Development of a 1D Noble Metal Transport and Flotation Code for Helium Bubbling Systems in Passive Molten Salt Reactors

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1. Introduction

Passive Molten Salt Fast Reactors (PMFRs) are integral-type molten salt reactor systems designed to operate under natural circulation without external pumping systems [1-4]. Due to their compact and integrated configuration, PMFRs provide limited space for auxiliary subsystems, and the attachment of external fission product separation loops may interfere with natural circulation and structural integrity. Consequently, in-vessel solutions for fission product management are required for long-term stable operation.

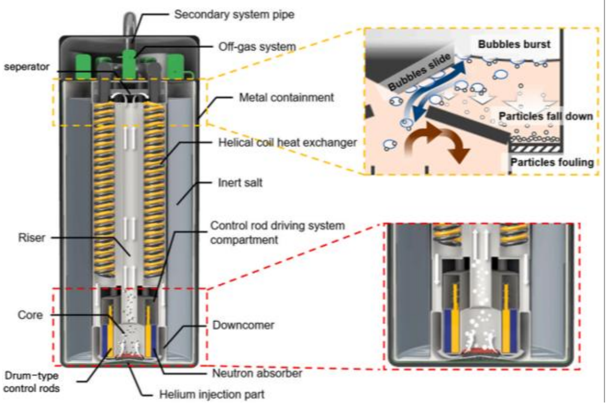

Fig. 1. Schematic of PMFR including helium bubbling system.

Among various fission products generated during operation, noble metals such as molybdenum (Mo), tellurium (Te), and ruthenium (Ru) are largely insoluble in molten salt and tend to exist in particulate form. If not adequately removed, these particles may induce reactivity perturbations, accumulate on structural surfaces, and cause fouling in heat exchangers, potentially degrading thermal performance and long-term operational stability. Therefore, an effective in-vessel removal strategy for noble metal particles is essential for PMFR systems.

Helium bubbling has been widely investigated as a fission product removal technique in molten salt reactors. Previous studies [5-10] have addressed helium bubble dynamics and two-phase flow behavior in molten salt environments, including experimental investigations of single bubble rise characteristics and system-level transient analyses under bubbling conditions. However, most studies have focused on hydrodynamic behavior rather than the quantitative transport and removal of insoluble noble metal particles. While species transport analyses for noble metal behavior in molten salt reactor systems have been reported, numerical frameworks directly coupling noble metal transport with probabilistic flotation-based removal under PMFR-specific riser injection conditions remain limited.

To address this gap, the present study develops a one-dimensional noble metal transport and flotation code for helium bubbling systems in PMFR environments. The model incorporates size-dependent transport behavior and probabilistic removal mechanisms and is structured to allow future coupling with neutronic calculations. The developed framework aims to provide a computational tool for evaluating noble metal removal performance and supporting multiphysics analysis of PMFR systems.

2. Noble Metal Transport

In the present study, noble metal particles are assumed to exist as insoluble particulates suspended in molten salt. A one-dimensional axial transport model is employed to evaluate particle behavior along the riser region where helium bubbling is introduced.

The governing transport equation is expressed as:

$$(1)\ \frac{\partial C}{\partial t} = D_{blow}\nabla^2 C - \nabla\left(u_{eff}C\right) - R(t)$$

where C(t)denotes the particle concentration, $D_B$is the Brownian diffusivity, ueffu_{\mathrm{eff}}ueffis the effective axial velocity, P_c, P_a, and P_c represent collision, attachment, and detachment probabilities, and SSSis the noble metal generation rate.

The Brownian diffusivity is defined as

$$(2)\ D_B = \frac{k_B T}{3\pi \mu_{solvent} d_p}$$

where k_B is the Boltzmann constant, T is temperature, μ is molten salt viscosity, and d_P is the particle diameter. This formulation captures the size-dependent diffusive behavior of small particles.

The effective velocity accounts for both bulk flow and gravitational settling and is written as

$$(3)\ u_{eff} = u - u_s$$

where u is the imposed axial velocity and the Stokes settling velocity is given by

$$(4)\ u_s = \frac{d_p^2(\rho_p - \rho_f)g}{18\mu}$$

with ρ_p and ρ_f representing particle and fluid densities. Larger particles exhibit increased settling velocity and reduced upward transport.

Particle removal by helium bubbling is modeled using a probabilistic flotation approach. The removal rate is expressed as

$$(5)\ R(t) = C(t)P_c P_a(1 - P_d)$$

The collision probability [11] is formulated as

$$(6)\ P_c = \left(\frac{3}{2} + \frac{4Re_b^{0.72}}{15}\right)\left(\frac{d_p}{d_b}\right)^2$$

where d_b is bubble diameter and Re_b is the bubble Reynolds number.

The attachment probability [12] is calculated as

$$(7)\ P_a = \sin^2\left[2\tan^{-1}\left(\exp\left(-\frac{45+8Re_b^{0.72}}{15D_b\left(\frac{D_b}{D_p}+1\right)}u_b t_i\right)\right)\right]$$

where u_b is bubble rise velocity and t_i denotes the induction time between bubble and particle. The detachment probability is evaluated from interfacial force balance considering contact angle and surface tension effects. In the present implementation, P_d is negligibe, and particles are assumed to be permanently removed once attachment occurs and subsequently transported to the upper separation region.

The noble metal generation term S(t) is obtained from external neutronic calculations. In the current study, a constant generation rate is applied, while future extensions will incorporate time-dependent two-way coupling with neutronic solvers.

Bubble diameter is treated as a stochastic variable sampled from a literature-based bubble size distribution corresponding to the given gas injection condition. Bubble rise velocity is estimated using a Stokes-type formulation consistent with the simplified one-dimensional modeling framework.

3. Algorithm Development

The numerical framework is implemented using a size-bin approach in which noble metal particles are discretized into multiple diameter groups. For each size bin, transport and removal processes are evaluated independently while sharing the same axial flow field.

At each time step, the noble metal source term is applied, after which bubble diameter is sampled from the prescribed distribution. Bubble rise velocity and Reynolds number are computed to evaluate collision and attachment probabilities. Brownian diffusivity and settling velocity are calculated for each particle size group, and the transport equation is solved using time-marching discretization. The removed particle mass is accumulated and considered transported to the separation region without further tracking.

In the present model, particle diameter remains fixed within each size bin. Since transport and removal behavior are strongly dependent on particle size, future development will incorporate particle growth and aggregation mechanisms. The overall framework is structured to enable subsequent multiphysics coupling with neutronic and thermal-hydraulic solvers for integrated PMFR analysis.

4. Results

To preliminarily assess the validity of the developed model, laboratory-scale experiments were conducted using a water-based facility designed to mimic the geometric characteristics of a PMFR riser. Helium injection was implemented at the lower section of the riser, and particle removal behavior was measured under varying particle diameters and gas injection rates.

The numerical model was applied to identical geometric and injection conditions. Figure 2-4 compares the temporal evolution of normalized particle concentration between experiment and simulation for representative cases. The model successfully reproduced the overall decreasing trend of particle concentration under helium bubbling conditions. In particular, the dependence of removal efficiency on particle diameter was consistently observed in both experiment and simulation, with larger particles exhibiting higher removal rates due to increased collision probability and reduced diffusive dispersion.

The influence of gas injection rate was also captured. Increased helium injection resulted in enhanced removal efficiency in both experiment and simulation, primarily due to increased bubble number density and collision frequency. Although minor quantitative discrepancies were observed, especially at higher injection rates, the overall trend agreement indicates that the probabilistic flotation formulation reasonably represents particle–bubble interactions under simplified conditions.

While the present comparison was performed using water instead of molten salt and under reduced-scale conditions, the results demonstrate the capability of the model to capture dominant removal mechanisms.

To evaluate the impact of helium bubbling, simulations were performed with and without bubble injection under identical source and flow conditions. Without bubbling, particle concentration gradually increased due to continuous noble metal generation and limited diffusive redistribution. In contrast, when helium bubbling was introduced, concentration reached a quasi-steady state determined by the balance between generation and flotation removal.

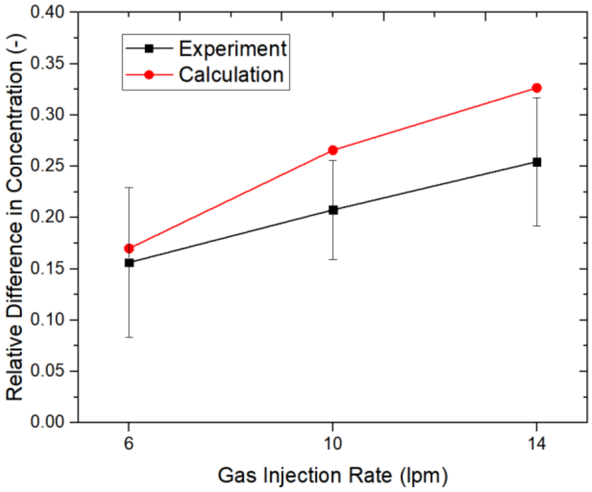

Fig. 2. Sensitivity Result with gas injection rate

The results indicate that helium bubbling significantly reduces steady-state particle inventory within the riser region. This confirms that in-vessel helium injection can function as an effective noble metal control strategy in PMFR systems.

Particle size strongly influenced transport and removal behavior. Smaller particles exhibited higher Brownian diffusivity, leading to more uniform axial distribution and reduced collision efficiency with bubbles. Larger particles showed increased settling velocity and collision probability, resulting in enhanced removal.

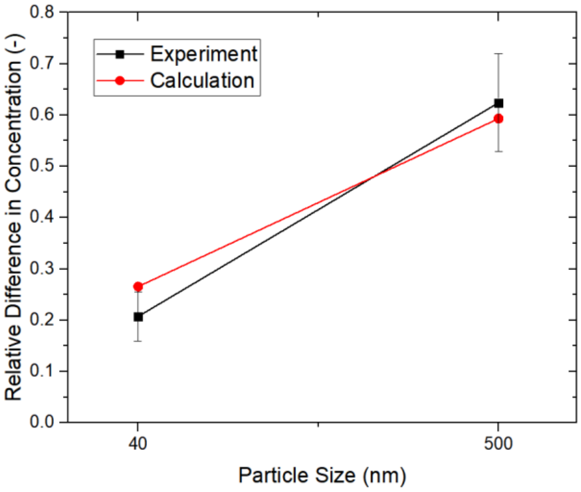

Fig. 3. Sensitivity Result with gas particle size

The simulation results demonstrated that removal efficiency increases with particle diameter within the investigated range. This size-dependent behavior was consistent with experimental observations and highlights the importance of incorporating diameter-resolved transport modeling.

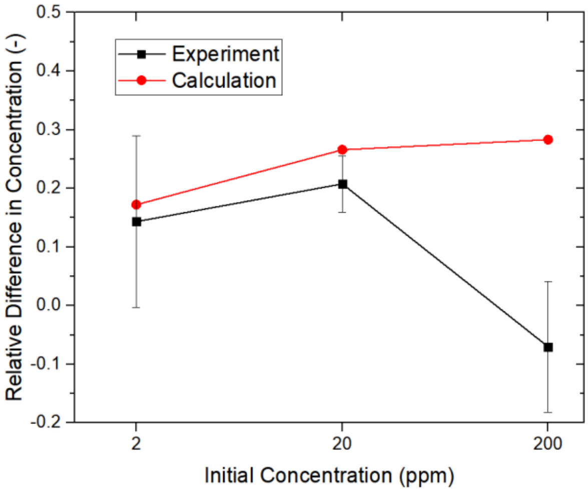

Fig. 4. Sensitivity Result with initial concentration

The effect of initial particle concentration was examined to evaluate system response under transient accumulation conditions. Higher initial concentrations resulted in increased absolute removal rates, while normalized removal efficiency remained relatively consistent. This indicates that the removal mechanism scales proportionally with particle inventory under the present probabilistic formulation.

Additional simulations were performed by varying the helium injection location along the riser. Injection at lower elevations increased the effective interaction length between particles and bubbles, leading to higher overall removal efficiency. Conversely, injection near the upper region reduced contact time and resulted in lower removal rates.

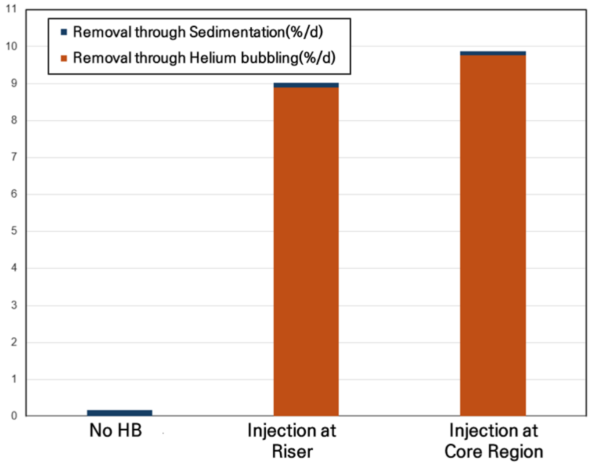

Fig. 5. Verification Result with injection position in PMFR system

These results suggest that injection position plays a critical role in determining removal performance and should be carefully considered in PMFR design optimization.

5. Conclusion

This study developed a one-dimensional noble metal transport and flotation code for helium bubbling systems in Passive Molten Salt Fast Reactors (PMFRs). The model incorporates size-dependent Brownian diffusion, settling velocity, and a probabilistic flotation removal formulation based on collision, attachment, and detachment mechanisms. Noble metal generation was implemented through an externally supplied source term derived from neutronic analysis, enabling future multiphysics integration.

Preliminary experimental comparisons using a laboratory-scale water facility demonstrated that the developed model captures the dominant trends of particle removal behavior. The simulation reproduced the dependence of removal efficiency on particle size and gas injection rate, as well as the influence of injection location on overall removal performance. Although quantitative discrepancies remain and further validation under molten salt conditions is required, the results indicate that the proposed framework reasonably represents key transport and flotation mechanisms.

Parametric analyses showed that helium bubbling significantly reduces steady-state noble metal inventory within the riser region. Removal efficiency increases with particle diameter and with earlier injection along the flow path due to extended interaction length. These findings support the feasibility of in-vessel helium bubbling as a noble metal control strategy for integral-type PMFR systems.

The developed code provides a reduced-order computational tool suitable for preliminary design evaluation and multiphysics coupling in PMFR analysis.

Future work will focus on three major extensions. First, time-dependent two-way coupling with neutronic solvers will be implemented to account for dynamically varying noble metal generation and feedback effects. Second, additional experimental validation under high-temperature molten salt conditions will be performed to improve quantitative accuracy. Third, particle growth and aggregation models will be incorporated to capture time-evolving particle size distributions, which are expected to significantly influence transport and removal behavior.

6. ACKNOWLEDGMENTS

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