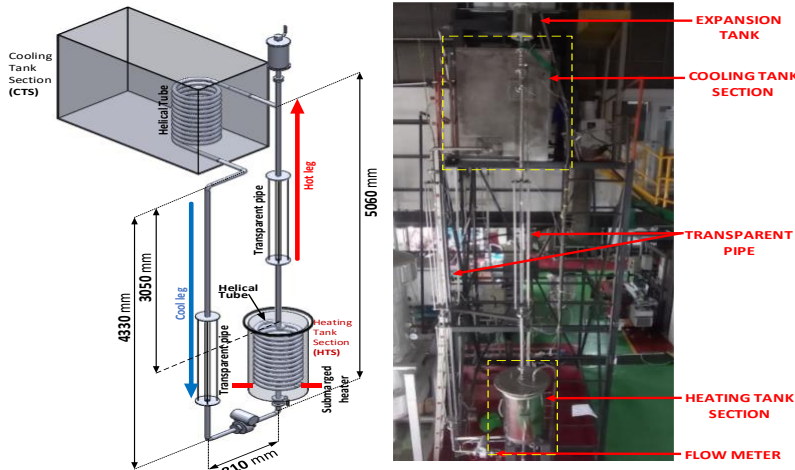


Figure 2. Geometrical dimensions and a picture of the FASSIP 03 NT Loop

Experimental Procedure

The heating fluid temperature (T_{HTS}) is an experimental variable used in this study. T_{HTS} varies from 40°C, 45°C, 50°C and 55°C. The T_{HTS} value is also used as a reference to send a command signal through the Ni-9476 module (heating control) by turning on and off the solid state relay (SSR). When T_{HTS} exceeds the set-point, the SSR will turn off the heater, while if T_{HTS} is less than the set-point temperature, the SSR will turn on the heater. This condition is maintained during steady-state conditions to keep T_{HTS} constant. The experiment was carried out with the initial condition of the cooling fluid temperature (T_{CTS}) in the CTS, namely 26.5 °C - 26.65 °C. Each experiment started from a stationary condition with a room temperature ranging from 27 °C - 30 °C, while the initial temperature of the fluid in the loop followed the room temperature. Before starting each experiment, T_{CTS} was adjusted with an external cooler and measured repeatedly. After achieving the desired condition, the external cooler is off, and the cooling fluid in the CTS is natural without any external intervention. In addition, the fluid volume in the loop, HTS, and CTS are at a fixed value for each experiment. Each process begins by turning on the data acquisition system and heating the power supply. Meanwhile, the operation is carried out following the sequential changes in the T_{HTS} settings, namely 8216 seconds, 8695 seconds, 9217 seconds, and 9766 seconds, until the heating power supply and data acquisition system are off.

Analytical Methods

The Re number is calculated by entering the flow rate parameters, loop diameter, and thermal properties of water into equation (1):

$$Re = \frac{\dot{m}D}{\mu A} \quad (1)$$

If the Re number is less than 2400, the fluid flow in the loop is laminar, and if the Re number is more significant than 4000, the fluid flow is considered turbulent. Then, if the Re number is between 2400 and 4000, the fluid flow is transitional.

The Grashof number (Gr) is the ratio of the buoyancy force to the viscosity force in a natural circulation flow. Mathematically, the Gr number is expressed as follows (Cheng et al. 2019).

$$Gr = \frac{\rho_0^2 \beta g \Delta T D^2 H}{\mu^2} \quad (2)$$

Based on the governing equations (continuity, momentum, and energy) in the loop and assuming a steady state condition described by (Vijayan 2002). Provides a solution to the system of equations in the form of non-dimensional number correlations (Vijayan and Austregesilo 1994).

$$Re = C \left(\frac{Gr}{N_G} \right)^r \quad (3)$$

Where

$$N_G = \frac{L_t}{D} + \frac{k}{f} \quad (4)$$

the friction factor (f) in the laminar flow region can be expressed

$$f = \frac{64}{Re} \quad (5)$$

3. Results and Discussions

Temperature is a critical parameter affecting the characteristics of natural circulation flow. The temperature characteristics discussed in this paragraph show the transient behaviors of local temperatures at $T_{H, out}$ in the loop against time with variations, the temperature of T_{HTS} is 40 °C, 45 °C, 50 °C, and 55 °C. Fig. 3 shows that the working fluid heated through the HTS can move naturally (without external force intervention). The condition of T_{HTS} at 40 °C, as shown in Fig. 3, shows that it takes 1016 seconds to reach a steady state, with $T_{H, out}$ of 38.77 °C. Of the four cases, the maximum temperature of the working fluid in the loop is around 51.1°C at $T_{H, out}$ when T_{HTS} is 55°C. This condition proves that the use of a helical tube in the FASSIP 03 NT loop is quite effective because it can reduce thermal resistance in the FASSIP 03 NT loop, which causes a relatively small temperature difference of around 3.07% to 7.1% between the working fluid in the loop and the heating fluid.

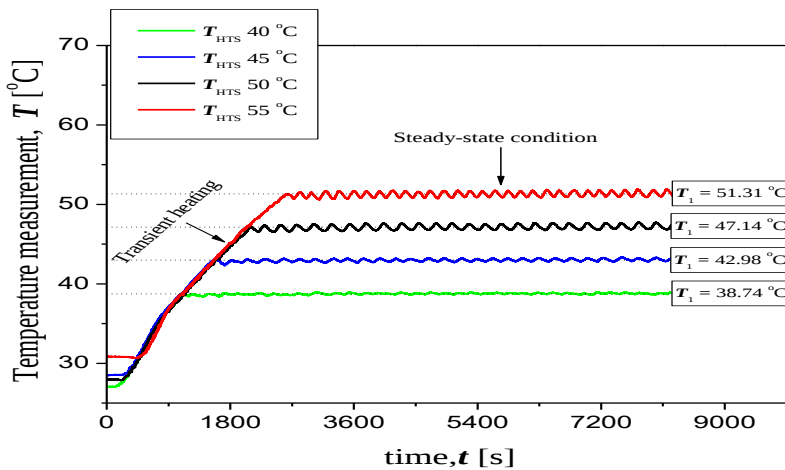


Figure 3. Temperature histories at point $T_{H, out}$ in the loop under T_{HTS} variations

Natural circulation flow is caused by buoyancy force, which is a function of temperature difference (ΔT), which is the difference between the temperature of the working fluid output from HTS ($T_{H, out}$) and the temperature of the working fluid output from CTS ($T_{C, out}$). Therefore, ΔT is one of the indicators of the formation of natural circulation flow. Fig. 4 shows the characteristics of ΔT in transient and steady-state conditions for each variation of T_{HTS} . In general, it can be seen that when T_{HTS} is

increased, ΔT will increase. Specifically, ΔT at T_{HTS} is 55 °C and has a more significant oscillation when compared to ΔT at T_{HTS} , which is 40 °C. Meanwhile, at steady-state conditions, ΔT tends to be constant. This condition indicates that heat is being removed from HTS to CTS or reduced temperatures in the system. The experimental results show that the minimum ΔT is 9.05 °C (T_{HTS} is 40 °C) while the maximum ΔT is 16.01 °C (T_{HTS} is 55 °C).

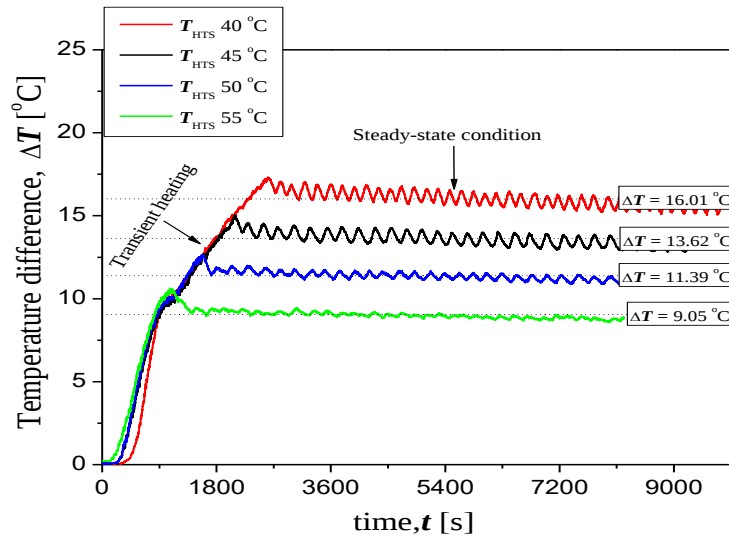


Figure 4. Temperature difference in the loop under T_{HTS} variations

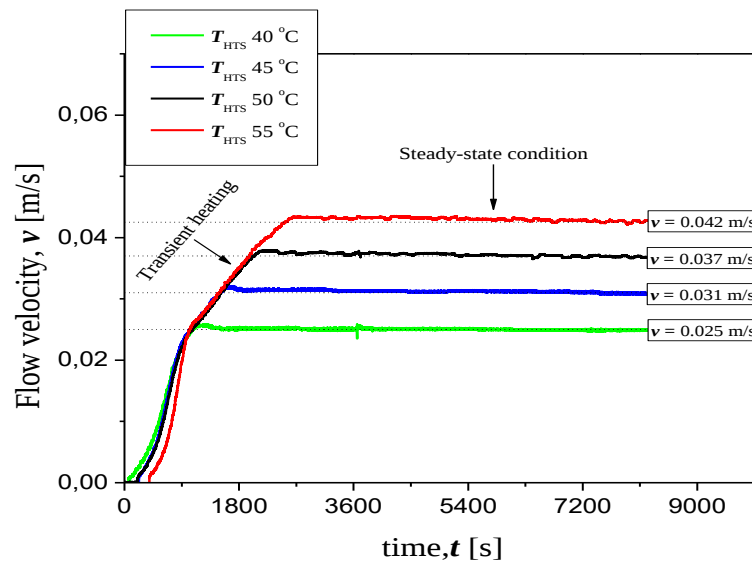


Figure 5. Flow velocity with T_{HTS} variations

Natural circulation flow velocity is a function of temperature changes and height differences. Natural circulation flow velocity is one of the critical parameters to determine the magnitude of the heat transfer rate. Based on Fig. 5, it can be seen that the natural circulation flow velocity constantly changes, fluctuating both in transient and steady-state conditions. This condition is because the natural circulation flow generated by the buoyancy force is susceptible to disturbances such as friction losses along the loop and ambient temperature. In addition, the thermal imbalance in the system is another cause of

irregular natural circulation flow. In steady-state conditions, the average flow velocity for each T_{HTS} variation is 40 °C, 45 °C, 50 °C, and 55 °C, respectively, namely 0.025 m/s, 0.031 m/s, 0.37 m/s, and 0.042 m/s. As shown in Fig. 4 and Fig. 5, the greater the T_{HTS} , the more significant the difference in temperature and flow velocity produced for both transient and steady-state conditions.

The experimental results on the FASSIP 03 NT loop with T_{HTS} variations show that the Re number value always increases along with the increase in T_{HTS} value. The Re number value ranges from 990 to 2114. The natural circulation flow produced is in the laminar regime ($Re < 2400$) for all T_{HTS} variations. Meanwhile, the maximum Gr number value is around 1.22×10^{12} when T_{HTS} is 55 °C, and the minimum Gr number value occurs at T_{HTS} of 40 °C, which is around 1.67×10^{11} . This condition shows that the heat transfer efficiency increases along with the increase in T_{HTS} . Fig. 6 illustrates the relationship between changes in the Re number value and the Gr/N_G parameter for each T_{HTS} variation.

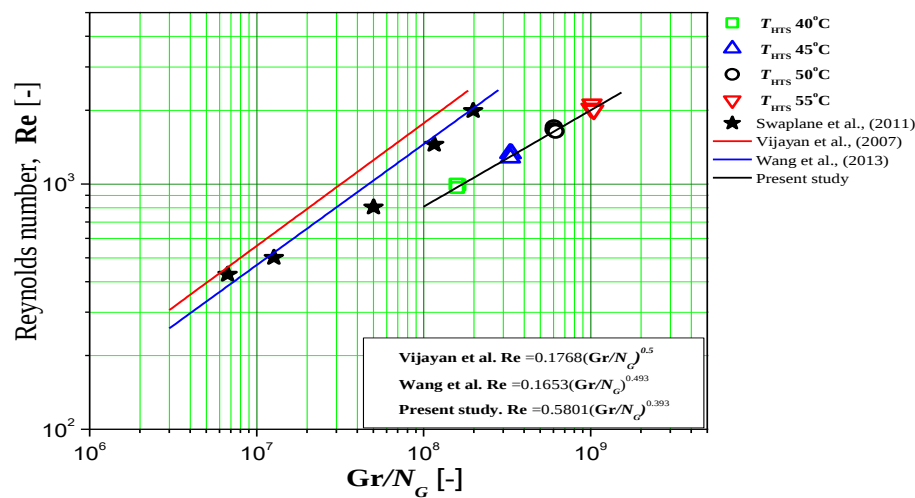


Figure 6. Comparison of Re numbers with Gr/N_G parameter

The results of this study lead to the development of an empirical correlation that connects the Re number and the Gr/N_G parameter. After obtaining the Re number and Gr/N_G parameter values, the relationship between the two can be expressed using correlation (3), where the constant values of C and r are determined based on the graph-fitting analysis of the experimental data. Based on the graph fitting analysis results, the constant value of C is 0.5801, and the constant value of r is 0.393. So, the correlation between the Re number and the Gr/N_G parameter can be expressed as follows;

$$Re = 0.5801 \left[\frac{Gr}{N_G} \right]^{0.393} \quad (5)$$

Fig. 6 shows the experimental results and correlation between Re number and Gr/N_G parameter, where triangle, circle, and square symbols are current experimental data, while star symbols are experimental data from (Swapnalee and Vijayan 2011). The black line is the correlation obtained from the study results, while the red line is the correlation built by Vijayan, and the blue line is the CFD simulation result from Wang, which is used as a comparison. (Wang et al. 2013), (Vijayan 2002). Based on Fig. 6 shows that the value produced from this study is the highest compared to other researchers. This condition is due to the difference in the geometric ratio (N_G), where the facilities used in this study are more significant than those used by Vijayan. However, the type of natural circulation flow produced is in the same laminar regime.

4. Conclusions

The study results concluded that the maximum temperature differences and flow velocities of 16.01 °C and 0.042 m/s occurred at a T_{HTS} of 55 °C. This condition indicates an increase in flow velocity and heat transfer capability because the buoyancy force produced is greater when T_{HTS} is increased, resulting in increased flow velocity and heat transfer through natural circulation flow becoming more efficient. Meanwhile, the non-dimensional number analysis results, namely the correlation between the Re number and the Gr/N_G parameter caused by variations in T_{HTS} , show that the higher the T_{HTS} , the greater the range of Re numbers. The same pattern also occurs at the Gr number. In this experiment, the range values for Re and Gr numbers are $990 < Re < 2114$ and $1.67 \times 10^{11} < Gr < 1.22 \times 10^{12}$. Then, based on the correlation between Re numbers and Gr/N_G parameters, the constant C value is 0.5801, and the constant r value is 0.393.

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