Preliminary Analysis of Helium Bubbling Effect on Two-phase Flow for Passive Molten Salt Fast Reactor (PMFR)

Won Jun Choi[a], Jae Hyung Park[a], Juhyeong Lee[a], Jihun Lim[a], Yun Sik Cho[a], Yonghee Kim[b], Youngsoo Yoon[c], Sangtae Kim[a], Sung Joong Kim[a, d*]
[a] *Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[b] *Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*
[c] *Department of Materials Science and Engineering, Gachon University, 1342 Seongnam-daero, Sujeong-gu, Seongnam-si, Gyeonggi-do, 13120, Republic of Korea*
[d] *Institute of Nano Science and Technology, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
** Corresponding author: sungjkim@hanyang.ac.kr*

1. Introduction

Hydrogen has been highlighted as the alternative energy source replacing fossil fuels due to the high energy density and no carbon emission. Several techniques have been reported to produce hydrogen, such as natural gas reforming, by-product hydrogen, and high temperature steam electrolysis (HTSE). However, significant carbon emission and low productivity are expected by natural gas reforming and by-product hydrogen, respectively. On the other hand, the HTSE is a highly feasible method to produce hydrogen owing to low carbon emission and high productivity. To secure high efficiency of hydrogen production by using the HTSE, however, an innovative system that can provide high operating temperature and efficient electricity generation is required. Accordingly, to achieve the efficiency higher than 40 % without carbon emission, the HTSE using molten salt reactor (MSR) as the high-quality heat source is proposed due to its high operating temperature ranging 600 ~ 750 ℃ and highly effective electricity production with efficiency larger than 40% [1].

To realize innovative and essential technologies for successful deployment of the MSR, a Research Center for Development of Innovative Original Technology of a Severe-Accident-Free Multi-Purpose Long-lifetime Small Modular Reactor (i-SAFE-MSR research center) was established in Republic of Korea since 2021. The i-SAFE-MSR research center proposed a Passive Molten salt Fast Reactor (PMFR), an advanced design of the MSR [2]. The major concepts and requirements for the PMFR are summarized as follows:

- ✓ Long-lifetime operation up to 20 years
- ✓ Natural circulation operation without pumps
- ✓ Severe-Accident free and passive safety system
- ✓ Non-soluble fission product removal system
- ✓ Low radioactive waste
- ✓ 3-D Multi-physics MSR analysis code platform

The fuel salts such as UF_4 and UCl_3 are dissolved in coolant salts such as FLiBe (LiF-BeF_2), NaCl, and KCl in the MSRs. In other words, the nuclear fuel materials and the fission products (FPs) exist in the primary system during operation. Accordingly, the reactor coolant pumps (RCPs) can be damaged due to the high temperature of eutectic mixture salt. The damaged RCPs can cause undesirable transition of the operation and safety of the reactor. To reduce the possibility of the situations induced by RCPs, the PMFR is designed to operate by natural circulation. Because fast neutron spectrum is adopted, the graphite moderator which is a significant obstacle for successful MSR development could be eliminated in the PMFR. Accordingly, the lower pressure drop can be achieved, which also facilitates the natural circulation of the PMFR. In addition, the large temperature difference between the inlet and outlet of the core could be achieved by as much as 150℃. Thus, the sufficient buoyancy force is expected to be generated. As such, the primary system of the PMFR can be simplified greatly, which is advantageous in natural circulation operation without relying on RCPs.

Because the fuel materials are dissolved in the molten salt of the primary system, the FPs generated during the fission reaction also exist to form during normal operation. Among various FPs, non-soluble materials such as gases and noble metals can affect the reactor stability. In addition, the noble metals can be deposited on the surface of the equipped structures or they can be circulated through the reactor core and affects the reactivity. As the accumulation increases, decrease of heat transfer and local material damage can be induced. Thus, the He-bubbling system was adopted to separate the non-soluble FPs from the primary coolant. Figure 1 shows the He-bubbling system for the PMFR. The gas injection part is installed on the bottom. As the He-bubbles move from the bottom to the free surface, the non-soluble FPs in the flow path move together. In other words, the noble metals can be removed in the top region of the PMFR by using an adequate removal system.

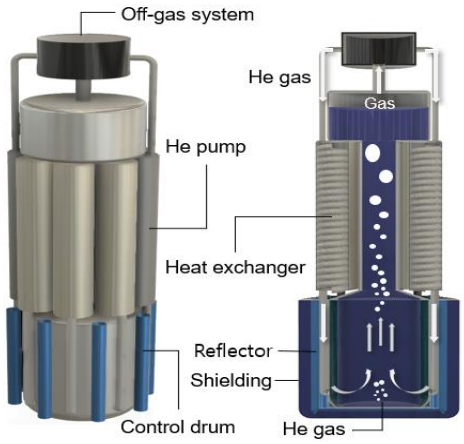

Fig. 1. 3-D schematic of helium bubbling system in PMFR

The PMFR can be operated with the buoyancy force due to the density difference caused by the large temperature difference. However, the reactor has to be larger to achieve same thermal power operated with pumps. Herein, the He-bubbling system adopted for FP removal can enhance the circulation performance of the molten salt fuel. He-bubbling can supply the additional driving force to the working fluid by the buoyancy due to the extremely large difference of density between He gas and molten salt. Thus, the larger thermal output can be achieved by using the He-bubbling system. Interestingly, the He-bubbling system promotes not only non-soluble FP removal but also the fluid circulation in the primary system. Previous 1-D preliminary analysis showed that the He-bubbling-assisted primary system could achieve the larger thermal power with injection rate [3].

Since the 3-D MSR analysis code platform is under development by the i-SAFE-MSR research center, OpenFOAM code, an open-source computational fluid dynamics (CFD) software, was selected for the 3-D thermal-hydraulic analysis. However, the available data to validate the simulation on the two-phase flow using molten salts and He-gas have not been reported so far. Accordingly, a lab-scale validation experiment, an adiabatic two-phase natural circulation experiment with water and He-gas, and the CFD modelling of the experiment are under development to produce the validation data.

Thus, the objective of this study is to simulate the experiment with appropriate numerical method by using the OpenFOAM code. In addition, as the preliminary analysis for the experiment, effects of the key relevant parameters such as gas injection rate, length of the channel on the two-phase flow were investigated through numerical analysis.

2. A reference system

The geometry and mesh of the experiment were generated by using the SALOME 9.6.0, an open-source software providing a generic pre- and post- processing platform for numerical simulation. The purpose of designing the reference system (Fig. 2) is to investigate the mesh sensitivity and region of steady-state.

Figure 2 illustrates a simplified domain of reference system for the adiabatic two-phase natural circulation experiment. The experiment facility consists of a riser, inlets, a downcomer, a buffer tank, and an upper pool as shown in Fig. 2 (a). From 9 inlets constructed by 3 × 3 in reference system shown in Fig. 2 (b), He-bubbles are injected and the bubbles move upward through the riser. As the injected He-bubbles move upward in the riser, the liquid circulates clockwise in the system. Water was selected as the simulant of the working fluid candidates such as NaCl-UCl$_3$ (0.65 ~ 1.3 mm^2/s) or KCl-UCl$_3$-UCl$_4$ (0.63 ~ 1.05 mm^2/s) of the PMFR primary system due to the similarity of the kinematic viscosity (0.8 ~ 1.0 mm^2/s) under room temperature.

In the reference system, the riser and downcomer are square and circular channels, respectively. The width of riser is 2 inches and diameter of downcomer is 1 inch. The diameter and height of inlets constructed by 3 × 3 as shown in Fig. 2 (b) are 0.25 and 4.5 inches, respectively. The helium injection rate is 1 LPM (0.0585 m/s) in reference system.

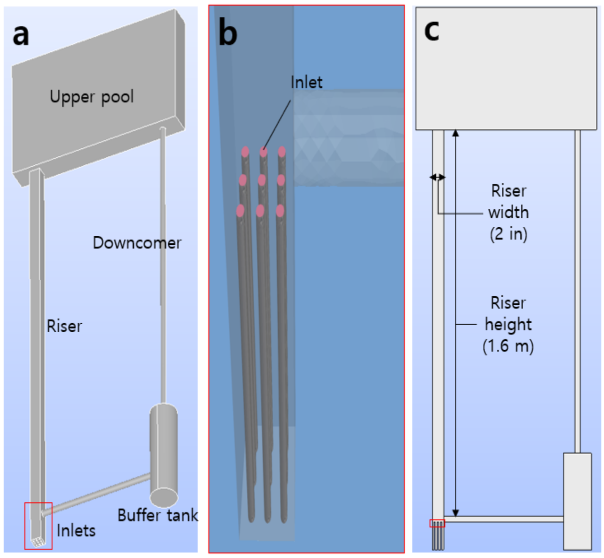

Fig. 2. (a) 3-D modelling of reference system, (b) 3 × 3 structure of inlet, (c) 2-D scheme of reference system.

3. Numerical analysis

3.1. Mesh sensitivity

In the base case analysis of the reference system, the major variables such as void fraction of helium and volumetric flow rate of water showed sufficiently stable after 15 seconds of the simulation time. Thus, the results after 15 seconds of each case were used to confirm the mesh sensitivity. To reduce the computational time and to investigate the proper mesh quality of the simulation, several cases were selected.

The mesh of reference system was divided into three cases as shown in Fig. 3. The meshes in three cases were made by NETGEN 1D-2D-3D algorithms based on tetrahedral type in SALOME. Among three meshes, Fig. 3 (a) shows the relatively coarse mesh of the reference system, where the number of tetrahedral cell mesh is 197,690. Figures 3 (b) and (c) show the moderate and fine meshes, where the numbers of cell mesh are 290,088 and 453,671, respectively. The maximum skewness of three meshes was less than 0.9, which indicates that the three meshes were moderately skewed. The range of average non-orthogonality and maximum aspect ratio in three meshes were in 15~17 and 5~7, respectively. Figures 3 (d), (e), and (f) show the cross section of mesh in the riser corresponding to Fig. 3 (a), (b), and (c), respectively.

Based on void fraction of helium and volumetric flow rate of water in the riser, the mesh sensitivity was confirmed. During the transient-state up to 15 seconds, the fine mesh and moderate-coarse mesh showed different values. However, after 15 seconds when the simulation reached the steady-state, the differences of fine-coarse mesh were approximately 0.02 % in void fraction and 0.8 % in volumetric flow rate. The differences were sufficiently small and can be neglected. Thus, the average number of mesh in most cases was selected as range of 190,000~240,000. Figures 4 and 5 show the void fraction of helium and volumetric flow rate of water in the riser with time according to 3 mesh qualities.

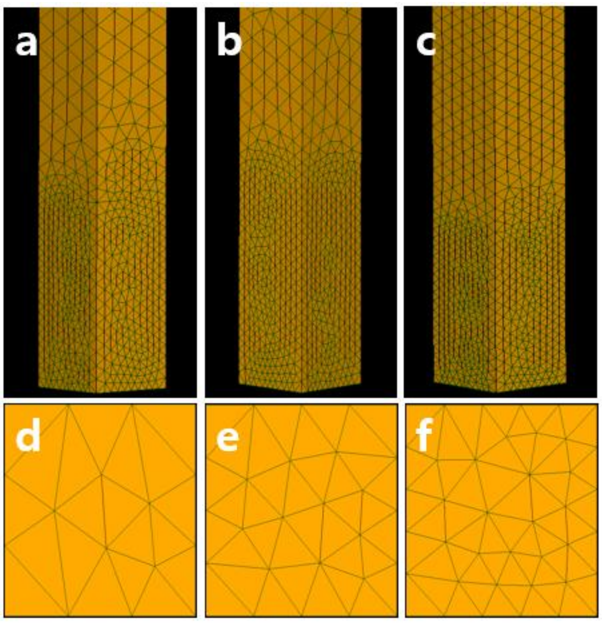

Fig. 3. (a) Coarse mesh and (b) moderate mesh and (c) fine mesh of the reference system in riser, cross-sectional views of (d) coarse mesh, (e) moderate mesh, (f) fine mesh.

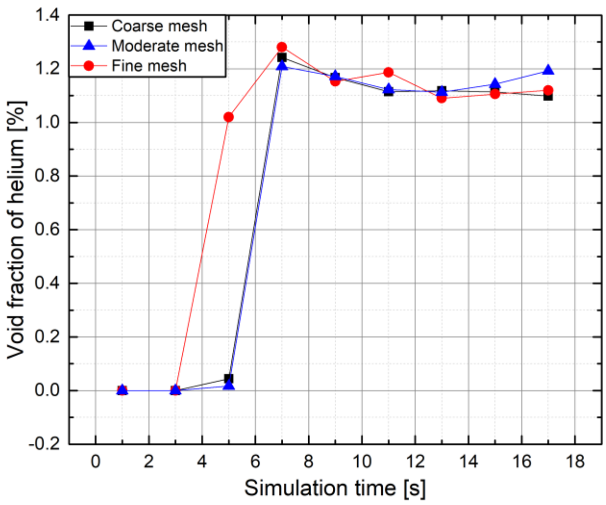

Fig. 4. Void fraction of helium according to the mesh qualities.

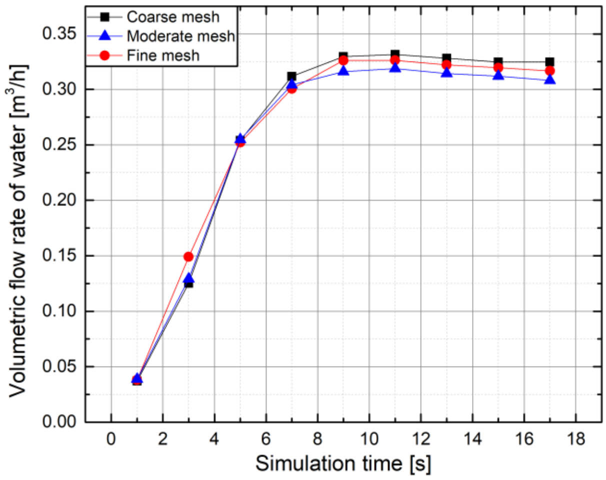

Fig. 5. Volumetric flow rate of water according to the mesh qualities.

3.2. OpenFOAM simulation

OpenFOAM contains several solvers and utilities to simulate various thermal-hydraulic phenomena. For the purpose of this study, multiphaseEulerFoam solver, which can calculate compressible fluid-phase was selected to simulate the two-phase flow. Large eddy simulation (LES) was used as the turbulence model because the Reynolds number (3000 ~ 7000) of water was predicted as turbulence flow at most cases. The SchillerNaumann model which can be used for dispersed bubbly flows and segregated model which can be used in regions with no obvious dispersed phase were selected as drag flux model. Utilizing the multiphase solver, the simulation of the reference system was conducted. The major parameters for the calculation were represented in Table 1.

Table 1. Major parameters for modelling of reference system.

Parameters	Values
Simulation	
Solver	multiphaseEulerFoam

Turbulence model	LES
Time step	0.001
Iteration and discretization	
Iterative solver	PIMPLE (Pressure -Velocity coupling algorithm)
Smoother	symGaussSeidel
Time term	Euler
Gradient term	Gauss linear
Drag flux model	SchillerNaumann segregated
Velocity boundary condition	
Inlet	fixed value (y velocity = 0.0585 m/s (He))
Outlet	pressureInletOutletVelocity
Walls	No slip condition
Mesh information	
Mesh type	Tetrahedral
Number of mesh	197,690
Max skewness	0.721956
Average non-orthogonality	16.66
Max aspect ratio	6.87757

According to experimental results obtained by Leitai et al, the height of riser and gas injection rate can be major variables for two-phase circulation [4]. Based on the results, effect by variables such as the height of riser and gas injection rate on the two-phase flow was investigated. The structure, diameter and height of inlet, and width of riser were fixed same as the reference system. Table 2 shows detailed information of parameters of two-phase flow simulation.

Table 2. Parameters of two-phase flow simulation

Parameters	Values
Gas injection rate	0.1, 0.3, 1, 3, 5, 7 [LPM]
Height of riser	1.6, 2 [m]
Structure of inlet	3 × 3
Diameter of inlet	0.25 [in]
Height of inlet	4.5 [in]
Width of riser	2 × 2 [in^2]

4. Results and Discussion

Figure 6 (a) shows the location where the water velocity and void fraction were calculated. In addition, Fig. 6 (b) and (c) show the velocity profile of water at the riser and downcomer in reference system. As shown in Fig. 6 (b) and (c), when He-bubbles are injected from inlets, water circulation in the system generates upflow at the riser and downflow at the downcomer. The He-bubbles which are injected from inlets move straightly along the riser and the upper pool. The He-bubbles are removed from top-side of upper pool set into patch type boundary condition called as pressureInletOutletVelocity. Thus, the pressurization of system can be prevented.

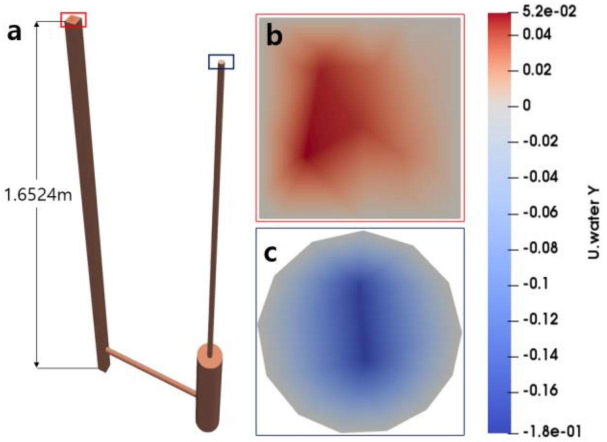

Fig. 6. (a) Location where the face-averaged values were measured and (b) Y-directional face-averaged water velocity in cross-section of riser and (c) downcomer

Because the cross-sectional area of riser is larger than that of downcomer by 5.09 times, the face-averaged water velocity in the upper part of downcomer was faster than the face-averaged water velocity of riser by 5.23 times during the steady-state. The void fraction in the riser was about 1.098 % during the steady-state and the void fraction in the downcomer is zero because no He-bubbles exist in the downcomer. Figure 7 illustrates the velocity profiles of water showing the value of 0.035 m/s in the riser and -0.183 m/s in the downcomer after 15 seconds.

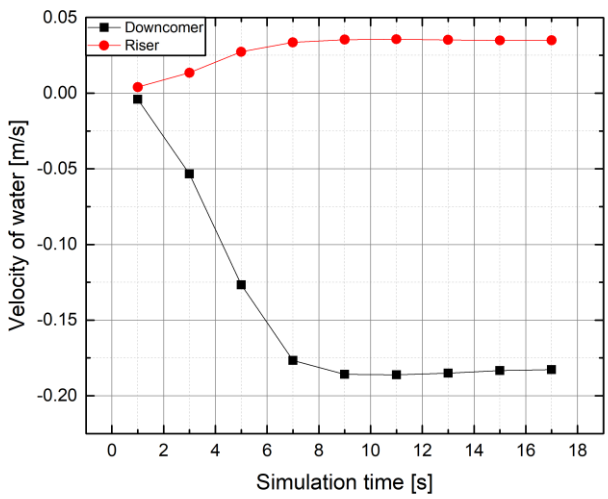

Fig. 7. Velocity profiles of water at the riser and downcomer in reference system.

According to different heights of riser and gas injection rates from reference system, void fraction change of helium and volumetric flow rate of water in the riser were investigated as shown in Fig. 8 and Fig. 9, respectively. The location where the face-averaged values were measured is 1.6524 m from bottom in the case whose height of riser is 1.6 m as shown in Fig. 6 (a). With the height of riser (2 m) higher than the riser with 1.6 m height by 0.4 m, the location where the face-averaged values were measured at 2.0524 m from bottom.

The void fraction is expressed as Eq. (1) where the V_g and V_l are volume of gas-phase and liquid-phase, respectively. Assuming that the total volume of liquid and gas was constant, the void fraction is proportional to the volume of the gas-phase, that is, the gas injection rate. Thus, as the helium injection rate increased, the void faction of helium increased almost linearly as shown in Fig. 8.

$$\alpha = \frac{V_g}{V_l + V_g} \tag{1}$$

The bubbly flow can enhance the two-phase circulation. However, as gas injection rate increases, the effect of enhancement on two-phase circulation can be reduced potentially due to combining bubbles with each other etc. [5]. Thus, the volumetric flow rate of water increased as shape of root function not linearly, as the helium injection rate increased.

Particularly, in the case of 2 m riser, the work done by working fluid increases because the distance exerted by driving force of He-bubbling lengthen. As a result, the kinetic energy of working fluid in the case with 2 m riser becomes higher than the case of 1.6 m riser. Thus, the volumetric flow rate of water through 2 m riser was slightly larger than that of the 1.6 m riser as shown in Fig. 9.

However, Fig. 9 shows that the differences of volumetric flow rate between 1.6 m riser and 2 m riser became smaller in 7 LPM, compared to 3 LPM or 5 LPM. Because the frictional pressure drop due to the presence of gas-phase (He) in the water became bigger as the gas injection rate increased as shown in Eq. (2) where Δp_{TP}, Δp_{SP} , $\emptyset^2$ are two-phase and single-phase frictional pressure drop and two-phase friction multiplier, respectively.

$$\Delta p_{TP} = \emptyset^2 \Delta p_{SP} \tag{2}$$

In other words, in the case of 2 m riser, the pressure drop becomes accumulated as He bubbles travel the longer distance than 1.6 m. Thus, the effect of buoyancy in the riser and gravity in the downcomer was offset by two phase pressure drop at high flow rates. As a result, the difference of volumetric flow rate between 1.6 m riser and 2 m riser could be reduced in the case of 7 LPM.

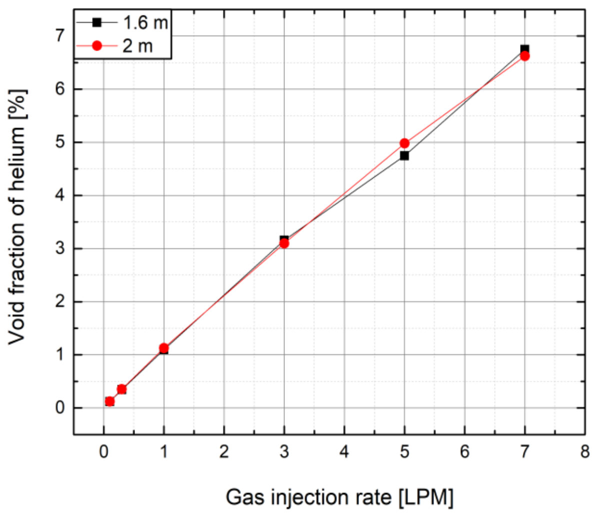

Fig. 8. Void fraction of helium according to gas injection rate and height of riser

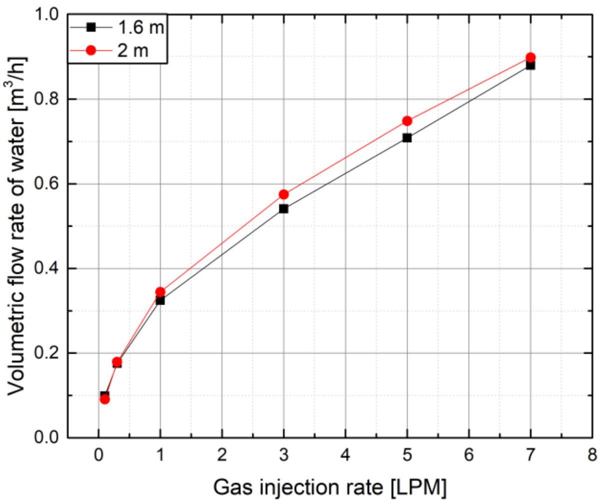

Fig. 9. Volumetric flow rate of water according to gas injection rate and height of riser

5. Conclusions

In this paper, a numerical analysis by using OpenFOAM code was carried out to assess the effects of He-bubbling on the molten salt circulation. Based on the adiabatic two-phase natural circulation experiment system, the analysis domain was generated. In addition, the effects of the parameters such as gas injection rate and height of riser were investigated. The major outcomes of this study can be summarized as follows:

- ✓ According to mesh sensitivity study, the appropriate number of mesh was assessed to range 190,000 to 240,000.
- ✓ Void fraction of helium showed similar tendency when the height of riser is 1.6 m and 2 m.
- ✓ Void fraction of helium increased almost linearly with the gas injection rate.
- ✓ With the same He gas injection rate, the higher riser cases showed the larger flow rate of water

because the bubbles could supply more driving force.

- ✓ As the gas injection rate increased from 0.1 to 7 LPM, the water velocity increased. However, the slope decreased because the two-phase flow showed more frictional loss.

As the CFD analysis was successfully conducted, the current numerical data can be used for further experimental validation. The CFD modelling method in this study will be validated by the experiment as the future work.

Acknowledgments

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