Preliminary Study on Mass Flow Rate in Passive Cooling Experimental Simulation During Transient Using NC-Queen Apparatus

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ABSTRACT

The research related to thermal management has been significantly inreased, especially for NPP safety. The use of passive cooling systems both during the accident and operation become reliable in the advanced reactor safety systems. Therefore it should be enhanced through experimental studies to investigate heat transfer phenomenon of the heat decay in transient cooling condition. An investigation has been performed through experiment using an NC-Queen apparatus constructed with rectangular loop. Piping were consisting of tubes of SS316L with diameter, length, and width of 3/4 inch, 2.7 m, and 0.5 m respectively. The height between heater and cooler was 1.4 m. The experiment used initial water temperature at 70°C, 80°C, and 90°C in heater area. Transient temperature was used as experimental data to calculate water mass flow rate. The results showed that the temperature in heater area and cooler area were decreasing of about 90.6% and 95.7% at initial temperatur of 80°C, and of about 71.1% and 59.4% at initial temperature of 70°C. Those results were at higher initial temperature of 90°C compared with the initial temperature of 90°C. The average of water mass flow rate increased 81.03% from initial temperatur of 70°C. It was shown that the averages of removed heat in every second from water due to heat loss and cooler, were 3.51 watts, 5.06 watts and 6.85 watts respectively. The initial condition of heat stored in the water was quite different, but to the cooler heat removal capacity and heat loss was almost the same.

INTRODUCTION

Thermal management in nuclear power plants (NPPs) is very important. Improperly managing this thermal issue can lead to serious accidents for example a Three Mile Island Unit 2 (TMI-2) accident for pressurized water reactor (PWR) in 1979[1] and a Fukushima Daiichi accident for boiling water reactor (BWR) on March 11, 2011[2]. Referring to Fukushima accident, the accident was initiated by the inavailability of the emergency cooling system due to loss of power to the pump failure. It was caused by station blackout and the power-backup system was damage due to tsunami. Since decay heat generated in the reactor core was not removed due to the pump failure, the heat in the core was accumulated. This condition leads to core melted and to the damage of the reactor pressure vessel (RPV), which causes radioactive material releases to the environment. This accident showed that thermal management failure can be a triger for a severe accident with loss of RPV integrity and requires more research and development in the scope of thermal-hydraulics and heat transfer for the safety of operating to the enhancement of future nuclear reactors. What we can learn from this accident is that thermal management failure could be avoided if Fukushima NPPs have a passive cooling system, which can work without pumps, to replace emergency cooling system to remove heat residual from the core. Therefore, understanding the passive system phenomenon, currently, becomes an appealing research topic in light water reactor (LWR).

A passive system is a concept of fluid circulation within loop without any external force or external intervention. This type of fluid circulation is known as natural circulation, which can happen due to the bouyancy force and gravitation force. These two forces are created by the density changes to the fluid in hot area and in cold area.

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For simplicity, natural circulation can be defined as the process of heat removal by the reactor cooling system without the need for a pump[3]. This passive heat removal mechanism can be implemented in both normal operation condition and in accident conditions[4]. Actually, before Fukushima Daiichi accident, the technology of reactor safety has been improved by introducing many innovations and realizing passive system to their safety features, such as AP1000 dan ESBWR[5]. Moreover, generation III+ nuclear reactor design, such as AP1000, have been equipped with passive safety system[6] as the result of the evolution in design development on nuclear safety technolgy[7]. The AP1000 is the first generation III+ NPP to obtain license from the United State – Nuclear Regulatory Commission (US – NRC) [8].

Many researchers have been investigating the phenomenon of natural circulation to be applied in a passive residual heat removals system (PRHRS). Welander has investigated bouyancy force, pressure drop and frictional force inside the pipe to understand the flow driving force [9]. Dobson has proposed a simple formulation schematic to show the non-linier behavior and transient inside the loop during natural circulatioan to describe laminar and single-phase condition[10]. However, flow instability has not been investigated yet. Furthermore, the stability and oscilation instability of flow inside natural circulation loop have also been studied through experimentation and computer simulation [11-13]. However, their boundary conditions have not been investigated as well. In addition, thermosypoon flows in common geometrical and their application have been done by K. Vijayan et al.[13], Grief[14] and Zvirin[15]. They conducted their researches on rectangular loop with open and closed loop. Investigation has been done for transient and steady state flow as well as the analysis on system stability based on heating and cooling variation. Misale[16] have considered the differences in thermal boundary condition, such as differences in the height of hot part and cold part for rectangular loop. The influence of conduction inside pipe has also been studied by a number of researchers[17-21]. It is an important parameter for mass flow rate during natural circulation to scale PWR and map PWR performance. However, all existing researches only investigated heat transfer phenomenon in steady state condition.

The objective of this study is to investigate thermal characteristic related to mass flow rate during transient cooling. The effect of water initial temperature in heater to mass flow rate inside rectangular loop during transient cooling simulation is analysed.

EXPERIMENTAL METHODS

Experimental apparatus

The experimental setup of the NC-Queen apparatus shown in Fig.1 consists of a rectangular loop (marked with 1) as the main object, computer (marked with 2) as the data recorder, NI-cDAQ 9188 (marked with 3) as the data acquisition system, expansion tank (marked with 4) as the pressure stability, refrigerator (marked with 5) as the cooler unit, heating-Queen (marked with 6) as the heat source and regulator voltage (marked with 7) as the power unit.

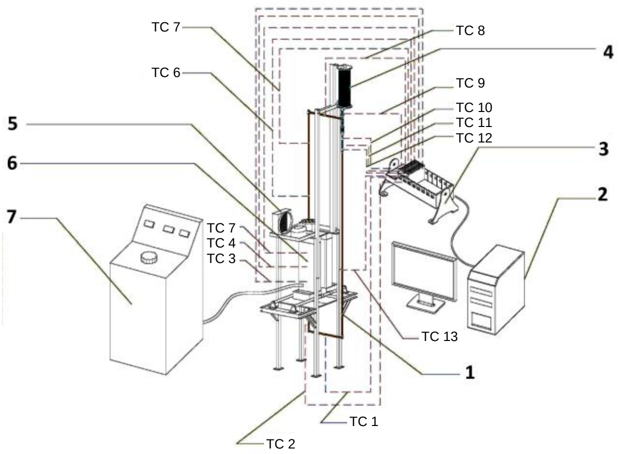

Fig. 1. Experimental Setup for NC-Queen Apparatus.

Meanwhile, Fig. 2 shows a rectangular loop whose function to be the main equipment of the passive system. It consists of a cooler with refrigerator whose power of 1/5 HP (149 watt) and cooling capability until -10^{o}C, a heater whose maximum power of 3000 watt and heating capability until 300^{o}C. A regulator voltage is used to control the heater power. The rectangular loop is formed of piping consisting 3/4 inch diameter tubes of SS316L with lenght 2.7 m and width 0.5 m. The height between cooler and heater is 1.4 m.

Mesurement was conducted using type K thermocouples, which are located in 13 different points along the rectangular loop and 1 point for measuring ambient temperature. The used thermocouples have been calibrated with average error for air measurement of 0.83% and for water measurement of 0.33%. All thermocouples are connected to the computer using NI-cDAQ 9188 to collect and record temperature history during experiment. Sampling rate during recording is set to be 1 sample/s. Transient temperature data used for calculation only from two measurement point. First measurement point is TC4 represented by water initial temperature in heater area (noted as

T_{Hi}), second measurement point is TC11 represented by water initial temperature in cooler area (noted as T_{Ci}).

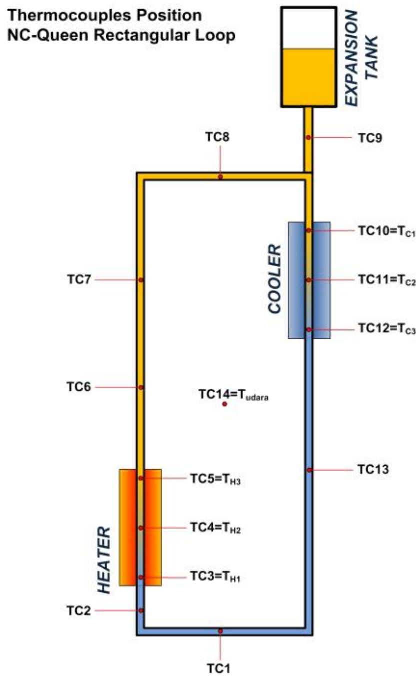

Fig. 2. Rectangular loop.

Experimental procedure

The condition scenario of the experiment is set to simulate decay heat in heater area. After simulation, the electrical heater is turned off and hence there is no heat added to the water from heater. Then, the cooling process is simulated to represent transient condition. The experiment matrix is shown in Table 1.

Table 1. Experiment matrix of NC-Queen apparatus

Parameter	Value	Condition
Height (***H***) between cooler-heater	1.4 m	given
Total lenght (***L***) of tube	6.4 m	given
Diameter tube (***D***)	0.0192 m or 3/4 inch	given
Initial temperature in heater ($\boldsymbol{T_{Hi}}$)	90°C, 80°C, 70°C	variabel

Experiment procedures are made in several stages. In the first stage, heater is turned on until the desired $\boldsymbol{T_{Hi}}$ of the heater has been reached. At this stage, the cooler is still off. After the expected $\boldsymbol{T_{Hi}}$ was reached, the heater is turned off and the cooler is then turned on. Temperature changes during this transient condition were recoreded until the intial water temperature before it got heated was reached.

Analysis

Outlet heater temperature ($\boldsymbol{T_{Hi}}$) data and cooler temperature ($\boldsymbol{T_{Ci}}$) data was used to define water density using the water physical properties formulation as shown in correlation(1).

$$\rho(T) = 1000.07 + 0.02093T - 0.00602T^2 + 0.0000162T^3 \quad (1)$$

Since the water density will follow temperature changes during transient cooling, the water density difference and average water density can be used to calculate average mass flow rate using correlation (2)[14,15] inside the rectangular loop during transient cooling. But, there is hydrodynamics resistancy and the paramater still related to the water density.

$$\dot{m}^2 = \frac{2gH\bar{\rho}_w(\rho_c - \rho_h)}{R} \quad (2)$$

where $\dot{m}$ (kg/s) is water mass flow rate, H (meter) is the height difference between heater and cooler, ρ (kg/m^3) is the water density both in heater and cooler and $\bar{\rho}_w$ is the average water density, g (m/s^2) is the gravitational acceleration and R (m^4) is the hydrodynamics resistancy. The multiplication of the water volume rate Q (m^3/s) with water density is shown in corelation (3).

$$\dot{m} = Q\bar{\rho}_w = Av\bar{\rho}_w \quad (3)$$

where A (m^2) is the hydrodinamics area, v (m/s) is the water velocity. After substituting correlation (2) into correlation (3), a new correlation is obtained as in (4).

$$v^2 = \frac{2gH(\rho_c - \rho_h)}{R\bar{\rho}_w A^2} \quad (4)$$

Meanwhile, the hydrodynamics resistancy can be calculated using correlation (5).

$$R = \frac{64\mu L + K\bar{\rho}_w vD^2}{\bar{\rho}_w vA^2D^2} \quad (5)$$

where L (m) is the loop total length, D (m) is the tube inside diameter, μ (kg/m.s) is the dynamics viscosity of water, and K is fricitional factor constanta (-).

Finnaly to calculate average water mass flow rate could be define using combination of correlations (2), (3) and (4), then become correlation (5).

$$\dot{m} = A\frac{\left(-64\mu L + \sqrt{(64\mu L)^2 + 8gHK\bar{\rho}_w D^4(\rho_c - \rho_h)}\right)}{2KD^2} \quad (6)$$

Analysis results will show the characteristic of average mass flow rate with time and the relationship between temperatur transeint and mass flow rate.

RESULTS AND DISCUSSION

Temperature transient

During heating process, the water around the rectangular loop received heat by free convection from heater through water. Then, water initial temperature in cooler area increased following the increase of water initial temperature in heater area. After cooler was turned on and heater was turned off, water temperature in heater and cooler began to decline subtly until 5000 seconds. Fig. 3, Fig. 4 and Fig. 5 presented the temperature profile during transien cooling for temperatures of 70°C, 80°C and 90°C. Curve explained three line of water temperature in heater area, water temperature in cooler area and the average temperature. This condition caused by there is no additional heat into the heater area and cooler worked to remove heat rapidly. Table 2 shows the capacity of heat removal, which is indicated by the temperature difference between heater area and cooler area.

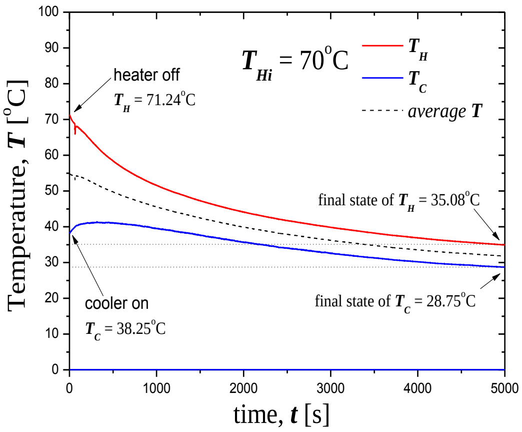

Fig. 3. Temperature measurement in heater and cooler area for initial temperature 70°C.

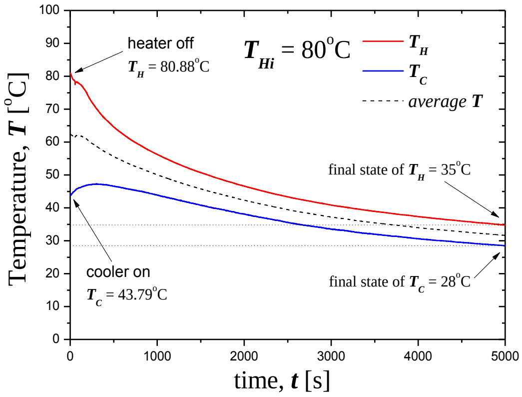

Fig. 4. Temperature measurement in heater and cooler area for initial temperature 80°C.

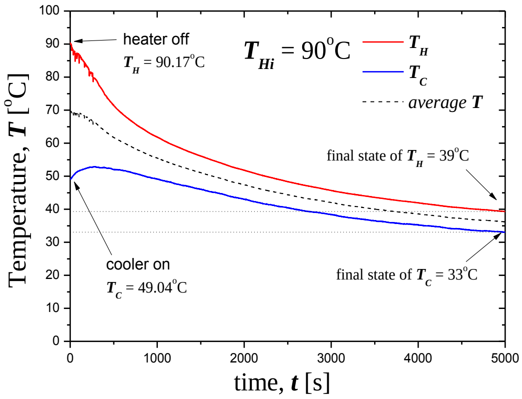

Fig. 5. Temperature measurement in heater and cooler area for initial temperature 90°C.

Table 2. Temperature difference in T_H and T_C

	T_{Hi} =	70°C	80 °C	90 °C
T_H [°C]	High	71.24	80.88	90.17
	Low	35.08	34.78	39.31
		36.16	46.1	50.86
T_C [°C]	High	38.25	43.79	49.04
	Low	28.75	28.47	33.04
		9.5	15.32	16

Average cooling rate for each variation of water initial temperature in heater area is showed in Fig. 6. It can be seen that the cooling rate for water initial temperatur of 80°C and 90°C were not too different in cooler area. This condition may be caused by the same amount of cooling capacity from refrigerant. Although the final state of temperature both in heater area and cooler area was not similar and gradual, but differences in initial temperatur and final temperatur changes in sequence according to the water initial temperatur in heater area. The different of final temperature maybe caused by changes in ambient temperatur during experiment.

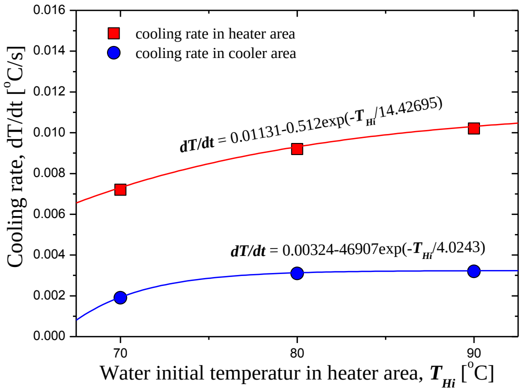

Fig. 6. Cooling rate characteristics.

The characteristics of the cooling rate was approached using an exponesial correlation as shown in Fig. 6.

Mass flow rate

The temperature differences can trigger the thermal-hydraulics parameters, such as mass flow rate. In Rectangular loop for single-phase natural circulation, the mass flow rate could be decided as function the power transferred to the liquid in particularly. But, in this case there is no power to be transferred to the liquid, and heat was decreased through surface of tube and cooler area. Meanwhile, the boundary condition of experiment is water initial temperature in heater area. Transient temperature data was converted into water density using correlation (1) then take into account to predict mass flow rate using correlation (5). Fig. 7 shows the characteristic of mass flow rate during transient cooling for 4000 seconds.

At the beginning of water mass flow rate as shown in Fig. 7 has a different value. Water mass flow rates of 0.000232 kg/s, 0.000320 kg/s and 0.000420 kg/s respectively for water initial temperatures of 70°C, 80°C and 90°C in heater area. Then, until to 4000 seconds, the mass flow rate has the same value, which is about 0.000025 kg/s. This condition approaches stable condition for mass flow rate, it means the temperature difference between heater and cooler is less then 8°C at 4000 seconds and the temperature difference drop is only about 5°C at 8000 seconds. Correlations based fitting process using Origin 8 software as shown in Fig. 7, it produces exponential equation of order 2 with an average error of about 1.5%. Although, there is a different in water initial temperature which causes differences in the amount of heat that must be taken by cooler. However, in the end (at 4000 seconds) of cooling process, it shows that the mass flow rate is nearly the same due to the capability of heat which was removed by cooler and through heat loss.

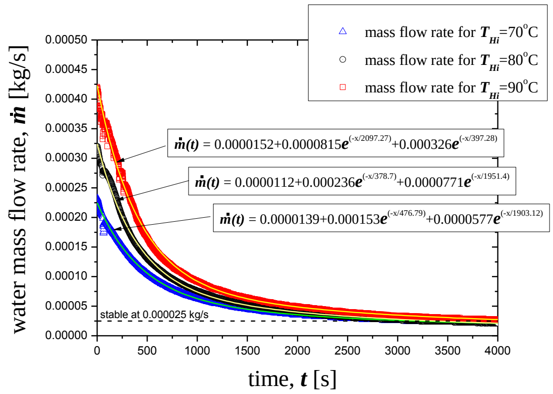

Fig. 7. Water mass flow rate characteristic.

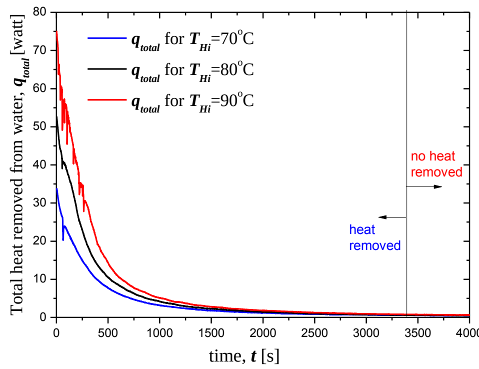

Fig. 8. Total heat removed from water.

Using heat balance, the heat loss (**q_{loss}**) was occurred through tube line from heater area to cooler. Heat was also transferred from water into cooler area (**q_C**). The total heat (**q_{total}**) is the summation of the heat released through the tube from the heater to the cooler and the heat extracted by the water cooler. Figure 8 shows total heat removed from water after 4000 seconds of operation. Correlation (7) and correlation (8) was used to calculate **q_{loss}** and **q_C** using temperature data and water mass flow rate from data in Fig. 7.

$$q_{loss} = \dot{m}c_p\left(T_C - T_H\right) \tag{7}$$

$$q_C = \dot{m}c_p\left(T_{C-in} - T_{C-out}\right) \tag{8}$$

and total heat indicated by the correlation (9),

$$q_{total} = q_{loss} + q_C \tag{9}$$

where **q** is heat transfer (watt) and water specific heat **c_p** (kJ/kg.°C) was calculated by correlation (10).

$$c_p(T) = \frac{17.48908904 - 0.03189591T}{\sqrt{1 - 0.00167507T - 0.0000028748T^2}} \tag{10}$$

The heat averages removed each second from water due to heat loss and cooler are 3.51 watt, 5.06 watt and 6.85 watt, respectively, for water initial temperature 70°C, 80°C and 90°C in heater area. As shown in Fig. 7 and Fig. 8, it can be said that the decreasing of mass flow rate is caused by a smaller temperature difference between temperature in heater area and temperature in cooler area. This is indicated by the reduced amount of heat transferred from the water. Total heat become stable and occure at 3400 second as shown in Fig. 8, total heat is about 0.57 watt with stable mass flow rate around 0.000025 kg/s (see Fig. 8).

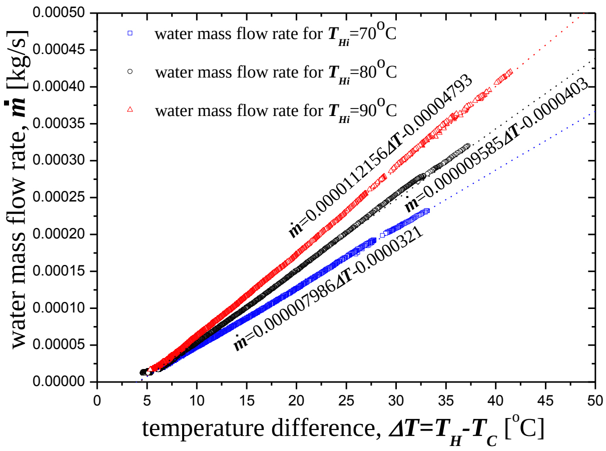

Fig. 9. Water mass flow rate versus temperature difference.

The gradient of water mass flow rate versus temperature differences also become high following water initial temperature in heater area (as shown in Fig. 9). The gradient of water mass flow rate for initial temperatures of 70°C and 80°C are 71.2% and 85.4% of water mass flow rate gradient at 90°C. The interval of water mass flow rate becomes longer if the temperature difference becomes bigger. The curves shows that the longer in line, then the greater heat was transferred. The amount of heat that is transferred will determine the magnitude of the onset of mass flow rate. But, due to the capacity of cooler is same, in the end the mass flow rate and temperature differences be almost the same. Transient cooling process for this experimental could be explained as an exponential process. Figure 10 shows that the relationship between water initial temperature variation in heater area with high water mass flow rate as a liner correlation with gradient 0.00000945. Increasing of water initial temperature will be influenced by the heat capacity in water and driven by the higher of mass flow rate in the begining.

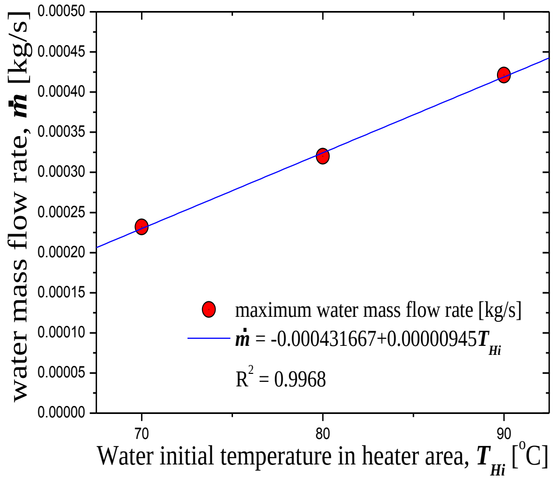

Fig. 10. High water mass flow rate base on initial temperature.

CONCLUSION

Experimental study to investigate the effect of water initial temperature in heater area to water mass flow rate has been done. This study shows that the temperature in heater area and cooler area decreased about 90.6% and 95.7% at initial temperature 80°C, about 71.1% and 59.4% at initial temperature 70°C all off which are compared with the initial temperature of 90°C. The average of water mass flow rate was increased 81.03% at higher initial temperature 90°C from initial temperatur 70°C. It is quite clear that, the averages of heat, which ware removed each second from water due to heat loss and cooler, are 3.51 watt, 5.06 watt and 6.85 watt,respectively for water initial temperatures of 70°C, 80°C and 90°C in heater area. It can be concluded that, although the initial conditions of heat stored in the water is quite different, but due to the cooler heat removal capacity and heat loss is almost the same. Then after an interval of 4000 seconds, the average of mass flow rate nearly the same.

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Nomenclatures

A	Hydrodinamics area (m^2)
c_p	Spesific heat (kJ/kg.^{o}C)
D	Internal diameter of tube (m)
g	Gravitational force (m/s^2)
H	Height between cooler and heater (m)
K	Frictional factor constanta (-)
L	Length of rectangular loop (m)
$\dot{m}$	Mass flow rate (kg/s)
Q	Water volume rate (kg/m^3)
q_{total}	Total heat transfer (watt)
q_{loss}	Heat loss (watt)
q_C	Heat removed by heater (watt)
R	Hydrodynamics resistancy (m^4)
T	Temperature (^{o}C)
T_{Hi}	Water initial temperature in heater (^{o}C)
T_{Ci}	Water initial temperature in cooler (^{o}C)
V	Velocity (m/s)
$\frac{dT}{dt}$	Cooling rate (^{o}C/s)

Greek Letters

ρ	Density (kg/m^3)
μ	Dynamics viscousity (kg/m.s)

Subscripts

C	Cooler
C-in	Inlet cooler
C-out	Outlet cooler
H	Heater
w	water
i	initial

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