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Numerical Analysis of Flow Stability in a Natural Circulation Loop

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ABSTRACT

Flow modeling of a natural circulation loop is of high importance in ensuring the stability of the system. As a system relying on buoyancy force, several parameters play a crucial role in determining stability. In this study, a one-dimensional numerical model is employed to predict the mass flow rate and stability due to the variation of heated riser and cooled faller locations. The result shows that the highest flow rate of 0.344 kg/s is obtained as the heater is located at the lowest position, while the cooler remains at the top. Furthermore, a stability map is plotted to show the condition for the stability, whereby the result demonstrates that the location with a relatively low mass flow rate exhibits a higher chance of oscillating flow.

I. Introduction

Efficient fluid circulation is of high importance in a thermal-hydraulic system. It ensures consistent mass and thermal transport, maintaining the temperature and performance of the system. Typically, fluid circulation relies on an external pumping system, allowing the fluid to flow based on the considered rates and directions [1]. This external power demands a high amount of energy, which reduces the system's overall efficiency. Some systems adopt an alternative approach by using the passive system to circulate the fluid to address this challenge. In cooling, for instance, thermosyphon and heat pipe can maintain the heat exchanging mechanism by relying only on buoyancy and capillarity phenomenon [2].

One popular alternative is natural circulation (NC). As its name implies, NC allows the flow to circulate without additional force. It relies on the buoyancy force due to temperature and density gradient [3] with a heater and cooler at different locations. This positioning allows the fluid to flow as the density alters within the channel [4]. One type of this system is the NC loop, wherein the flow circulates in a closed-loop configuration [5]. Due to its characteristics, NC loops are implemented in a wide range of applications, such as nuclear power plants [6], electronic cooling [7], and solar heat collectors [8].

As this system relies on buoyancy force, careful consideration of the design and working parameters is utterly fundamental. In contrast to the pump-based flow which can regulate the flow rates and directions, the NC loop is sometimes unstable and unsteady [9]. It also has a relatively low mass flow rate as a result of a small buoyancy force that needs to counter friction and gravitation. Numerous studies have been conducted to analyze the design parameters for ensuring the stability of the flow. Jain and Rizwan-uddin [10] investigated the supercritical flow instability of the NC loop. This study numerically investigated the stability boundary region for the flow at different heat and mass fluxes. A similar study was conducted by Vijayan et al. [11], whereby the fluid stability was obtained by altering the diameter of the channel. The study showed that in a certain condition, the mass flow rate due to buoyancy force will be chaotic. A two-dimensional numerical model for the NC loop and its validation was developed by Hariyanto et al. [12]. The model represents the mass flow rate of various geometrical and flow rate variations of the system. Both numerical and experimental studies show a distinctive change in mass flow rate as the pipe length doubled.

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In addition to the NC loop geometrical design, the flow phase and properties also have a direct impact on the buoyancy-driven flow. Vijayan et al. [11] compared the circulation between single-phase and two-phase fluid in an NC loop, whilst the effect of fluid properties was observed by Tlili et al. [4]. In both studies, it is clear that the properties and phase of the fluid highly affect the stability map of the NC loop.

A number of studies have been conducted to find the stability behavior of a flow in an NC loop. However, so far little work has been done in analyzing the effect of heater locations on the stability map. This study aims to develop a model of a simple NC loop for various heating and cooling locations. By formulating and implementing a mathematical model using Python, this study seeks to quantify the impact of heating and cooling positions on the mass flow rate and its stability map.

II. Method

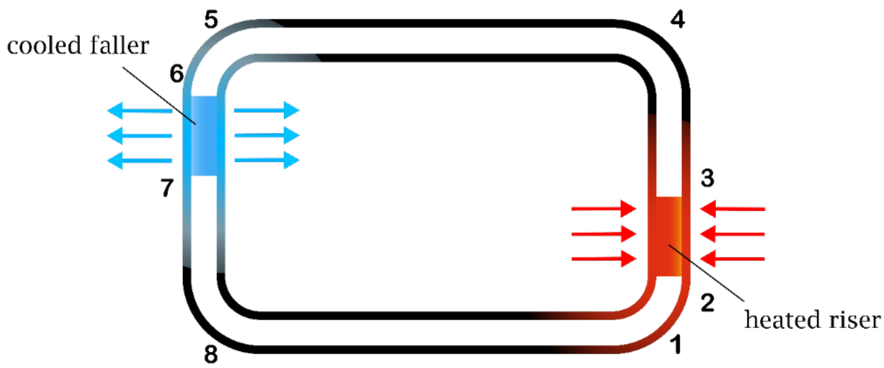


Fig. 1. Schematic diagram of the simulation domain.

The simulation test case features an NC loop with a total length of 8 meters, organized into a square configuration where each side measures 2 meter. It includes a heat source positioned at the "heated riser" to introduce thermal energy, and a cooling mechanism at the "cooled faller" to extract heat, creating a temperature gradient necessary for fluid circulation. The test case explores two configurations: the first with both the heated riser (l_{23}) and cooled faller (l_{67}) extending 1 meter each, and the second reducing these lengths to 0.5 meters, to study the system's response to variations in heating and cooling lengths. Additionally, the locations of the heater (l_{12}) and cooler (l_{56}) are adjusted to assess the impact on the fluid's natural circulation dynamics. In this study, the fluid used in the loop is water under atmospheric pressure. The schematic diagram of the simulation domain is presented in Fig. 1.

The simulation was constructed by one-dimensional approximation of mass, momentum, and energy conservation as presented in Equation (1) to (3). The equations were then discretized and calculated in a loop by a Python programming language. In order to ensure the calculation stability, the time-step (Δt) and number of nodes (I) were varied and validated accordingly.

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial \dot{m}}{\partial x} = 0 \tag{1}$$

$$\frac{1}{A}\frac{\partial \dot{m}}{\partial t} + \frac{1}{A}\frac{\partial}{\partial x}(\dot{m}u) = -\frac{\partial P}{\partial x} + \rho B - \frac{2f}{d_h A}\dot{m}u \tag{2}$$

$$c_p\frac{\partial(\rho T)}{\partial t} + c_p\frac{\partial}{\partial x}(\rho T u) = -P\frac{\partial u}{\partial x} + Q + \frac{2f}{d_h A}\dot{m}u^2 \tag{3}$$

Furthermore, as the flow relies on the density gradient due to temperature change, the Boussinesq approximation was employed to predict the density change over time, as presented in Equation (4).

$$\rho = \rho_0\big(1 - \beta(T - T_0)\big) \tag{4}$$

Finally, the model was validated by comparing the result to the analytical solution, whereby the steady analytical approximation of a specific heating and cooling location can be derived from

Equation (5) to Equation (6). In this approximation, the total pressure drop of all sections in a loop is equal to zero.

$$-\Delta p - \frac{\tau P l}{A} - \bar{\rho} g(\hat{\boldsymbol{l}} \cdot \hat{\boldsymbol{k}}) l = 0 \tag{5}$$

$$m^3 = 2\left\{-\frac{l_{23}^2}{2} - l_{23}l_{34} + l_{23}l_{67} - \frac{l_{67}^2}{2} + l_{23}l_{78} - l_{67}l_{78}\right\}\left(\frac{\dot{q}'\beta g \rho_0^2}{c_p}\right)\frac{A^3}{fpL} \tag{6}$$

Verification and validation were conducted by increasing the number of nodes. In this process, mass flow rate at steady condition was selected as the quantity of interest. As presented in Fig. 2, both 250 kW and 100 kW test cases demonstrated that convergence was achieved at 160 nodes. Beyond this point, further increases in the number of nodes led to only minimal changes in the results, indicating a stable solution. Additionally, the comparison with analytical solutions revealed a remarkably low error rate of 1.32%. Given these findings, the configuration has been adopted for further steps of the research.

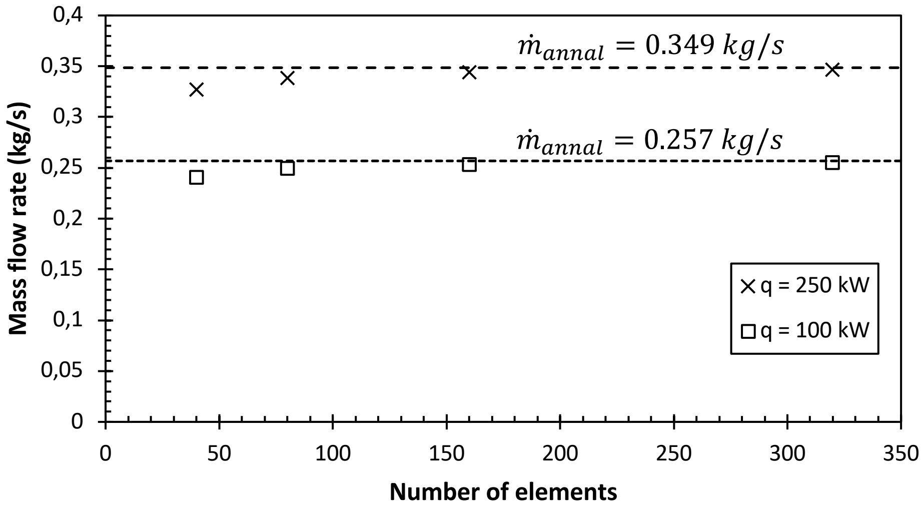


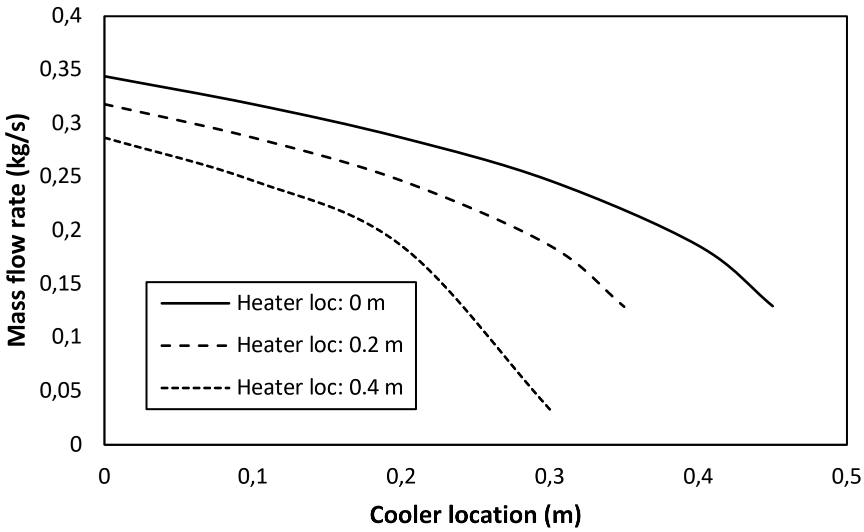
Fig. 2. Verification and validation of the numerical model.

III. Results and Discussion

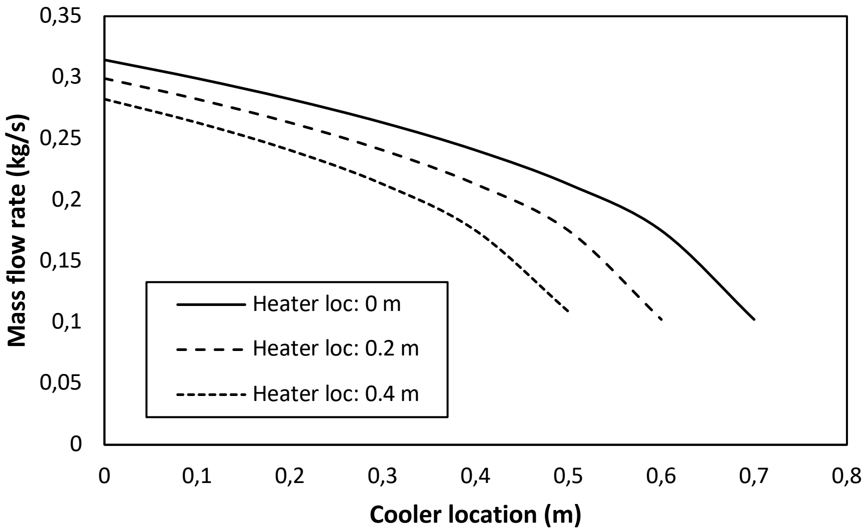
The simulation was conducted by varying heater and cooler lengths (l_{23} and l_{67}) and positions (l_{12} and l_{56}). For each heater and cooler length, the position was altered from attached to the edge toward the next elbow, with an increment of 0.2 m. This process stops if the result showcases an unsteady or oscillating output of the mass flow rate. In this test case, all heat flux is maintained at 250 kW.

Fig. 3 (a) and (b) depict the mass flow rate of the system with the length of the heated riser and cooled faller of 1 m and 0.5 m, respectively. The result shows a reducing trend as the heater and cooler location increases. This result proves that the highest mass flow rate can be obtained by maintaining the heater as low as possible while installing the cooler at the highest part of the system. This trend is expected, since the buoyancy force will move upward from the location with the lowest density, i.e. heated part. Hence, lowering the heater location will result in more movement of fluid along the vertical pipe. Similarly, higher density is obtained at the cooled part, allowing the fluid to drop along the faller.

Furthermore, albeit having a 50% reduction in the heating and cooling area, the mass flow rate reduction in Fig. 3 (b) shows only a slight reduction. The highest mass flow rate is observed at 0.344 kg/s for the 1 m test case and 0.314 kg/s for the 0.5 m test case. In the second test case, the maximum location before getting unstable is higher at around 0.7 m, whilst the first test case can only reach below 0.5 m. However, please note that since the length is different, both locations show more or less similar locations when measured from the other side. This trend will be discussed further in the next part.



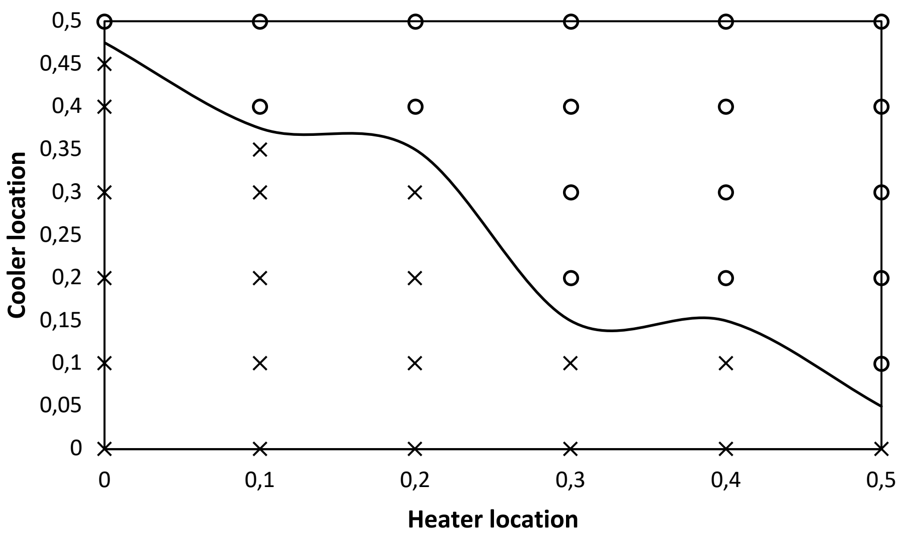
(a)



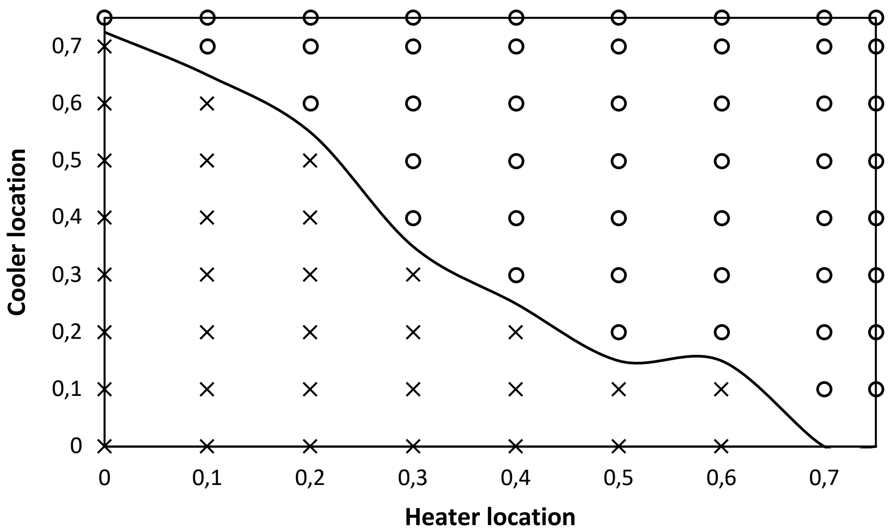
(b)

Fig. 3. Mass flow rate of different heater and cooler locations for (a) l_{23} = 1 m and (b) l_{23} = 0.5 m.

The stability maps are plotted and presented in Fig. 4 (a) and (b). The maps illustrate the region where the flow results in the steady or oscillating result of mass flow rate. In this figure, location is non-dimensional and can be obtained by comparing the heater and cooler location to the total length of the vertical pipe. In physical meaning, the steady solution demonstrates the configuration where the flow circulates in one direction (counterclockwise) in a steady condition after a certain amount of time. Meanwhile, the oscillating result indicates that the mass flow is unstable, circulating both clockwise and counterclockwise, and never reaching a steady condition as the time rises.



(a)



(b)

Fig. 4. Stability map for (a) l_{23} = 1 m and (b) l_{23} = 0.5 m. The cross marks indicate stable result, while circle marks indicate oscillation.

Furthermore, both stability maps are presented in a single plot of Fig. 5. By comparing both boundaries of steady and oscillating region, it is demonstrated that the test case with shorter heater has more stable area than the longer one. However, both has the same trend, whereby the instability will most likely occur as the heater rises and the cooler location lowered. This trend is as a result of buoyancy phenomenon. Similar to its impact on the mass flow rate, the non-ideal positioning of the heater and cooler will result in the unstable movement of the fluid. In this study, it is found that the unsteady condition for the first test case is obtained as the heater and cooler reach 0.5 of the total length, while the second test case start to oscillate at around 75% of the total vertical length.

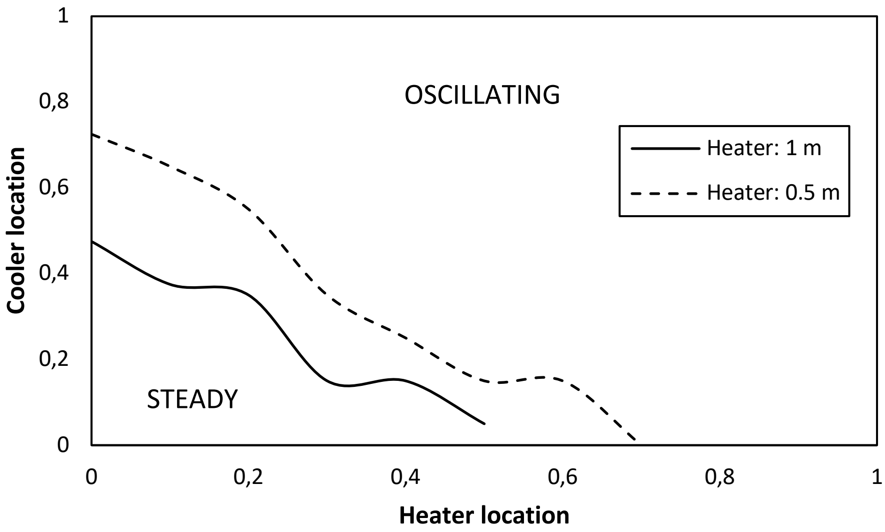


Fig. 5. Stability map comparison.

IV. Conclusion

A numerical model of the NC loop has been built and validated by a one-dimensional approximation of mass, momentum, and energy conservation. Some key findings of this study are as follows:

1. A steady mass flow rate reduces as the heater location rises while lowering the cooler will result in the same trend. This result is expected since the buoyancy-driven flow will be effective when the lowest density is located at the bottom of the system. The highest mass flow rate is observed at 0.344 kg/s and 0.314 kg/s for the first and second test cases, respectively.
2. The stability map shows that the oscillating flow will occur as the heater and cooler locations move to the top and bottom, respectively. The limit for the steady flow is observed at around 50% of the vertical length for the 1 m heater test case, and about 0.75 for the 0.5 m heater test case.

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