Preliminary Analysis of the Effect of the Gas Injection on Natural circulation for Molten Salt Reactor Type Small Modular Reactor System Operated without a Pump

Jihun Lim[a], Doyoung Shin[a], Taeseok Kim[a], Jae Hyung Park[a], Juhyeong Lee[a], Yun Sik Cho[a], Yonghee Kim[c], Sangtae Kim[a], Sung Joong Kim[a, b*]
[a] *Department of Nuclear Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[b] *Institute of Nano Science and Technology, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea*
[c] *Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*
** Corresponding author: sungjkim@hanyang.ac.kr*

1. Introduction

Molten salt reactor (MSR) is one of the advanced reactors identified by the Generation IV International Forum. The unique feature of the MSR distinguished from any other reactors is its liquid fuel. In the MSR system, fissile materials are dissolved with the coolant as a form of halogen compounds. The compound circulates the primary system of the MSR and the heat is generated only when it passes through the core region. Due to the physicochemical characteristics of molten halide salts, the MSRs have the following unique safety advantages [1]:

1) A low-pressure system due to its low vapor pressure and high boiling temperature (~1400°C).
2) Exclusion of hydrogen explosion for chloride-based salt reactors.
3) Solidification of the salt when the leakage occurs trapping the radioactive materials.

However, there exists some insoluble fission products called noble metal and noble gas in the salt. The undesirable metal particles in the salt may continuously be deposited on the surfaces of major components. Deposition of these particles has potential risks such as local damage induced by the high heat flux due to the focusing effect. Thus, the persistent purification of the salt is needed during operation. The most promising technique to resolve this issue is deemed as a helium bubbling method. The helium is injected into the core in a form of bubble, and it not only collects gaseous precursors, but also carries the noble metals attached on the interface of the bubbles.

Recently, the MSR-type SMR called Passive Molten salt Fast Reactor (PMFR) was suggested. The injected helium significantly affects the salt circulation because the PMFR has been designed as a natural circulation system without any pumps. While helium bubbles can reduce the density of the fuel salt providing additional buoyancy in the core, it can also result in increased friction loss of the salt, a competing force against buoyancy.

The main objective of this study is to investigate the effects of helium bubbling on natural circulation for the PMFR. A one-dimensional preliminary analysis was performed to evaluate the amount of helium injection required to achieve the desired reactor power. The results were compared with the maximum achievable reactor power only with single-phase natural circulation operation under the same conditions.

2. Methodology

2.1 Reactor models

Figure 1 shows the layout of the PMFR system under development. The major components of the PMFR are a core and a riser, six helical-coil heat exchangers, and downcomers. A two-phase flow occurs from the core to the riser as helium is injected from the bottom of the core. Because the helium bubbles are released by the separator located at the end of the riser, the heat exchangers and downcomers are regarded as a single-phase flow. Here, the separator was designed as a simple cylindrical tank.

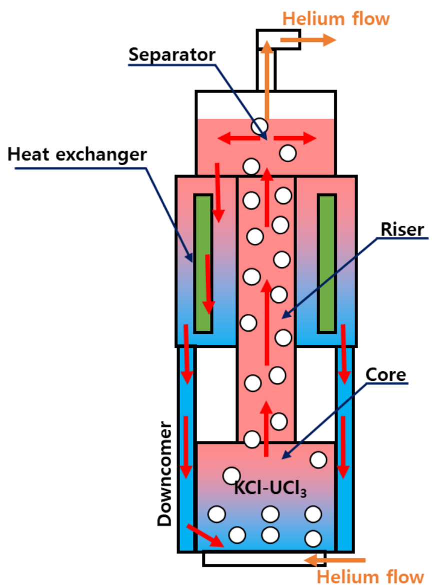

Figure 1. A schematic of the natural circulating PMFR

UCl_3-$UC1_4$-KCl was implemented as the fuel salt and its thermodynamic properties were excerpted from the experimental measurements data [2–4]. The properties of helium were evaluated based on the National Institute of Standards and Technology (NIST) database program. The temperature of the helium was assumed to be same with the fuel salt and the heat transfer between two fluids was neglected.

The heat generation of the core was evaluated by homogeneous cylindrical reactor model. To simplify the analysis, decay heat generation of the fuel material outside the core region was neglected.

Natural circulation was determined by balancing the pressure drop, the frictional loss and buoyancy force in the system. Consequently, the geometric parameters, such as the riser diameter and length, significantly affect its performance. Thus, in this study the riser diameter and length were given in the ranges of 0.5–1.0 m and 8–18 m, respectively. The desired reactor power was set to 200 MWt in these geometry conditions. The system design parameters are summarized and listed in Table 1.

Table 1. Design parameters of the MSR system.

Parameters	**Values**
Reactor	
Desired power	200 MW_t
Core diameter	2 m
Core length	2 m
Riser diameters	0.5 m – 1 m
Riser lengths	8 m – 18 m
Core inlet-outlet temp.	600°C–750°C
Fuel salt properties	UCl_3 – UCl_4– KCl
Salt composition	36.03%-9.1%-54.9% (mol)
Heat capacity	98.90 J/mol·K
UCl_3 [2]	129.7 J/mol·K
UCl_4	Assumed (129.7 J/mol·K)
KCl [3]	73.6 J/mol·K
Viscosity [4]	$10^{(\frac{1458}{T}-4.124)}$ Pa·sec
Density [4]	$3952.4-0.9276T$ kg/m^3
Heat exchangers	
Length	6 m
Diameter	1.35 m
Surface area of tubes	500 m^2
Diameter of tubes	0.017 m
Numbers of heat exchanger modules	6

2.2 Hydraulic models

Because the effect of decay heat was neglected, the mass flow rate of the fuel salt follows the simple energy balance as shown in Eq. (1).

$$Q=\dot{m}\,c_p\,\Delta T \quad (1)$$

The circulation cycle of the salt in the system can be divided into two paths. One path is upward stream starting from the bottom of the core to the top surface of the separator. The other is the downward stream returning to the core through the heat exchangers and downcomers. Each path was nodalized into 100 nodes in the axial direction.

The liquid level of the salt was fixed assuming the steady-state condition. In other words, the salt velocity of node 1 could be assumed to be 0. Also, the pressure of node 1 and 100 in each path was assumed as the same. The pressure balance equations for each path were derived as shown in Eqs. (2) and (3). The indicator *i* is a node number with a value between 1 and 100. Subscripts *tp* means the two-phase flow state.

For upward path,

$$P_n+\Sigma_i^n(\rho_i g\Delta z)_{tp}+\Sigma_i^n P_{loss}=P_i+\left(\frac{1}{2}\rho_i {v_i}^2\right)_{tp} \quad (2)$$

For downward path,

$$P_n+\Sigma_i^n(\rho_i g\Delta z)=P_i+\frac{1}{2}\rho_i v_i^2+\Sigma_i^n P_{loss} \quad (3)$$

The core and riser were modeled as the cylindrical pipe, and the two-phase flow friction loss was evaluated by Lockhart and Martinelli [5] approach.

$$\Delta P_{tp}=\Phi^2\left(f\frac{L}{D}\frac{1}{2}\rho v^2\right)_{f,superficial} \quad (4)$$

$$\Phi^2=1+\frac{C}{X_{tt}}+\frac{1}{X_{tt}^2} \quad (5)$$

$$X_{tt}=\left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_{He}}{\rho_f}\right)^{0.5}\left(\frac{\mu_f}{\mu_{He}}\right)^{0.1} \quad (6)$$

X_{tt} and Φ are Lockhart and Martinelli parameters and the two-phase friction multiplier.

The reduction pressure loss of the flow channel between the core and the riser was evaluated by Eq. (7):

$$\Delta P_{reduction}=\left(1-\frac{D_{riser}^2}{D_{core}^2}\right)\left(\frac{1}{2}\rho v^2\right)_{t.p} \quad (7)$$

The shell side friction factor of the helical coil heat exchangers was assumed as the constant value, which is the same design of the steam generator of System-integrated Modular Advanced ReacTor [6].

3. Results & Discussion

Figures 2 and 3 show the frictional pressure loss of the core and riser with and without helium injection, respectively. In the single-phase flow cases, the longer riser length resulted in the more friction loss at the core and riser due to the flow length difference. On the other hand, more pressure loss was observed than 18 m riser cases despite the shorter flow length. This was because the injected helium increased the friction loss beyond the effect of increased flow path length. This tendency was evident in the riser diameter of 0.6 m or less.

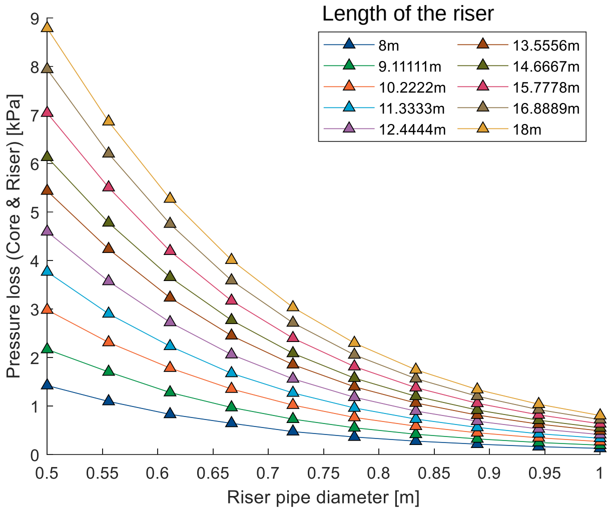

Figure 2. Frictional pressure loss of the core and riser without helium injection (single phase).

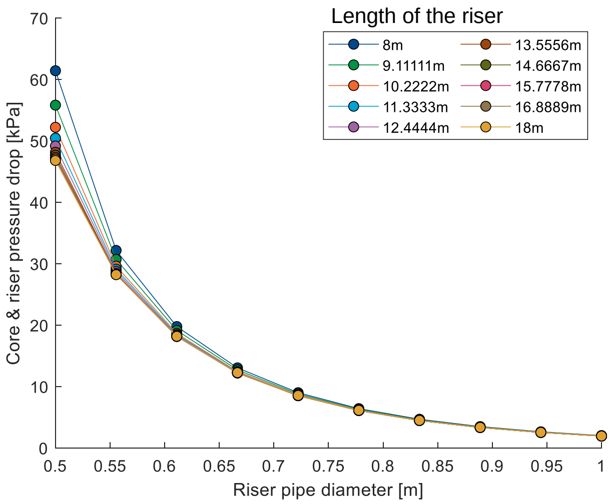

Figure 3. Frictional pressure loss of the core and riser with helium injection (two-phase).

Figure 4 shows the maximum achievable reactor power without helium injection of the MSR in this study. The power could be increased up to 131.5 MW_t only with single-phase natural circulation. The riser length of 8 m case showed the lowest power due to insufficient buoyancy force from the temperature difference. Without helium injection, only 55 MW_t of the power was achievable. The effect of riser diameters was as significant as the riser lengths. The power with the riser diameter of 0.5 m decreased by 27.3–29.7% for all cases compared to the diameter of 1 m.

The amount of helium required to achieve the reactor power of 200 MW_t for each riser geometry condition was shown as the core mean void fraction in Fig. 5. For the 18 m riser with 1 m diameter case, only 2.66% of helium void fraction at the core were required for the desired power. However, it was found that the required helium void fraction sharply increased regardless of the riser length. In case of 8 m riser length, the required void fraction to achieve the same desired power increased up to 22.83%.

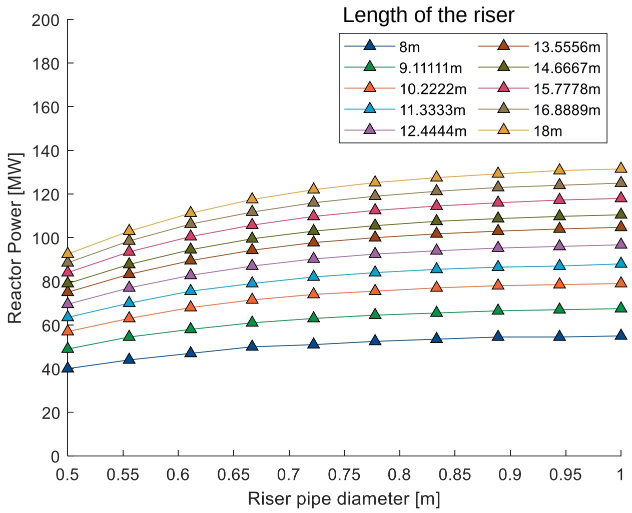

Figure 4. Achievable powers without helium bubbling (single phase).

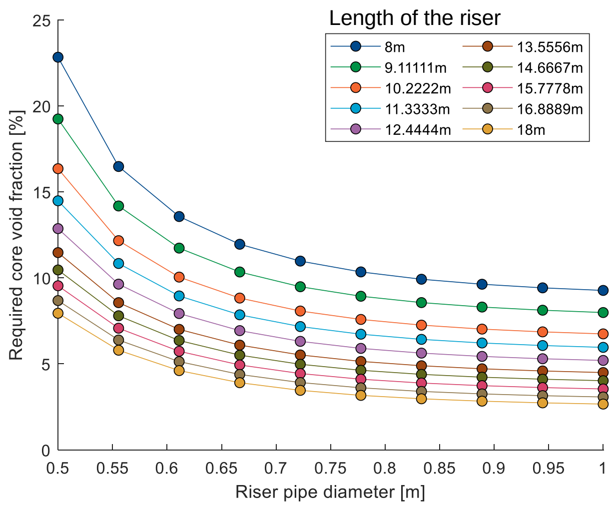

Figure 5. Required core void fraction to achieve the reactor power of 200MW_t (two-phase).

4. Conclusion

This study was conducted to investigate the feasibility of natural circulation operation for the PMFR by using helium bubbling. A one-dimensional preliminary analysis according to the cases with or without helium injection was performed under the projected reactor design parameters. The main results of this preliminary analysis were summarized as follow.

- ✓ The larger length and diameter of the riser showed a positive effect on natural circulation, resulting in the increased achievable reactor power.

- ✓ The maximum achievable reactor power was 131.5 MW_t without helium injection. The power was reduced to 40 MW_t according to the riser geometry conditions.
- ✓ Even under the disadvantageous riser geometry conditions, it was possible to achieve the desired power, but the helium void fraction had to be increased to 22.83%.
- ✓ Higher helium void fraction caused more friction losses at the same reactor power conditions. This tendency became more significant as the pipe diameter decreased to 0.5 m. Despite no obstructions to both the core and riser, the friction losses induced by two-phase flow could be significant.

This preliminary study did not reflect any constraints of the reactor physics which is essential to evaluate fuel heat generation rate. As the fuel itself is the coolant, the hydraulic behavior of the molten salt directly affects the neutron transport relationship and fission reaction. Therefore, the multi-physics analysis of reactor physics and thermal hydraulics should be conducted as a future study.

Acknowledgments

This research was supported by the National Research Foundation of Korea (NRF), funded by the Ministry of Science, ICT and Future Planning, the Republic of Korea (No. NRF- 2021M2D2A2076382), and the Nuclear Safety Research Program through the Korea Foundation of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (grant number 2003006-0120-CG100).

REFERENCES

[1] T.J. Dolan, Molten Salt Reactors and Thorium Energy, Woodhead Publishing, Cambridge, USA (2017).
[2] J. Fuger, V. B. Parker, W. N. Hubbard, F. L. Oetting, The chemical thermodynamics of actinide elements and compounds: Pt 8. The actinide halides, International Atomic Energy Agency, Vienna, (1983).
[3] M.W. Chase, Jr., NIST-JANAF Themochemical Tables, Fourth Edition, J.Phys. Chem. Ref. Data, Monograph 9, (1998).
[4] S. Katyshev, Yu Chervinskii, V. Desyatnik. Density and viscosity of fused mixtures of uranium chlorides and potassium chloride. Atomic Energy, (1982).
[5] R.W. Lockhart, R.C. Martinelli, Proposed correlation of data for isothermal two-phase, two-component flow in pipes. Chem. Eng. Process. 45, 39–48, (1949).
[6] H. Kang, H. Han, Y. Kim, Thermal-hydraulic Design of a Printed-Circuit Steam Generator for Integral Reactor, The KSFM Journal of Fluid Machinery 17, (2014).