Natural Circulation Flow Rate Comparison Using Water and Al2O3 as Working Fluids Based on Power Control in Medium-Scale Passive Cooling Experimental Facility

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Abstract. The use of natural circulation as a passive cooling safety system in reactors has been applied by nuclear power plants around the world, including the AP1000 reactor from Westinghouse and SMART from KAERI with a passive cooling system, namely, Passive Residual Heat Removal System (PRHRS) to prevent overpressure from overheating in the reactor cooling system during an accident. The type of working fluid used affects the natural circulation flow rate. This research compared the mass flow rate of natural circulation based on water and Al2O3-nanofluid working fluids to changes in heater power used for steady-state conditions. The experiment was conducted by varying heater power in the heating tank from 1400 W, 2800 W, and 4200 W. Data collection was carried out experimentally and analyzed calculations to obtain the mass flow rate value in water and nanofluids as working fluids that will be used. The results indicate that using nanofluids can increase the value of the mass flow rate compared to ordinary water because there is a difference in density values that affect the mass flow rate. Where the high mass flow rate value is at 4200 powers with a value of Al2O3-nanofluids mass flow rate is 0.0456 kg/s and water mass flow rate is 0.0454kg/s.

Keywords: natural circulation, mass flow rate, nanofluids, power, Al2O3, passive cooling

1 Introduction

The use of natural circulation as a passive cooling safety system in reactors has been applied by nuclear power plants in the world, including the AP1000 reactor from Westinghouse using the PRHR system. [1]. The Korea Atomic Energy Research Institute (KAERI) also developed a reactor called SMART equipped with a passive cooling system, the Passive Residual Heat Removal System (PRHRS), to prevent overpressure from overheating the reactor cooling system during an accident [2]. Natural circulation flow occurs due to differences in the density of the working fluid in the heating and cooling sections. The heated fluid will absorb heat from the heater so that the fluid decreases in density and causes buoyancy. So that the fluid that has been heated will be cooled again by the cooler so that it experiences an increase in density and causes gravity to occur [3]–[5].

Research related to natural circulation has been carried out both experimentally and in simulation has been done by many researchers, including Greif 1988 [6] and Vijayan 1992 [7] until now, both in single-phase and two-phase conditions with open and closed loops [8]–[12]. Vijayan 2002 [13] researched phenomena that occur in single-phase and two-phase flow in steady and transient conditions against the influence of pressure on the rectangular loop so that it can determine the effect of geometry size on flow instability in the loop. Research related to changing boundary conditions by changing geometry has been done, such as the position of heat sources and coolers and the slope's size in the pipe, for initial conditions has been conducted by changes in power, and the type of cooling fluid to determine the increase in natural circulation flow rate in a closed loop [14]–[16].

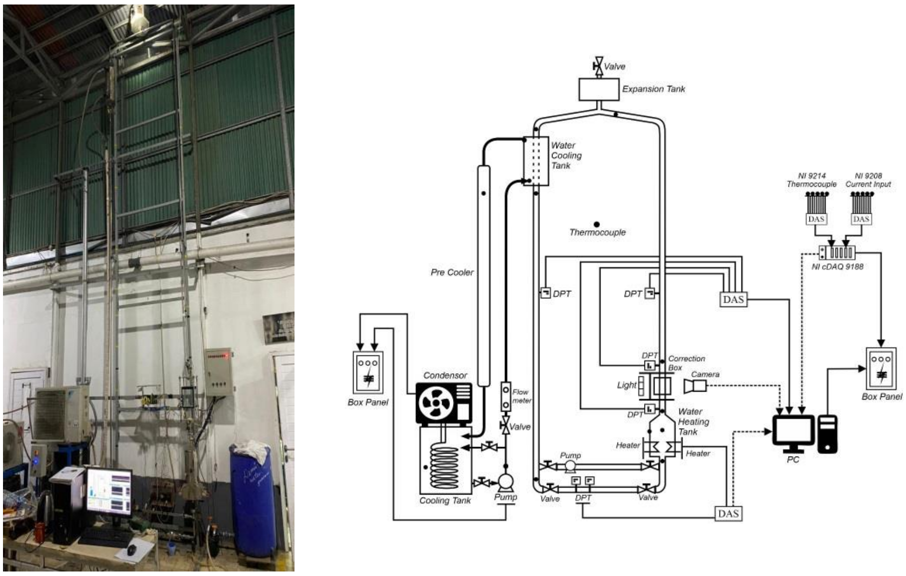
Experiments aimed at improving heat transfer by using nanofluids as the working fluid and increasing the natural circulation flow rate have been conducted with variations in the type of nanoparticles used and the volume fraction ratio between the base fluid and the nanoparticles used [17], [18]. Nanofluids technology is also widely used in heat exchanger equipment, mainly aiming to improve heat transfer capability, reduce heat exchanger volume, and save energy [19]. The tremendous potential of nanofluids makes nanofluids used for a broader range of applications, including pharmaceuticals, water treatment medicine, oil recovery soil decontamination, and CO2 geosequestration [20]. By changing the heater power, the experiment focuses on the temperature characteristics and mass flow rate between the base fluid and Al2O3 nanofluid at a steady state.

2. Methodology

2.1. Setup Experimental

The research was carried out experimentally and analyzed calculations using the tool (Passive System Simulation Facility-04 Version.2) FASSIP-04 Ver.02, which can be seen in Figure 1. FASSIP-01 Ver.2 is a medium-scale experimental facility used to investigate flow rate phenomena in rectangular loops. The experimental tool can be categorized into two parts. The primary part consists of a heating tank (HT) as a heat source. The cooling tank (CT) functions as a heat release and an expansion tank to maintain pressure so that it is always in one atmospheric condition. While the secondary part, consisting of a cooling bath (CTB), accommodates water that will be distributed to the cooling tank (CT) in the primary section using a pump, the condenser works to cool the water in the cooling tank. The pre-cooler works to remove residual heat in the cooling tank before entering the cooling tank.

The measurement system used for temperature readings uses a type K thermocouple sensor. In contrast, the tool for reading the value of the flow rate that occurs uses a magnetic flowmeter sensor. The reading results are processed by changing the voltage and current read by the sensor using the NI 9214 and NI 9203 modules attached to the CDAQ 9188. Then, the data is displayed in the form of numbers on a personal computer using a monitoring application.



(a) (b)

Fig. 1. (a) Experimental equipment FASSIP-02 Ver.2 (b) Instrument scheme of experimental facility FASSIP-02 Ver.2.

The following is the geometry data of the FASSIP-04 Ver.2 experimental tool can be seen in Table 1.

Table1. Data sheet of FASSIP-04 Ver.2 ractangular-TP loop

Tool Description	Value	Unit
Loop height	6000	mm

Loop width	1320	mm
Outside diameter	25,4	mm
Inside diameter	22,4	mm
Total loop length	14640	mm
Volume of working fluid in the loop	20	liter
Heater power	10	kW
Refrigeration power	2	kW

The data collection matrix this time focuses on the cooling tank (TC) by varying the power in the heating tank (TH) by 1400 W, 2800 W, and 4200W and setting the temperature at (CTB) 10oC. For the fluid used, demineralized water is then modeled by adding property data for Al2O3 nanofluids as much as 0.1%. The experimental data used for this discussion are TC IN, TC OUT, and flow rate measure data.

2.2 Analysis

The density of water is affected by several factors, including temperature, pressure, and humidity. Generally, the higher the water temperature, the lower the density. Similarly, the higher the air pressure, the higher the density value, the calculation of density as a function of temperature to find the mass flow rate value using equation 1.

$$\rho = \left(1004.78904 + (-0.046283 \times T_F) + (-7.9738 \times 10^{-4} \times T_F^2)\right) \quad (1)$$

Where

T_F : $(1.8 \times T) + 32$

With density of water is ρ (kg/m^{3}and temperature measured data is T_F (^{o}C). Then calculate the nanofluid density value to be correlated [21] in predicting the results of the mass flow rate value in the Al_2O_3-Nanofluids fluid using equation (2).

$$\rho_{\mathrm{nf}} = (1 + \varphi)\rho_{\mathrm{bf}} + \varphi\rho_{\mathrm{np}} \quad (2)$$

With the density of nanofluids is ρ_{nf} (kg/m^3), volume concentration is φ (%), and the density of based fluids (water) is ρ_{bf} (kg/m^3).

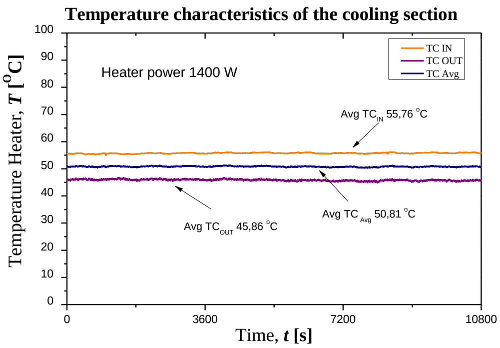
Furthermore, the flow rate measured on the FASSIP-04 Ver.1 rectangular loop can be known by the flowmeter (Q) obtained from the conversion of the flow rate per minute (LPM) into m^3/s units. So that the mass flow rate ($\dot{m}$) can be calculated using equation (3).

$$\dot{\mathrm{m}} = Q \; x \; \rho \quad (3)$$

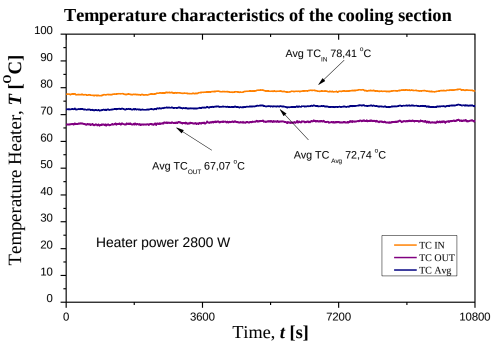
With mass flow rate is $\dot{\mathrm{m}}$ (kg/s), volumetric of water flowing through the channel per unit time is Q (m^3/s) and the density of working fluids (water/nanofluids) is ρ (kg/m^3).

3 Result and Discussion

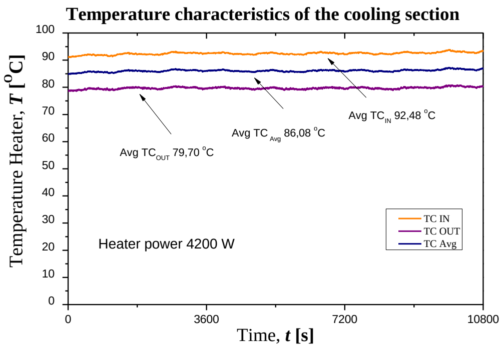
Based on Fig. 1 the data obtained is the result of thermocouple sensor readings on TC IN and TC OUT and flowmeter. Data retrieval is carried out during steady state for 10800 seconds with power changes of 1400 W, 2800 W, and 4200 W. As for setting the temperature at CTB in a constant state of 10^{o}C.



(a)



(b)



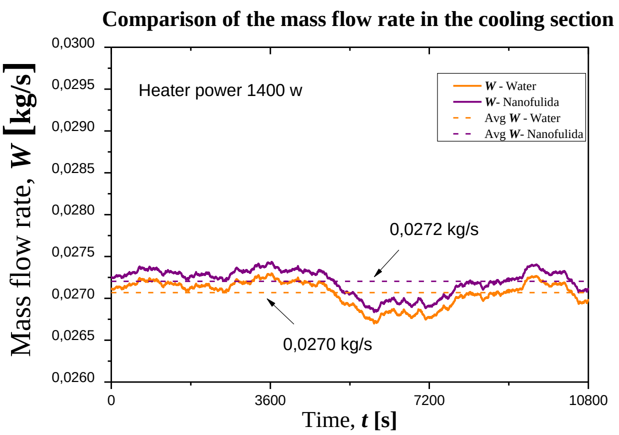
(c)

Fig. 2. Temperature characteristics of the cooling section with heater power of 4200 watts.

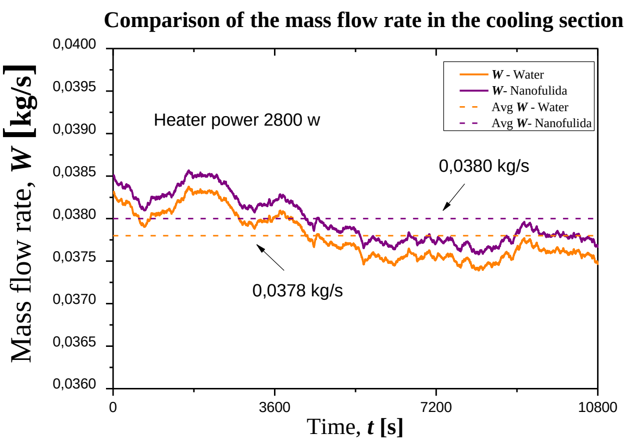
The temperature characteristic data obtained is used to analyze the mass flow rate that occurs in the cooling section. The data on temperature characteristics for each change in heating power can be seen in Fig.2.

Fig.2 (a) shows the average temperature characteristics of TC water against the heater power of 1400 W with a data collection time of 10800 seconds at steady state experiencing fluctuations. The conditions happen because the fluid carries heat from the heat source and is cooled by the cooling tank, so there is a heat release process in the loop. The average temperature value through a cooling tank is 50.81°C, with an incoming temperature of TC IN is 55.76°C and an outgoing temperature of TC OUT is 45.86°C. So, the heat that can be absorbed by the pending tank in the loop is 9.90°C. Fig.2 (b) shows that the temperature characteristics in the TC have increased due to the power used to heat the fluid in the heater tank by 2800 W, so the fluid in the loop has increased in temperature. Therefore, the average temperature through the cooling tank is 72.74°C, with an incoming temperature of TC IN is 78.41°C and an outgoing temperature of TC OUT is 67.07°C. The temperature release in the loop after going through the cooling tank is 11.32°C. Fig.2 (c) experiences the same increase in temperature characteristics as the previous graph data. However, at a power change of 4800 W of working fluid in the loop, tiny bubbles are formed due to the heating process in the heating tank. So, the average temperature through the cooling tank (TC Avg) is 86.08°C, with an incoming temperature of TC IN 92.46oC and an outgoing temperature of TC OUT is 79.70°C. The temperature release in the loop after going through the cooling tank is 11.32°C.

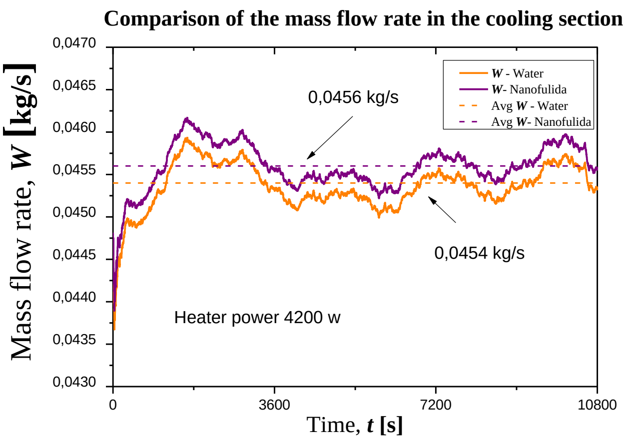
The results of the temperature characteristics obtained can be used as a source of data to be analyzed to find the value of the mass flow rate of the water base fluid with the value of the mass flow rate modified using nanofluid properties in the calculation. Data on the mass flow rate using the basic fluid of water with the primary fluid modified by nanofluid property can be seen in Fig 3.


Comparison of the mass flow rate in the cooling section
Heater power 1400 w
W - Water
W- Nanofulida
Avg W - Water
Avg W- Nanofulida
0,0272 kg/s
0,0270 kg/s
Mass flow rate, W [kg/s]
Time, t [s]
0,0300
0,0295
0,0290
0,0285
0,0280
0,0275
0,0270
0,0265
0,0260
0
3600
7200
10800

(a)


Comparison of the mass flow rate in the cooling section
Heater power 2800 w
W - Water
W- Nanofulida
Avg W - Water
Avg W- Nanofulida
0,0380 kg/s
0,0378 kg/s
Mass flow rate, W [kg/s]
Time, t [s]
0,0400
0,0395
0,0390
0,0385
0,0380
0,0375
0,0370
0,0365
0,0360
0
3600
7200
10800

(b)



(c)

Fig. 3. Comparison of mass flow rate of water base fluid with nanofluid modified fluid.

Based on Fig.3 (a), the data displayed in the graph results from thermocouple readings in the cooling tank and flowmeter. Then, the temperature data obtained is analyzed using equations (1) and (2) to obtain the density value. As for the flow rate data obtained using the flowmeter sensor, it is converted into the form of m3/s. The flow rate data is analyzed smoothly using analysis software with points of windows 1000 with polynomial order 2. The smooth results obtained are used to calculate the mass flow rate in the cooling tank using equation (3). Based on Fig.3 (a). The mass flow rate at a power of 1400 W shows a difference between the base fluid of water and the base fluid modified with nanofluids properties. The average mass flow rate value at 1400 W with water base fluid is 0.0270 kg/s, while the mass flow rate value with the base fluid modified with nanofluid properties is 0.0272 kg/s. Based on Fig.3 (b), the mass flow rate at 2800 W, the average mass flow rate value with water base fluid is 0.0378 kg/s, while the mass flow rate value with base fluid modified nanofluids properties is 0.0380 kg/s. Fig.3 (c) has in common with the previous one that there is a difference between the water base fluid and the base fluid modified with nanofluids properties. The magnitude of the mass flow rate at 4200 W of power, the average mass flow rate value with water base fluid is 0.0454 kg/s, while the mass flow rate value with the base fluid modified with nanofluids properties is 0.456 kg/s.

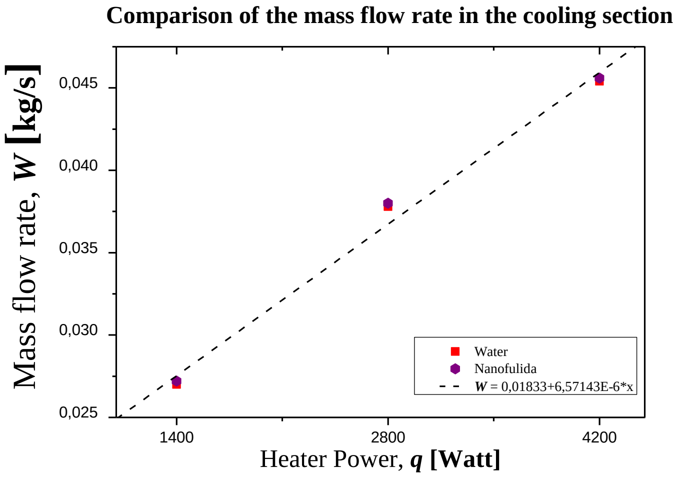


Fig. 4 Comparison of power to mass flow rate.

Fig.6 is a comparison of mass flow rate values with heater power variations of 1400 W to 2400 W. The graph above is analyzed using linear fitting analysis using software, the linear fitting correlation $y = a + b * x$ is obtained with a value of a is 0.01833 and a value of b is 657143x10^{-6}. Based on the fitting results, it can be stated that there is an increase in mass flow rate when there is a change in heater power. the greater the heater power, the greater the mass flow rate value in the fluid to be used.

4 Conclusion

Based on the results of this experiment, it shows that the value of the mass flow rate is influenced by the fluid properties used and the change in heater power given. The greater the heater power and fluid density used, the better the flow rate value. Where the high mass flow rate value is at 4200 powers with a value of Al2O3-nanofluids mass flow rate is 0.0456 kg/s and water mass flow rate are 0.0454kg/s.

5 Acknowledge

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