# Sensitivity Assessment of Gas Injection Effect on the Natural Circulation Performance through Adiabatic Two-Phase Experiment

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## 1. Introduction

The molten salt reactor (MSR) has been actively researched worldwide owing to its notable advantages, including the high thermal efficiency and inherent safety. In 2021, an i-SAFE-MSR research center at Hanyang Univ. proposed the concept of an advanced liquid-fueled MSR referred to as a passive molten salt fast reactor (PMFR) [1]. The PMFR, aiming for a target thermal power of 370 MW envisions the natural circulation operation to avoid undesirable transitions caused by frequent pump failure.

However, a major issue related to insoluble fission products (IFPs) exists in the PMFR system. The IFPs circulating the primary system alongside the liquid-fuel can stick to materials such as a heat exchanger. The adhered IFPs are likely to cause an acceleration of corrosion and a decrease of heat transfer efficiency [2]. In this regard, IFPs need to be removed in the system while not affecting its normal operation.

To remove IFPs, the PMFR employs a helium bubbling system, which has been frequently utilized in the MSR. Fig. 1 illustrates the helium bubbling system. When the helium bubbling system injects the helium bubbles into the system, the IFPs adhere to the surface of the bubbles. The helium bubbles attaching the IFPs move upward due to buoyancy. The helium bubbles burst when they meet the free-surface between the atmosphere and liquid-fuel. Thereafter, IFPs are separated from the surface of helium bubbles. The separated IFPs are eliminated through a removal device of IFPs installed at the upper part.

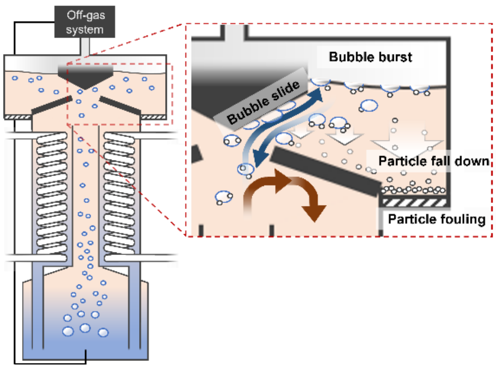


Fig. 1. A schematic of helium bubbling system

Simultaneously, the helium bubbling system has an additional effect associated with the natural circulation performance beyond the removal of IFPs. The drag of injected helium bubbles is applied as a driving force for the circulation of working fluid [3]. In particular, the natural circulation enhancement induced by the drag of bubbles has significance in PMFR, where the natural circulation operation is adopted. Therefore, it is crucial to thoroughly investigate the helium bubbling effect on natural circulation performance as this is the key feature of the PMFR.

Thus, this study examined the effect of helium bubbling on natural circulation performance through adiabatic two-phase experiments. In addition, the bubbles were visualized to confirm the two-phase flow regime under different conditions.

## 2. Experimental setup

### *2.1. Experimental apparatus*

Figs. 2 (a) and (b) illustrate a schematic of the adiabatic two-phase experimental facilities and an actual loop, respectively. The experimental loop consists of a riser, an upper pool, a downcomer, a buffer tank, a bottom line, and nozzles. The helium injection rate was controlled using a mass flow controller (MFC). The injected helium gas was released from the loop through four venting holes located on the upside of the upper pool. As the total area of four venting holes is 12.67 $cm^2$, the helium gas within the loop could be sufficiently removed without the pressurization of the system by the helium gas.

The experiment utilized a glycerol-water solution as a working fluid to adjust its viscosity. The experiment was conducted at room temperature (20 °C) and normal pressure (1 atm). The behavior of bubbles was captured at the visualization region as shown in Fig. 2 (a) through a high-speed camera and a lighting device.

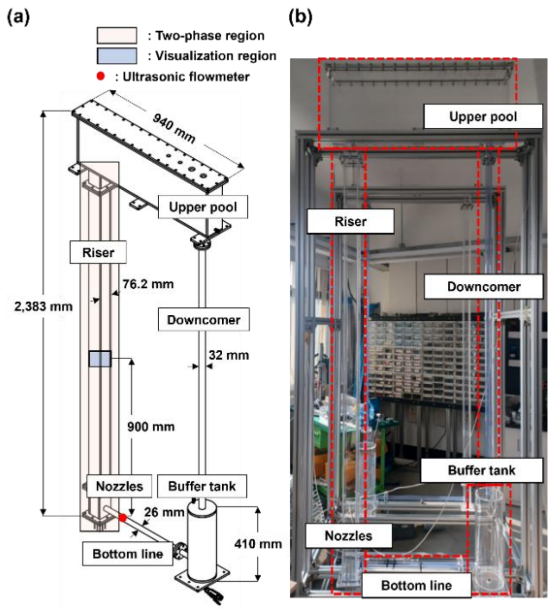


Fig. 2. (a) A schematic of the adiabatic two-phase experimental facilities (riser with a width of 3 inches) and (b) actual loop

The major thermal-hydraulic parameters that should be evaluated in this experiment were selected as the working fluid velocity and void fraction. The working fluid velocity, serving as an indicator of natural circulation performance, was measured by an ultrasonic flowmeter installed at the bottom line as shown in Fig. 2 (a). Due to the difficulty of measuring the void fraction on a system scale, the volume-averaged void fraction in the riser channel was calculated using a correlation.

$$\varepsilon_g = \frac{U_{g,s}}{C_0 U_M + U_{GM}} \qquad (1)$$

$$U_{GM} = 0.35\sqrt{gD} \qquad (2)$$

A theoretical correlation proposed by Nicklin et al. was utilized because this correlation can predict the void fraction in a vertical channel at the reliable level, using the working fluid velocity measured in this experiment [4]. This correlation was presented in Eq. (1). Here, $C_0$ is the distribution parameter, $U_M$ and $U_{GM}$ are the two-phase mixture velocity and the drift velocity, respectively. The distribution parameter ($C_0$) is assumed as 1.2 in the Nicklin et al. correlation. The drift velocity ($U_{GM}$) can be calculated through Eq. (2) where $g$ and D are the gravitational acceleration and hydraulic diameter of the riser channel, respectively.

### *2.2. Sensitivity variables*

The sensitivity variables were decided based on the variables that significantly affect the two-phase flow [5]. In this experiment, the sensitivity variables were established as the type of gas, the amount of gas injection rate, the viscosity of the working fluid, and the width of the riser channel. Air was also utilized in addition to helium, to compare the drag effect by the respective gas. The amount of helium and air injection rate was regulated through helium and air MFC, respectively, from 1 to 15 lpm (liters per minute).

To evaluate the viscosity effect on the natural circulation performance, the viscosity of the working fluid was modified by adjusting the weight percent of glycerol. The 1 and 4 cP of viscosity values were determined by considering the viscosity of liquid-fuel like $KCl$-$UCl_3$-$UCl_4$ (1.34-3.49 cP) or $NaCl$-$UCl_3$ (1.84-4.11 cP) under the PMFR operating conditions. The riser channels with widths of 2 and 3 inches were used in the experiment to confirm changes in bubble interaction according to the size of channel. Table 1 shows the test matrix reflected in the experiment. Every case presented in Table 1 was repeatedly performed five times to ensure precision.

Table 1. Test matrix for the experiment

| The amount of gas injection rate: 1-15 lpm | | | | |
|---|---|---|---|---|
| Width of the riser channel | 2 inches | | 3 inches | |
| Gas type / Viscosity | Helium | Air | Helium | Air |
| 1 cP (pure water) | Case 01 | Case 03 | Case 05 | Case 07 |
| 4 cP | Case 02 | Case 04 | Case 06 | Case 08 |

## 3. Results and discussion

### *3.1. Visualization of bubbles*

The helium bubbles alone were captured as shown in Figs. 3-6 with a time step of 0.05 seconds because the changes in flow patterns were similar between the injection of helium and air. Each figure illustrates the transition of flow regime from dispersed bubbly flow to slug flow as helium injection rates increase from 1 to 15 lpm.

Figs. 3, 4 and 5, 6 show the sensitivity over the width of the riser channel. In the riser channel with a width of 2 inches (narrow riser channel), bubble interaction like bubble coalescence was dominant compared to 3 inches riser channel (wide riser channel). Thus, the periodic slug was observed more frequently in the 2 inches riser channel. Figs. 3, 5 and 4, 6 illustrate the sensitivity of a working fluid viscosity. As a viscosity of working fluid increases from 1 to 4 cP (centipoise), a single bubble in the fluid tends to be a more spherical shape.

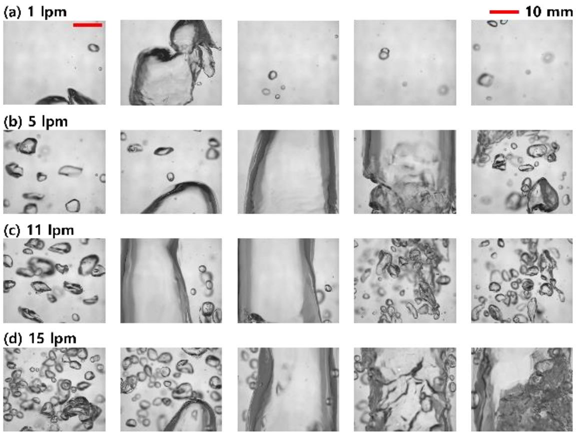


Fig. 3. Visualization of helium bubbles injected by the amount of (a) 1 lpm, (b) 5 lpm, (c) 11 lpm, and (d) 15 lpm into 1 cP working fluid in the riser channel with a width of 2 inches (Case 01)

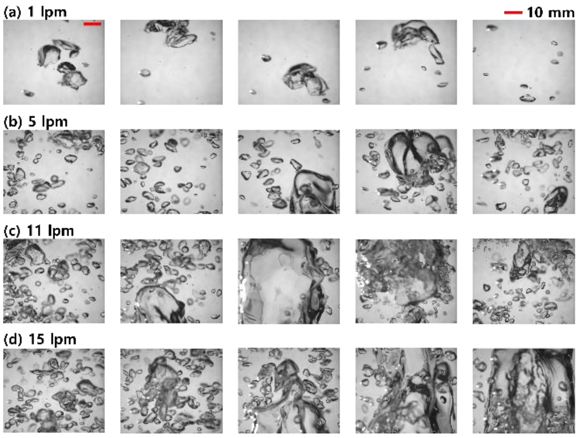


Fig. 4. Visualization of helium bubbles injected by the amount of (a) 1 lpm, (b) 5 lpm, (c) 11 lpm, and (d) 15 lpm into 1 cP working fluid in the riser channel with a width of 3 inches (Case 05)

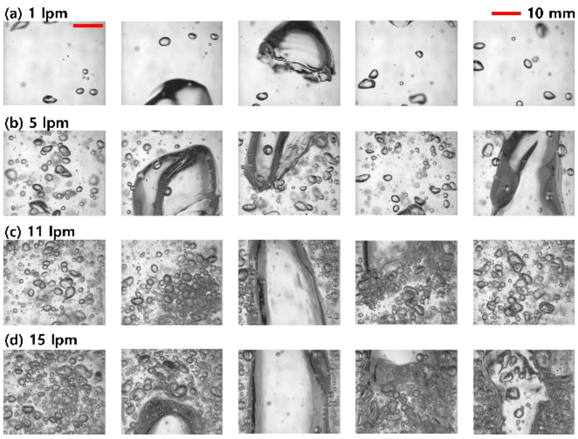


Fig. 5. Visualization of helium bubbles injected by the amount of (a) 1 lpm, (b) 5 lpm, (c) 11 lpm, and (d) 15 lpm into 4 cP working fluid in the riser channel with a width of 2 inches (Case 02)

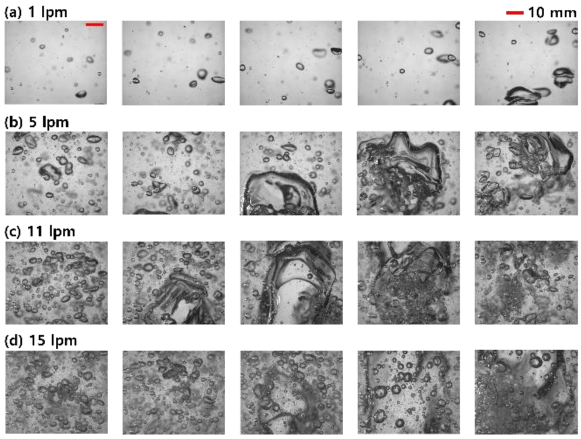


Fig. 6. Visualization of helium bubbles injected by the amount of (a) 1 lpm, (b) 5 lpm, (c) 11 lpm, and (d) 15 lpm into 4 cP working fluid in the riser channel with a width of 3 inches (Case 06)

### *3.2. Experimental results*

Figs. 7 and 8 show experimental results on the working fluid velocity measured at the bottom line when widths of riser channel are 2 and 3 inches, respectively. According to experimental results, helium injection exhibited a positive effect on the natural circulation performance of working fluid. Helium increased the working fluid velocity by 3.96-13.43% more than air. This enhancement is attributed to the greater buoyancy of helium mainly resulting from its lower density compared to air.

As gas injection rates increase from 1 to 15 lpm, the natural circulation performance of working fluid was improved due to intensified drag. When the gas was injected as 15 lpm, the working fluid velocity increased by 184-349% at each case compared to 1 lpm gas injection rate. However, a gradient of increasing velocity decreased as gas injection rates increase from 1 to 15 lpm since a two-phase frictional pressure drop also increased.

As the viscosity of working fluid increased from 1 to 4 cP, the natural circulation performance worsened. The working fluid velocity at the viscosity of 4 cP decreased about 0.13-20.43% compared to 1 cP due to a larger resistance on the flow. The velocity gradient exhibited a similar pattern between working fluids with the identical viscosities, as depicted in Figs. 7 and 8. Furthermore, the working fluid velocity at the bottom line in the loop with 2 inches riser channel increased by 27.45-46.87% compared to the loop with 3 inches riser channel due to conservation of mass and more occurrence of slugs.

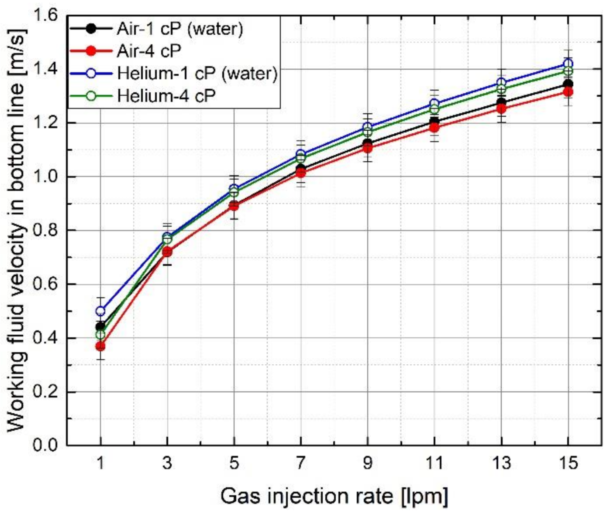


Fig. 7. Working fluid velocity at the bottom line according to the amount of gas injection rate, the type of gas, and a viscosity of working fluid in the riser channel with a width of 2 inches (Case 01-04)

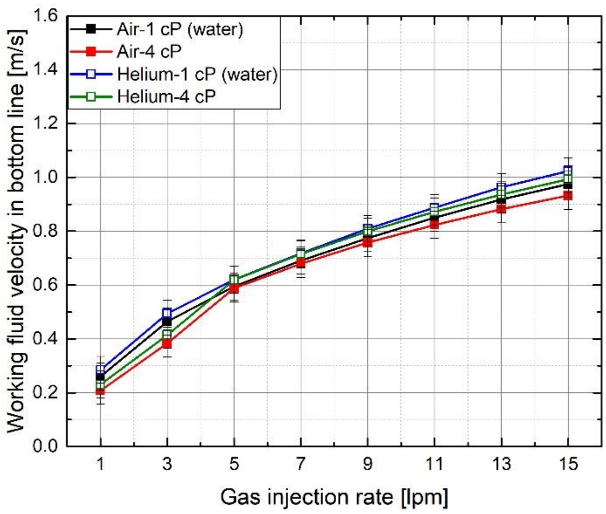


Fig. 8. Working fluid velocity at the bottom line according to the amount of gas injection rate, the type of gas, and a viscosity of working fluid in the riser channel with a width of 3 inches (Case 05-08)

Figs. 9 and 10 show the volume-averaged void fraction in the riser channel when widths of riser channel are 2 and 3 inches, respectively. The experiment exhibited that the volume-averaged void fraction increased as gas injection rate increases from 1 to 15 lpm. At identical gas injection rates, the volume-averaged void fraction in the riser channel slightly decreased as working fluid velocity at the bottom line increases. However, there were no significant differences in void fraction values according to change of gas type and working fluid viscosity.

The void fraction was substantially influenced by the cross-sectional area of the riser channel. The void fraction in the riser channel with a width of 2 inches was larger than the riser channel with a width of 3 inches, because the narrow riser contained a smaller volume of working fluid.

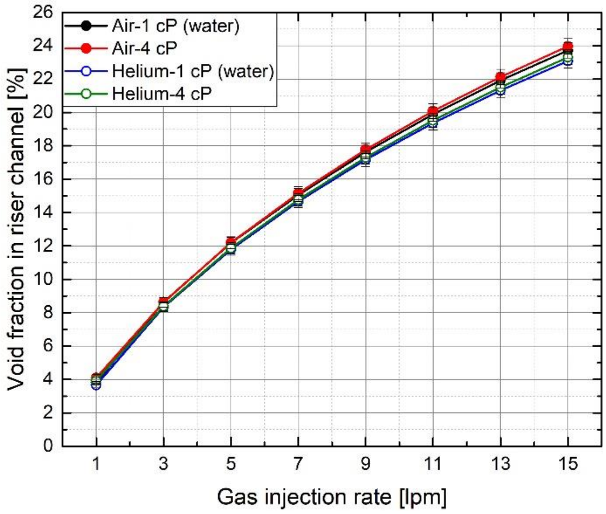


Fig. 9. Void fraction at the riser channel according to the amount of gas injection rate, the type of gas, and a viscosity of working fluid in the riser channel with a width of 2 inches (Case 01-04)

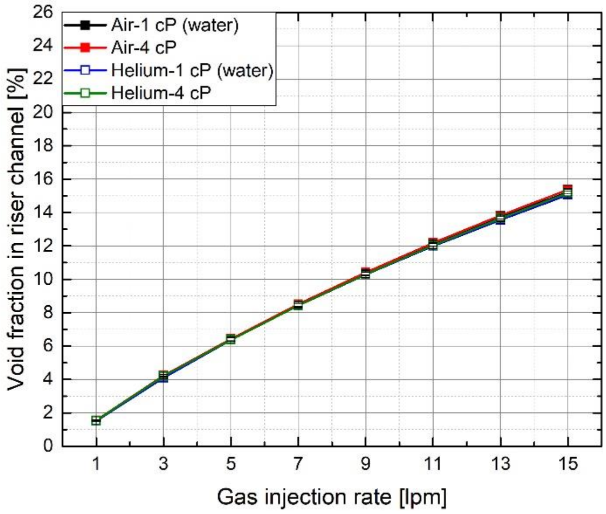


Fig. 10. Void fraction at the riser channel according to the amount of gas injection rate, the type of gas, and a viscosity of working fluid in the riser channel with a width of 3 inches (Case 05-08)

## 4. Summary and conclusion

This study focused on evaluating the helium bubbling effect with respect to natural circulation performance in various conditions. According to the adjusted sensitivity variables, working fluid velocity and void fraction were quantitatively evaluated. Furthermore, the bubbles' behavior affecting the flow patterns was captured and analyzed. The major findings of this study can be summarized as follows:

- ✓ The flow regime was changed from the dispersed bubbly flow to the slug flow as gas injection rates increase from 1 to 15 lpm.
- ✓ The helium injection was more effective to reinforce the natural circulation performance compared to air about 3.96-13.43%.
- ✓ The working fluid velocity at the viscosity of 4 cP decreased about 0.13-20.43% compared to 1 cP due to a larger resistance on the flow.
- ✓ The working fluid velocity in the 2 inches riser channel was larger than the 3 inches riser channel about 27.45-46.87%
- ✓ The void fraction in the riser channel with a width of 2 inches was larger than the riser channel a width of 3 inches.

Based on the findings of the adiabatic two-phase experiment, a non-adiabatic two-phase experiment applying a similarity law will be performed for the PMFR development. These experimental results will contribute to advancing the concept of PMFR.

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