Geometry aspect review of the natural circulation system as innovation in passive cooling of nuclear reactor

D Hariyanto¹, S Permana¹,²*, Suprijadi³
¹Nuclear Physics and Biophysics Research Division, Physics Department, Institut Teknologi Bandung
²Department of Nuclear Science and Engineering, Institut Teknologi Bandung
³Theoretical High Energy Physics and Instrumentation Research Division, Physics Department, Institut Teknologi Bandung
⁴Instrumentation and Control Engineering Department, Institut Teknologi Sumatera

*E-mail : psidik@fi.itb.ac.id

Abstract. The passive nuclear reactor cooling system has become a fascinating topic, especially since the nuclear incident in Fukushima Daiichi, Japan. This study proposed to review a natural circulation-based passive cooling system in the geometry aspects of the loop. The numerical review was carried out using COMSOL Multiphysics software to study the geometry effect on the loop's fluid characteristics. Moreover, related research data to the study of the effect of fluid flow rate on one of the advanced nuclear reactors, namely the Molten Salt Reactor and the effect of loop geometry experimentally, are presented in this study for enrichment purposes. This study clearly showed that geometry aspects need to be considered in designing a natural circulation-based passive cooling system of a nuclear reactor.

1. Introduction
The natural circulation system has an essential role in remove heat from high-temperature sources without the support of external power or mechanical devices [1-2]. The fluid flow of the natural circulation is produced by the differences in density due to temperature gradients [3-5]. Hence, the natural circulation system began to be applied as passive safety in the new advanced nuclear reactors such as advanced pressurized water reactor (APWR), pressurized heavy-water reactor (PHWR), and molten salt reactor (MSR) [6-8]. In this case, nuclear power plants' safety using a passive safety system has become an exciting method that has been developed and applied widely [9]. Especially to deal with the failure of an active cooling device due to a lack of electricity supply resulting from natural disasters, such as the nuclear incident in March 2011 at Fukushima Daiichi, Japan [10,11].

The study of the instability of natural circulation began to be widely investigated as reported in related papers. Papers [12-14] studied the effect of the working fluid in the form of molten nitrate salt consisting of a mixture of KNO3-NaNO2-NaNO3 on the instability of the natural circulation loop (NCL). Papers [15-17] presented experiments on NCL using nanofluids as working fluids. Paper [18] discussed experimentally and numerically the instability of NCL using working fluid in the form of Lead Bismuth Eutectic (LBE). Paper [19] conducted an experimental and numerical analysis regarding the effect of low and moderate heating power on the instability of NCL using water working fluids.

*Corresponding author.
E-mail address: psidik@fi.itb.ac.id
The work in paper [20] analyzed the effect of loop diameter on the instability of NCL with the horizontal heater horizontal cooler (HHHC). Papers [21,22] investigated the performance of the mini NCL by varying the inclination angle. Paper [23] revealed that the NCL with vertical heater and cooler orientation was the most stable. The effect of vertical height on the NCL with vertical heater and vertical cooler has also been reported in papers [24,25]. Then, paper [26] proved experimentally that the expansion tank placement is crucial in single-phase NCL. Motivated by the description, this paper presents a review of the natural circulation-based passive cooling system in the loop’s geometry aspect.

2. Research Method
The computational fluid dynamic (CFD) module in COMSOL Multiphysics software was used to model the effect of loop geometry on the natural circulation system. In this case, COMSOL Multiphysics software was used to solve the governing differential equations regarding fluid dynamics and heat transfer in the fluid based on the finite element method. A set of governing equations in this simulation are mass conservation equation (Equation 1), Navier–Stokes momentum equation (Equation 2), two-dimensional heat transfer dynamic equation (Equation 3).

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = \mathbf{0} \quad (1)
\]

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = \nabla \cdot \left[-p \mathbf{I} + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) - \frac{2}{3} \mu \nabla \cdot \mathbf{u} \mathbf{I}\right] + \rho g \quad (2)
\]

\[
d_2 \rho c_p \frac{\partial T}{\partial t} + d_2 \rho c_p \mathbf{u} \cdot \nabla T + \nabla \cdot (-d_2 k \nabla T) = d_2 Q + q_0 \quad (3)
\]

The buoyancy effect in the momentum equation was set using Boussinesq approximation, as written in equation (4). In this case, the buoyancy is generated by the change in fluid density produced from temperature differences. In Equation 4, \( \rho_0 \) is the fluid reference density at room temperature, and \( \beta \) is the coefficient of thermal expansion at constant pressure as in Equation 5.

\[
\rho = \rho_0(1 - \beta(T - T_0)) \quad (4)
\]

\[
\beta = -\left(\frac{1}{\rho_0}\right)\frac{\partial \rho}{\partial T} \quad (5)
\]

3. Results and Discussions
In the initial step, COMSOL Multiphysics software was used to model the natural circulation experiment in paper [27] at the heater power of 150 watts. Modelling was carried out with a two-dimensional approach to simplify problem-solving. The modelling purpose to improve the conducted modelling in paper [27]. In this case, the effect of the thermal conductivity of the pipe was considered in the modeling. Table 1 shows the parameters used in modelling the natural circulation loop. Meanwhile, Figure 1 shows the input geometry in the COMSOL Multiphysics software.

| No. | Name    | Description                    | Value       |
|-----|---------|--------------------------------|-------------|
| 1   | \(R_i\) SS | Inner radius of the stainless steel pipe | 0.795 cm    |
| 2   | \(R_o\) SS | Outer radius of the stainless steel pipe | 1.065 cm    |
| 3   | \(R_i\) PVC | Inner radius of the PVC pipe | 0.950 cm    |
| 4   | \(R_o\) PVC | Outer radius of the PVC pipe | 1.100 cm    |
| 5   | \(L_h\)   | Length of heater pipe          | 18.00 cm    |
| 6   | \(\rho\) SS | Density of stainless steel     | 8000 kg/m³ |
| 7   | \(c_p\) SS | Heat capacity of stainless steel | 500 J/kgK  |
| 8   | \(k\) SS  | Thermal conductivity of stainless steel | 16.2 W/mK |
| 9   | \(\rho\) PVC | Density of PVC                  | 1400 kg/m³ |
| 10  | \(c_p\) PVC | Heat capacity of PVC            | 900 J/kgK  |
| 11  | \(k\) PVC  | Thermal conductivity of PVC     | 0.15 W/mK  |

Table 1. The constants and Parameters input of COMSOL multiphysics
Figure 1. The geometry as COMSOL multiphysics software input

Figure 2. Comparison of experimental results in paper with simulation results [24]

Figure 3. Simulation results for the width variation of the loop with a height of 100 cm
Figure 2 shows that the modeling is following the experimental results in the paper [27]. However, the early minutes of modeling show several peaks caused by a significant increase in temperature in a short time. The temperature increase starts from TS1, TS3, TS4, and TS2, which show the counterclockwise fluid flow, as presented in Figure 2. Next, the modeling was carried out to determine geometry's effect on the natural circulation system's characteristics in the loop made of stainless steel pipe.

Figure 3 shows that the width variation has no significant impact on the fluid flow rate. However, it can be observed that the wider the loop, the lower the fluid flow rate in the loop. The height variation has a significant effect on the fluid flow rate, as shown in Figure 4. The highest fluid flow rate can be observed at the loop height of 350 cm, while the lowest fluid flow rate can be observed at 100 cm. Therefore, the height doubling of the loop increases the flow rate. These results indicate that the loop geometry of the natural circulation-based nuclear reactor cooling system is an important aspect to improve the passive safety system to deal with possible accidents due to operational failure or accidents due to natural disasters. In this case, the fluid rate of a nuclear reactor can affect the neutron precursors' power, as reported in the paper [28]. As shown in Figure 5, the number of neutron precursors in the Molten Salt Reactor core is affected by changes in the fuel flow rate. As the fuel flow rate decreases, the power generated by the neutron precursor increases exponentially.

![Figure 4. Simulation results for the height variation of the loop with a width of 50 cm](image)

![Figure 5. Number of total powers produced by neutron precursors [28]](image)
4. Conclusions
COMSOL Multiphysics simulation with input parameter values based on the experimental results provided some excellent results for validation. Based on the simulation results, the counter-clockwise fluid flow could be found when the temperature rise began from above the heater, then followed by above and under the cooler, and finally under the heater. The simulations indicated that the flow rate decreased due to the doubling of horizontal length and increased significantly due to the vertical length doubling. The results confirmed that the optimization of loop geometry in designing the natural circulation system of advanced nuclear reactors is fundamental to enhance passive safety aspects.

Acknowledgments
The author would like to acknowledge to Decentralization Research Program of the Ministry of Research, Technology, and Higher Education, Indonesia, for the support and fund.

References
[1] Devia F and Misale M 2012 Int J Therm Sci 59, 195–202
[2] Jiang Y Y and Shoji M 2003 Nucl Eng Des 222 (1), 16–28
[3] Vijayan P K and Austregesilo H 1994 Nucl Eng Des 152 (1–3), 331–347
[4] Vijayan P K 2002 Nucl Eng Des 215 (1–2), 139–152
[5] Misale M and Frogheri M 1999 Int Commun Heat Mass Transf 26 (5), 597–606
[6] Zvirin Y 1982 Nucl Eng Design 67 (2), 203-225
[7] D’Auria F and Galassi G M 2009 Proc. the GCNEP-IAEA course on natural circulation phenomena and passive safety systems in advanced water cooled reactors, Pisa.
[8] Pauzi A M, Cioncolini A, and Iacovides H 2015 AIP Conf Proc 1659 (1)
[9] Lim J, Yang J, Choi S W, Lee D Y, Rassame S, Hibiki T, and Ishii M 2014 Prog Nucl Energy 74, 136–142
[10] Juarsa M, Witoko J P, Giarno G, Haryanto D, and Purba J H 2018 Atom Indonesia 44 (3), 123
[11] Antarikswan A R, Widodo S, Juarsa M, Haryanto D, Kusuma M H, and Putra N 2018 IOP Conf Ser Earth Environ Sci 105, 012090
[12] Kudariyawar J Y, Srivastava A K, Vaidya A M, Maheshwari N K, and Satyamurthy P 2016 Appl Therm Eng. 99, 560–571
[13] Srivastava A K, Kudariyawar J Y, Borghoin A, Jana S S, Maheshwari N K, and Vijayan P K 2016 Appl Therm Eng. 98, 513–521
[14] Wu Y, Cai C, Wang K, Jiao X, Yang Q, He Z, and Chen K 2019 J Nucl Sci Technol, 1–7
[15] Nayak A K, Gartia M R, and Vijayan P K 2008 Exp Therm Fluid Sci 33, 184-189
Nayak A K, Gartia M R, and Vijayan P K 2009 Nucl Eng Des 239, 526-540.
[16] Bejjam R B, Kumar K K, and Balasubramanian K 2018 J. Thermal Sci Eng Appl
[17] Naphade P, Borghoin A, Raj R T, and Maheshwari N K 2013 Procedia Eng 64, 936–945
[18] Saha R, Sen S, Mookherjee S, Ghosh K, Mukhopadhyay A, and Sanyal D 2015 J Heat Transf 137 (12), 121010
[19] Vijayan P K, Nayak A K, Saha D, and Gartia M R 2008 Sci Technol Nucl Install, 1–17
[20] Misale M, Garibaldi P, Passos J C, and de Bitencourt G G 2007 Exp Therm Fluid Sci 31 (8)
[21] Garibaldi P and Misale M 2008 J Heat Transf 130 (10), 104506
[22] Vijayan P K, Sharma M, and Saha D 2007 Exp Therm Fluid Sci 31 (8), 925–945
[23] Abdillah H, Saputra G, Novitrian, and Permana S 2017 J Phys Conf Ser 877, 012047
[24] Septiawan R R, Abdillah H, Novitrian, and Suprijadi 2014 Proc 2014 Int Conf Adv Edu Tech, Bandung, Indonesia
[25] Hariyanto D and Permana S 2020 Int J Electron Electr Eng 8 (2), 24-30
[26] Hariyanto D, Permana S, and Suprijadi 2020 Int J Energy Res, 1-12
[27] Aji I K, Waris A, and Permana S 2015 5th Int Conf Math Nat Sci, Bandung, Indonesia