Flow rate and temperature characteristics in steady state condition on FASSIP-01 loop during commissioning

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Abstract. The need for large-scale experimental facilities to investigate the phenomenon of natural circulation flow rate becomes a necessity in the development of nuclear reactor safety management. The FASSIP-01 loop has been built to determine the natural circulation flow rate performance in the large-scale media and aimed to reduce errors in the results for its application in the design of new generation reactors. The commissioning needs to be done to define the capability of the FASSIP-01 loop and to prescribe the experiment limitations. On this commissioning, two scenarios experimental method has been used. The first scenario is a static condition test which was conducted to verify measurement system response during 24 hours without electrical load in heater and cooler, there is water and no water inside the rectangular loop. Second scenario is a dynamics condition that aims to understand the flow rate, a dynamic test was conducted using heater power of 5627 watts and coolant flow rate in the HSS loop of 9.35 LPM. The result of this test shows that the temperature characterization on static test provide a recommendation, that the experiments should be done at night because has a better environmental temperature stability compared to afternoon, with stable temperature around 1°C - 3°C. While on the dynamic test, the water temperature difference between the inlet-outlets in the heater area is quite large, about 7 times the temperature difference in the cooler area. The magnitude of the natural circulation flow rate calculated is much larger at about 300 times compared to the measured flow rate with different flow rate profiles.

Keywords: natural circulation, flow rate, temperature, commissioning, large-scale, FASSIP-01
1. Introduction
The effectiveness of natural circulation depends on various thermal-hydraulic parameters. Natural circulation in the reactor for core heat removal takes place due to the density difference between the cold regions coming down in the down comer with the heated and/or two-phase flow going upward in the core, referred to the buoyancy. The change of density due to the increase of temperature will affect the buoyancy force. Many researches on passive cooling system with focusing on the investigations on natural circulation phenomena have been carried out. Since 1967, Welender has investigated the effects of buoyancy force, pressure drop and friction loss in the pipes against a fluid flow driving force [1]. Several years later, K. Vijayan et al. [2] and Zvirin [3] studied the effect of geometrical variation on the natural circulation flow. The research was conducted using a small rectangular loop by 2.6 meter in length and 0.7 meter in width using 1 inch in diameter stainless-steel pipe. The research focused on analyzing the stability of steady and transient flow using heater and cooler control. The problem in natural circulation phenomenon is the stability flow, which was affected by boundary condition (BC) changes, by geometrical changes such as diameter, length and height. Thermal hydraulics parameter has given an influence also to the changes of BC. The differences of thermal boundary conditions, geometrical variations, a heat transfer effect and the mass flow rate parameters during natural circulation have been studied [4-9]. However, the research was done in a steady state condition using a small scale experimental apparatus. Then, the development of test facilities and thermal-hydraulic system codes have significant role in the assessment of passive safety system design, evaluation and certification to the design of advanced reactors and safety features in light water reactor (LWR) in the present.

A large-scale facility has been constructed to study natural circulation phenomenon of passive cooling system in LWR and SMRs. KAERI (Korea) made a large-scale experimental facility (ATLAS, advanced thermal-hydraulics test loop for accident simulation). The ATLAS condition refers to APR-1400 (advanced power reactor-1400MWe) reactors type [10] and using 3 inch size for natural circulation experiment. Object of experiments focused on identifying characteristics of the loop of the reactor coolant system (RCS) and compare the results with computer code. The PANDA facility (Switzerland) was constructed to simulate in RPV's natural circulation BWR reactor type. The LINX facility is a medium-scale experimental facility constructed to study passive cooling system [11]. In Indonesia [12-14], several researches were conducted to investigate natural circulation phenomenon as a preliminary experimental research in passive cooling system development. The research was done using the USSA-FT01 Loop as a small-scale rectangular loop (1.5 x 1.0 meters) with 1 inch size pipe diameter and a NC-QUEEN loop with rectangular geometry is 2.7 x 0.5 meters and 1 inch size tube diameter. However, it is very difficult to obtain information and comparison data such as geometric data, primary data from those researches, the variation of working fluid and also power magnitude which was used as well as experimental results from these facilities. To extend the research goal in the field of passive cooling system development, from 2015 to 2016 in BATAN, the new experimental facility called FASSIP-01 (Indonesian: FAsilitas Simulasi SIstem Pasif) or Passive System Simulation Test Facility with medium-scale rectangular loop (3.5 m x 6 m) has been build. The first step of research activity is conduct a commissioning of FASSIL loop to understand and to collect technical data, performance and characteristic of FASSIP-01 loop before experiment scenario (base on experimental matrix) will be conducted.

2. Methodology

2.1. Experiment apparatus
From 2015 until 2016, FASSIP-01 loop has been constructed as a research facility used to investigate the flow of natural circulation on the rectangular loop in medium size. FASSIP-01 loop consists of two main parts, the HSS (heat sink system) loop and the rectangular loop, where the research object is a rectangular loop with geometrical size are 3.5 m wide and 6 m high, which was placed in a vertical position. The experiment setup of FASSIP-01 loop is shown in Figure 1.
As shown in Figure 1, the rectangular loop consists of a heater tank as a heat source (non-direct, water to water, hot water is heated-up by submerged heater connected to the slide regulator 25 kVA), cooler tank (non-direct, water to water, cold water from HSS loop) and an expansion tank to compensate a sudden pressure rise during experiment. The piping system of rectangular loop composed of 32 sections and 4 elbows made by 1 inch diameter SS304 pipe with length of each section is 50 cm. Each section was connected by flanges. Around 50 thermocouples of type K (error average: 4.2%) were installed along the rectangular loop (including 6 thermocouples in every tank) and 1 flow meter FLR1009ST-I type for low flow with maximum flow 0.5 LPM (error: 6.43%). The HSS loop consists of pre-cooler tank as a cold water source which is cooling by coil connected to the refrigerant. High speed pump, a Grunforce Rotation Varity model was installed in HSS loop with maximum flow of 45.09 LPM and it connected to an inverter to vary the flow rates. A reservoir tank is connected to the HSS loop as a water supply during operation. The explanation of FASSIP-01 loop including error analysis, construction and other reports were explained in previous paper [15-18].

Figure 2 shows the indication of temperature measurement in cooler tank with blue colour and temperature in heater tank with red colour including natural circulation flow rate in rectangular loop.
and water flow rate in HSS loop. As measurement system, 14 thermocouples of type K and 1 electromagnetic flow meter (error: 2.5%) were installed in HSS loop. All data from measurement points was collected in PC through data acquisition system (DAS) consisting of a few of temperature module (NI-9213 and 9214) and a universal module for flow and pressure (NI-9203). The modules were plugged in cDAQ-9188 using USB cable connecting to PC. In PC monitor, a virtual instrumentation (VI) was made using LabView 2011 software to evaluate parameter changes during experiment. Figure 2 shows the VI display in PC monitor.

2.2. Experiment procedure for commissioning

Experiment scenario was made to conduct the FASSIP-01 Loop commissioning which consists of two scenarios i.e.: a static test and a dynamics test. The static test was done for about 24 hours, with two steps of testing. The first step is done without water in the inside of rectangular loop, heater tank and cooler tank. All measurement temperature was done for about 24 hours as well. This test is intended to understand the characteristics and response of thermocouples reading to the air around the laboratory for 24 hours. The second step is done also by filling water into the inside of rectangular loop pipe, heater tank and cooler tank for 24 hours experiment. The dynamic test is done by filling the water into the FASSIP-01 loop and heating water inside heater tank and cooling water inside cooler tank. The dynamics test was conducted by the water flow rate in HSS loop is 9.35 LPM and using heater with electric power of 5627 watt for heating the water inside heater tank for 7 hours.

2.3. Analysis

The analysis was done by fitting all temperature histories data into several graphs for static and dynamics test. Natural circulation flow rate from the temperature changes in rectangular pipes inside heater tank and cooler tank is also calculated. The result calculation of the flow rate compared to flow rate measurement. Calculation was done using equation which was derive from natural circulation law inside rectangular loop [19]. Natural circulation flow rate is a function of total loop length, height differences between heater and cooler areas, pipe diameter, temperature and constantan K have influenced into flow rate.

\[
Q = \frac{A^{-64\mu LH} + \sqrt{(64\mu LH)^2 + 8gHK\rho(\rho_c - \rho)D^4}}{2D^2\rho K}
\]

Where \( Q \) is flow rate (m\(^3\)/s; LPM), \( D \) is pipe diameter (m), \( L \) is total length of rectangular pipes, \( A \) is pipe cross-section area (m\(^2\)), \( \rho \) is water density (m\(^3\)/kg) which is the value depends on the temperature change, \( \mu \) is dynamics viscosity (N.s/m\(^2\)), \( K \) is frictional loss of piping components, and \( g \) is gravitational acceleration (9.89 m/s\(^2\)).

3. Result and discussion

3.1. Temperature characteristics

The temperature history curve for statics test in 24 hours both for no-water and there is water inside pipe is shown on Figure 3a and Figure 4a. Ambient temperature in the air around laboratory also was measured for 24 hours, shown in Figure 3b and Figure 4b. Figure 3a shows a temperature profile during 24 hours from 13.00 o’clock on July 19, 2016 to 13.00 o’clock on July 20, 2016. As shown in Figure 3a and Figure 3b, since the beginning recording data was started at 13.00 until the end of recording data during 24 hours, the air temperatures which were measured for all points of thermocouples have a same profile. At 13.00, ambient temperature around 32°C and higher temperature in the FASSIP-01 loop was 40.5°C. All temperatures data indicating begin to drop at 15.00 due to rain, but all temperature data shows a stable condition start at 17.30 on July 19, 2017 until 06.30 on July 20, 2016 with only a temperature change of about 2.2°C.
In Figure 5, water temperature inside pipe in heater area has a stable condition at 100°C and 103°C. It points in pipe inside heater tank. The same number of measurement points for cooler area. Inside points, inlet temperature in pipe into heater area, outlet temperature in pipe from heater area, and 2 rectangular loop. Then, the differences of water temperature inlet and outlet between heater areas is seems there is boiling inside pipe due to temperatures reached saturation temperature of water. But done from 18:00 to 06:00 (12 hours) with temperature differences between 1 oC - 3 oC. But, if the with only a temperature change of about 1.5 oC. Based on these conditions, the experiment should be become drop at 16.32 the become stable since 17.29 on July 21, 2016 until 06.00 on July 22, 2016.

The same conditions also occur for static tests with water inside pipe of the FASSIP-01 loop, shown in Figure 4a and Figure 4b. But, there is no rain at July 21, 2016 in the afternoon. Ambient temperature become drop at 16.32 the become stable since 17.29 on July 21, 2016 until 06.00 on July 22, 2016 with only a temperature change of about 1.5°C. Based on these conditions, the experiment should be done from 18:00 to 06:00 (12 hours) with temperature differences between 1°C - 3°C. But, if the experiment must be conducted in the morning the temperatures differences from the morning until afternoon is around 7°C – 8°C. Figure 4 shows temperature histories for several measurement points inside pipe in rectangular & HSS loop.

Measurement points are consists of a heater area and a cooler area. In heater area there are 4 points, inlet temperature in pipe into heater area, outlet temperature in pipe from heater area, and 2 points in pipe inside heater tank. The same number of measurement points for cooler area. Inside curve of Figure 4, there is 1 point for bulk temperature to measure the ambient temperature. As shown in Figure 5, water temperature inside pipe in heater area has a stable condition at 100°C and 103°C. It is seems there is boiling inside pipe due to temperatures reached saturation temperature of water. But it is believed that there is no boiling in the heater area due to an increase of pressure inside pipe of rectangular loop. Then, the differences of water temperature inlet and outlet between heater areas are...
around of 49°C. In the cooler area, the differences of water temperature inlet and outlet between cooler areas are around of 7°C. It can be said that there is heat loss when the natural circulation flow was flowing and bring heat from the heater are to the cooler area and vice versa. Thus, the consideration to coat pipe surface of the FASSIP-01 loop with a thermal insulator becomes a necessity in the further experiments.

As shown in Figure 5, there is an interesting condition about this dynamic test is that there is an unstable condition during temperature rise from 0 second to 6935 seconds. Then, from 6936 until the end of experiment at 25000 seconds, water temperatures inside pipe and in inlet-outlet pipe at the heater area are stable. This condition indicates that there is an average of natural circulation flow rate of water inside rectangular pipe of FASSIP-01 loop.

3.2. Flow rate characteristics

Natural circulation flow rate has been obtained through the calculation result and the measurement result, as shown in Figure 6.

![Temperature Histories in Rectangular Loop](image)

**Figure 5.** Characteristics of all temperatures measurement in FASSIP-01-01 Loop during dynamic experiment

![Natural Circulation Flow Rate](image)

**Figure 6.** Characteristics of flow rate in rectangular loop of FASSIP-01-01 during dynamic experiment
Figure 6 shows characteristic of natural circulation flow rate both for calculation and measurement. Figure 6a explains natural circulation flow rate profile based on measurement result using flow meter FLR1009ST-I type. And Figure 6b explains the result of calculation for natural circulation flow rate profile using equation (1). Based on Figure 6a, the measured flow rate profile is very interesting, since there is 2 times the increase in flow rate. The flow rate was increased starting from of 0.0085 LPM to 0.0325 LPM in 5229 seconds (from 2212 seconds up to 7441 seconds). Then, starting from 7441 seconds, the flow rate was increased from 0.0325 LPM to 0.0415 LPM. The different results are shown from flow rate calculations, where there is no increase in flow rate as much as 2 times as the result of measurement. Since the beginning of heating at 0 second until 6994 seconds, the flow rate increased from 0 LPM to 9.75 LPM. Then since that time, the natural circulation flow rate becomes stable until the end. Meanwhile, a particular concern is the difference between the calculation results with the measurement results, where the calculation results are approximately 300 times greater than the measurement results. In the meantime, the analysis believes more on measurement results. Thus, it is necessary to modify and improve on equation (1) the calculation result with the dimensionless number. Various data with variations of parameters in the experimental matrix forward must be made to obtain the result of modification of the equation which results close to the measurement data. In the meantime, the analysis believes more on measurement results. Thus, it is necessary to modify and improve on equation (1) by applying a dimensionless number. Various data with variations of parameters in the experimental matrix in the future must be made to obtain the result of modification of the equation which has the data of the calculation results close to the measurement data. Meanwhile, in addition there is a different flow rate profiles. Where, the flow rate profile of the calculation results almost similar to the water temperature change curve in the heater region, especially in the outlet pipe of the heater and in the heater area. The condition seems reasonable, since the flow rate equation includes the average temperature parameters in the heater area and in the cooler area as the input data into calculation.

4. Conclusion

The commissioning of FASSIP-01 loop has been done to characterized temperature histories of water inside pipe and natural circulation flow rate using measurement data. Also a calculation to define natural circulation flow rate was occurred using temperature data from experiment. The result of temperature characterization on static test shows that, experiments should be done at night with better environmental temperature stability compared to noon, about 1°C - 3°C. While on the dynamic test, the water temperature difference between the inlet-outlets in the heater area is quite large, about 7 times the temperature difference in the cooler area. The magnitude of the natural circulation flow rate calculated is much larger at about 300 times compared to the measured flow rate with different flow rate profiles. This test indicates that the natural circulation flow rate has been formed within the FASSIP-1 strand rectangular pipes and the flow rate measurements need to be validated by visualization.

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References

[1] IAEA, Design Safety Considerations for Water Cooled Small Modular Reactors Incorporating Lessons Learned from The Fukushima Daiichi Accident, IAEA-TECDOC 1785, Vienna, 2016.
[2] P. Welander, On the oscillatory instability of a differentially heated fluid loop, Journal of Fluid Mechanics, Vol.29, No.1, pp.17-30 (1967).
[3] P.K.Vijayan, H. Austregesilo, V. Teschendorff, Simulation of unstable oscillatory behaviour of single-phase natural circulation with repetitive flow reversals in a rectangular loop using computer code ATHLET, Nuclear Engineering and Design, Vol.155, pp.623-641 (1995).
[4] Y. Zvirin, A review of N. C. loops in PWR and other systems, Nuclear Engineering and Design 67 (1981) p.203–225.
[5] M. Misale, F. Devia, P. Garibaldi, Some considerations on the interaction between the fluid and wall tube during experiments in a single-phase natural circulation loops, Proceedings of the 3rd IASME/WSEAS Int. Conf. on Heat Transfer, Thermal Engineering and Environment, Corfu, Greece, August 20-22, p.128-133 (2005).
[6] Y.Y. Jiang, M. Shoji, Flow stability in a natural circulation loop: influence of wall thermal conductivity, Nuclear Engineering Design, Vol. 222, No.1, pp.6–28 (2003).
[7] M. Misale et al., Experiments in a single-phase natural circulation mini-loop, Experiment Thermal Fluid Science, Vol. 31, pp.1111-1120 (2007).
[8] F. D’Auria, M. Frogheri, Use of a natural circulation map for assessing PWR performance, Nuclear Engineering Design, Vol. 215, pp.111-126 (2002).
[9] F. D’Auria et al., Scaling of natural circulation in PWR Systems, Nuclear Engineering and Design, Vol.132, pp.187-205 (1991).
[10] P.K. Vijayan, Experimental observations on the general trends of the steady state and stability behavior of single-phase natural circulation loops, Nuclear Engineering and Design, Vol. 215, pp.139–152 (2002). Experimental thermal-hydraulics group, http://www.psi.ch/teg/facilities, accessed in January 8th, 2015, time 15.00.
[11] J. Vikas et al., Experimental investigation on the flow instability behavior of a multi-channel boiling natural circulation loop at low-pressures, Experimental Thermal and Fluid Science, Vol. 34, pp.776–787 (2010).
[12] M. Juarsa, dkk., Analysis on Natural Circulation Flow with Reynolds Number Based on Slope Angle Variation in Natural Circulation Simulation Loop, Prosiding Seminar Nasional Thermofluid V dan Pameran Teknologi Gas Tahun 2011, Jurusan JTMI, FT UGM, Yogyakarta, 4-5 Oktober 2011, (in Indonesian).
[13] Y.S. Gaos, dkk., The effect on Slope Angle Revolution to Heat Transfer and Water Flow Rate in Natural Circulation Loop, Tri Dasa Mega, Vol.14, No.1, (2012) pp.39-53.
[14] M. Juarsa, et al., Preliminary Study on Mass Flow Rate in Passive Cooling Experimental Simulation During Transient Using NC-Queen Apparatus, Atom Indonesia Vol.40, No.3, (2014) pp.141-147.
[15] Giarno, dkk., Characterization on the Pre-Cooler as the Heat Sink System of the Loop FASSIP-01, Prosiding Seminar Nasional Teknologi Energi Nuklir 2016, Batam, 4-5 Agustus 2016, p.425-432 (in Indonesian).
[16] Giarno, dkk., Designing the Heat-Sink System of Fassip-01 Loop by Software Cycle-Tempo, Prosiding Seminar Nasional Teknologi Energi Nuklir 2015, Bali, 15-16 Oktober 2015, p.489-195 (in Indonesian).
[17] G. Bambang Heru K, dkk., Design on Calculation Program of Water Mass Flow Rate Based on Temperature Changes Using LabView, Prosiding Seminar Nasional Teknologi Energi Nuklir 2015, Bali, 15-16 Oktober 2015, p.481-488 (in Indonesian).

[18] Khairina Natsir, dkk., Evaluation on Uncertainty of Flowmeter Measurement Results Using Data Acquisition System, Prosiding Seminar Nasional Teknologi Energi Nuklir 2015, Bali, 15-16 Oktober 2015, p.534-541 (in Indonesian).

[19] Mulya Juarsa, et al., Passive System Simulation Facility (FASSIP) Loop for Natural Circulation Study, Prosiding Seminar Nasional Teknologi Energi Nuklir 2016, Batam, 4-5 Agustus 2016, p.673-680.