Estimation of natural circulation flow based on temperature in the FASSIP-02 large-scale test loop facility

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Abstract. In the future, the use of passive cooling system without electrical power input become highly considered to be implemented in the design of nuclear reactor safety system. Moreover, the lessons learned from the Fukushima-Daiichi accident encourage the incorporation of such passive cooling system. The passive safety cooling system is aimed to cope with both design bases as well as severe accidents. The natural circulation is one example parameter of the passive cooling system features being widely considered. However, some of the parameters involving in natural circulation are still being investigated, in particular the problem of flow instability. BATAN is designing a large-scale test loop facility, named FASSIP-02 loop, with a height of 11 meters between a heat source and a cooling source. The FASSIP-02 loop is designed to simulate the residual heat in the reference reactor. To ensure the validity of the design prior to the construction, it is necessary to make an analytical calculation using some correlations to estimate the natural circulation flow rate. The calculation method is performed by using the derived two principle correlations of the buoyancy force in the heating section and the gravitational force on the cooling section. The water temperatures in the heating section are varied at 50°C, 60°C, 70°C, 80°C and 90°C with the water temperature in the cooling tank pool are varied at 10°C, 20°C, 30°C, 40°C and 50°C. The calculation results can estimate the water temperature and volume are required. In addition, it could be used to determine the experimental matrix that is based on the FASSIP-02 loop design.

1. Introduction
The severe accident at Fukushima Dai-ichi nuclear power station has became a lesson learn to involving the passive system in nuclear safety system. The involving of passive system can reduce the recurrent of accident in nuclear power station. Due to the removal of heat generation after reactor shutdown, especially in station blackout case, the use of passive cooling system becomes highly considered to be implemented in the design of nuclear reactor safety system.

The additional of passive safety system features in advanced reactors are involved to prevent the accident occur. These passive safety system features are expected to enhance the nuclear reactor safety and prevent the release of radiation to the environment [1, 2].

The studies on using of passive safety system, such as passive residual heat removal system (PRHSR), in nuclear power station have done by many researchers using experiment and simulation.
Xia et al. have conducted the calculation analysis using RELAP5 on the natural circulation characteristics of passive residual heat removal system for integrated pressurized water reactor on accident condition [3]. Mangal et al. has investigated the natural circulation behavior using RELAP5 based on their experiment test section data [4]. Zou et al. has done the assessment of PRHRS cooling capability in core under design basis accidents and beyond design basis accidents [5]. Their results showed that the PRHRS has good performance to remove heat generation from primary coolant system under accident condition.

Specific investigation of thermal-hydraulics characteristics on passive system have been conducted by many researchers. Yan et al. studied the flow characteristics in two-phase passive cooling system loop of System-integrated Modular Advanced Reactor (SMART) design. The combination both experiment and simulation was conducted to know it characteristics. The characteristics obtained were used for standard design approval of SMART to verify its design bases, design tools, and analysis methodology [6].

We have also been conducted the previous investigation on heat pipe capability to remove the heat generation in nuclear spent fuel storage pool. Experiment and RELAP5 simulation were used to know the characteristics and thermal performance of heat pipe as passive cooling system under station blackout accident. The results showed that heat pipe has good cooling capability and can be proposed as passive cooling system in nuclear spent fuel storage pool [7, 8]. In another investigation, as a preliminary research, previous research has been done using small test loop called NC-QUEEN for transient condition [9].

We also have been constructed the FASSIP-01 loop research facility in order to investigate natural circulation flow based on the rectangular loop with medium size which is placed vertically. The HSS (heat sink system) loop used as cooling system to the cooler thank in the rectangular loop. The geometrical size of the rectangular loop is 3.5 m width and 6 m high, which was placed in a vertical position. From the investigation it’s also founded the thermal characteristics of natural circulation flow in rectangular loop [10].

From the previous studies, there were no investigation which applied the large-scale test loop facility, named FASSIP-02 loop, with a height of 11 meters between a heat source and a cooling source. The FASSIP-02 loop is designed to simulate the residual heat in the reference reactor. To ensure the validity of the design prior to the construction, it is necessary to make an analytical calculation using some correlations to estimate the natural circulation flow rate. The calculation method is performed by using the derived two principle correlations of the buoyancy force in the heating section and the gravitational force on the cooling section.

2. Methodology

2.1. Design of FASSIP-02 Loop

The FASSIP-02 loop as a Large-Scale Test Loop Facility has been design to fulfil the needed of investigation on natural circulation phenomenon in large scale. The facility was named FASSIP-02 (the extension of Fasilitas Simulasi Sistem Pasif) unit 02. In the framework of understanding and mastering of the basic engineering to apply the natural circulation characteristics into passive cooling system for advanced nuclear reactors, it need to be made and carried out research using experimental facilities for the simulation of a passive cooling system. Figure 1 shows the design of FASSIP-02 loop.
There are several parameters that affect the natural circulation flow, where thermal hydraulics parameter is fluid temperature \( T \) and the geometrical parameters are height differences between heater and cooler \( H \), total loop length \( L \) and pipe diameter \( D \). The loss frictional of pipe defined base on elbow, tee, enlargements and contractions with K constantan. Then, then the design of FASSIP-02 loop was designed base on components and equipments related to thermal hydraulics and geometrical...
parameters. Design was done using 3D drawing software where figure 1 shows a heat source is a water heating tank and a heat sink tank (water cooling tank) which can simulate the temperature difference between hot area (bellow, to make density of water decreased) and cold area (upper, to make the density of water increased). Table 1 shows the geometry of FASSIP-02 loop.

2.2. Analytical

The concept of passive systems is the system which circulating the cooling fluid inside a loop without any intervention from outside forces and based on natural laws. The phenomenon of this fluid flow rate in the passive system called natural circulation, which occur due to differences in fluid density in hot and cold region [11]. Effect of fluid density changes in hot regions will lead to buoyancy force and the effect of fluid density changes in cold will cause the gravitational force. Thus, the implementation of passive systems in a nuclear power plant can be used for normal and non-normal condition (condition accident, transient) [12]. Figure 4 shows the simple concept of natural circulation based on buoyancy force and retarding frictional force with cold region in the top and hot region in the bottom of rectangular loop [13-16]. In the natural circulation loop, there is a hot part which is always placed at the bottom and the cold part placed at the top of a loop. In steady state condition, a phenomenon that occurs can be described by equation (1) as buoyancy force come from hot part (left side eq. 1) and in cold part is retarding frictional force (right side eq.1).

\[ -g \int \rho dz = \frac{R_h \dot{m}^2}{2 \rho} \]  

(1)

With the general hydro dynamics resistance is \( R_h [m^4] \) as in equation (2)

\[ R_h = \sum_{i=1}^{N} \left( \frac{f \times L}{D} + K \right) \frac{1}{A^2} \]  

(2)

Then, equation (2) could be reform like,

\[ R_h A^2 = \left( \frac{f \times L}{D} + K \right) \]  

(3)

After equation (1) was integrated become,

\[ g(\rho_h - \rho_c)H = \frac{R_h \dot{m}^2}{2 \rho} \]  

(4)

\[ \dot{m}^2 = \frac{2g \rho(\rho_h - \rho_c)H}{R_h} \]

The flow rate derivates using pipe frictional coefficient for laminar flow.

\[ f = \frac{64 \mu}{D \rho v} \]  

(5)

Then, equation (5) substituted into equation (4). The new equation for hydrodynamics resistance is

\[ R_h = \frac{64 \mu L + D^2 \rho v K}{D^2 \rho v A^2} \]  

(6)

Then, equation (6) substituted by the equation (2) and \( \dot{m} = \rho v A \), finally

\[ \dot{m} = \frac{-64 \mu L + \sqrt{(64 \mu L)^2 + 8 g H K (\rho_h - \rho_c) D^4}}{2 D^2 \rho K} \]  

(7)
Equation (7) is natural circulation flow rate inside pipe rectangular loop derivative from to natural laws. It is mean that, all parameters consisting of total loop length \((L)\), height differences \((H)\) between heater and cooler, pipe diameter \((D)\), temperature \((T)\) and constantan K have influenced into natural circulation flow velocity. For estimation, the water temperatures in the water heating tank are varied at 70°C, 75°C, 80°C, 85°C and 90°C with the water temperature in the water cooling tank at 10°C, 20°C, 30°C, 40°C and 50°C. The calculation results obtained will be used as a basis for construction and commissioning test using FASSIP-02 loop.

3. Result and Discussion

Using water temperature simulation as described in above, the using the correlation for water density \(\rho(T) = 1004.789042 - 0.046283(1.8T + 32) - 7.9738 \times 10^{-4} (1.8T + 32)^2\) and dynamics viscosity of water \(\mu(T) = \exp \left[ \frac{(A + CT)}{(1 + BT + DT)} \right]\) finally obtained natural flow rate curve to temperature difference in hot part and cold part as shown in following figure 2 and figure 3.

![Figure 2. NC velocity for water temperature in WHT (hot part)](image1)

![Figure 3. NC velocity for water temperature in WCT (cold part)](image2)

Figure 2 shows the trend of NC flow velocity for each water temperature variation in WHT. The velocity of natural circulation (NC) was increased for each water temperature variation in hot part. Then, Figure 3 shows that the velocity of NC was decreased for each water temperature variation in cold part. It is shown that, the differences of temperature was increased causing the velocity flow of NC was increased as shown in Figure 4.
4. Conclusion
Based on estimation with water temperatures in the heating section are varied at 50°C, 60°C, 70°C, 80°C and 90°C with the water temperature in the cooling tank pool are varied at 10°C, 20°C, 30°C, 40°C and 50°C can be concluded that the higher NC velocity flow is 0.628 m/s. The lower one is 0.1765 m/s for water temperature in WHT is 50°C and in WCT is 40°C.

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Figure 4. NC velocity for water temperature differences between hot part and cold part
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