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Multiphase Sloshing Dynamics of Water and Molten Salt in Drain Tanks using OpenFOAM

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1. Introduction

Recently, there has been an increase in the interest toward Molten Salt Reactors (MSRs) for marine applications in Korea. MSRs have several safety and efficiency benefits compared to conventional nuclear reactor designs, primarily because of their operating features with molten salt as fuel and coolant. Maritime MSRs can be a good solution for reducing carbon emissions. For this purpose, the design of drain tank for MSR is vital to safe use of MSR.

Drain tanks are the major components for the management of molten salt reactor accidents. They are designed to contain all fuel salts before the accident evolves to severe accident. Such storage improves the inherent safety of handling decay heat and radioactive material. At higher reactor outputs, drain tanks become more complex and expensive. Number, shape, and size of the tanks are all important details for design. These factors are critical not just for safety, but also for economic and spatial considerations of the ship. Furthermore, the aspect ratio of tanks influences how salts slosh under different ocean conditions. When ship's motion induces sloshing in the fluid-containing tank, the sloshing affects the fluid dynamic loading to the wall.

In this study, Computational Fluid Dynamics (CFD) simulations are conducted using OpenFOAM to investigate the dynamics of molten salt sloshing within drain tanks. Dynamic characteristics are then compared to those of water sloshing under the same geometric constraints to illustrate how molten salt fluid can be different from water. From this comparison, unique characteristics of molten salt behavior are identified, and information for drain tank design can be also obtained.

2. Methodology

The geometry utilized in OpenFOAM were three cylinders, identical in volume but varying in height to investigate the effect of aspect ratio on sloshing. The baseline shape was the same as the drain tank in the Molten-Salt Reactor Experiment (MSRE). The tank is cylindrical, 50 inches (1.27 m) in diameter, 86 inches (2.1844 m) in height, and 80 cubic feet (2.265 cubic meter) in volume. [1] Figure 1 shows the fuel salt drain tank of MSRE. The only difference in design between the coolant salt drain tank and fuel salt drain tank is the absence of internal structures.

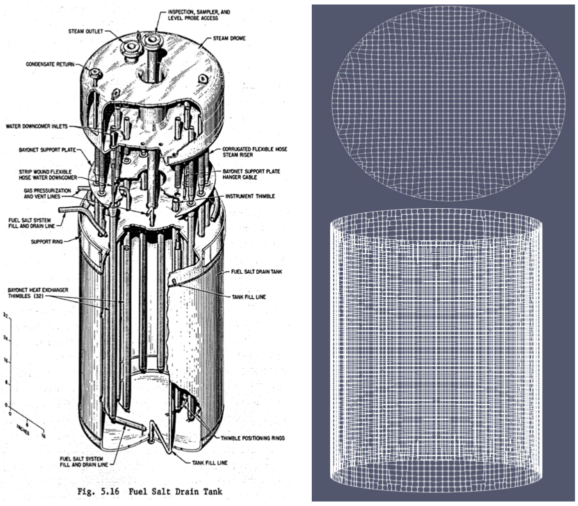

Figure 1. MSRE drain tank and meshed geometry

Based on the actual volume occupied by the salts, the MSRE drain tank is modeled as a cylinder with a diameter of 1.27 meters and a height of 1.788 meters. Three different geometries are examined to observe how different aspect ratios affect sloshing dynamics.

<Aspect Ratio>

- Aspect Ratio : 2.884
  Diameter 1 m, Height 2.884 m (High)
- Aspect Ratio : 1.408
  Diameter 1.27 m, Height 1.788 m (MSRE)
- Aspect Ratio : 0.855
  Diameter 1.5 m, Height 1.282 m (Low)

Before simulating, it was assumed that each tank was half-filled of liquid. The liquid is water or MSRE coolant salt. The air was present above the liquid to consider cover gas. The simulations were conducted using OpenFOAM v2312. [2] The interFoam solver was used for the multiphase simulations. This solver employs a Volume of Fluid (VOF)-based interface capture technique. It is intended to simulate two incompressible, isothermal, immiscible fluids. This makes it suitable for modeling sloshing dynamics in partially filled tanks that are exposed to external disturbances.

noSlip velocity boundary condition was applied to all solid surfaces. Fixedfluxpressure boundary condition was utilized to dynamically modify the pressure in accordance with the flux determined by the velocity boundary condition. Table 1 shows the particular boundary conditions for the simulation variables.

Table 1. The boundary condition for interFOAM

Dictionary Variable	Walls
alpha.water	zeroGradient
U	NoSlip
p_rgh	fixedFluxPressure

3. Sloshing Validation with a Real Experiment

The simulations were carried out on the assumption of laminar flow. The simulated molten salt was a 70% to 30% LiF-BeF$_2$ mixture used as a coolant salt in the MSRE. Both water and molten salt were assumed to have constant physical properties at ambient temperature (25°C) and 600°C, respectively.

Air is to be considered at room temperature and assumed to have a minimal effect on sloshing. Physical properties, excluding surface tension, is up to four significant digits of precision. Surface tension is up to one significant digit of precision. Table 2 shows more detailed property values : dynamic viscosity, density, surface tension coefficient.

Table 2. The transport properties

	Water	Molten Salt	Air
Transport Model	Newtonian		
$\nu\ (Pa \cdot s)$	89.00E-05	0.009756	1.845E-05
$\rho\ (kg/m^3)$	997.1	1972	1.181
$\sigma\ (N/m)$	0.07	0.2	

To validate the CFD results, the solution's reliability needs to be ensured through comparison with findings from other research conducted within the OpenFOAM framework. Abramson and Ransleben have conducted an experiment simulating a scenario where a small lateral excitation in the x-axis is applied to an upright cylinder. **[3]** This lateral excitation is represented by a sinusoidal function. In addition, Ibrahim proposed an analytic solution that ignores visibility damping in lateral excitation sloshing.**[3]**

$$\boldsymbol{X(t) = X_0 \sin(\Omega t)}$$

The experiment measured the change in maximum pressure according to the height divided by fres-surface-height under the following circumstances. Specific experimental conditions were as Table 3.

Table 3. The simulated condition of lateral excitation sloshing

Fluid	water
$\frac{\Omega^2 R}{g}$	1.51
$\frac{h}{R}$	2
$time(t)$	$\Omega t\ = \frac{\pi}{2}$

The analysis was performed on "High" cylinder geometry under the same conditions as above, and the later excitation condition was adjusted by setting $\boldsymbol{\frac{X_0}{R} = 0.1666}$. The OpenFOAM setting accordingly is in Table 4.

Table 4. The initial values for simulating lateral excitation sloshing

Variable	Value
Initial fluid depth	1 m
Radius	0.5 m
Amplitude	(0.0833 0 0)
Omega	5.443

The y-axis was plotted against a dimensionless height based on the initial fluid depth, and the x-axis was plotted against a dimensionless pressure divided by $\boldsymbol{\rho g X_0}$. The pressure distribution is shown in Figure 2.

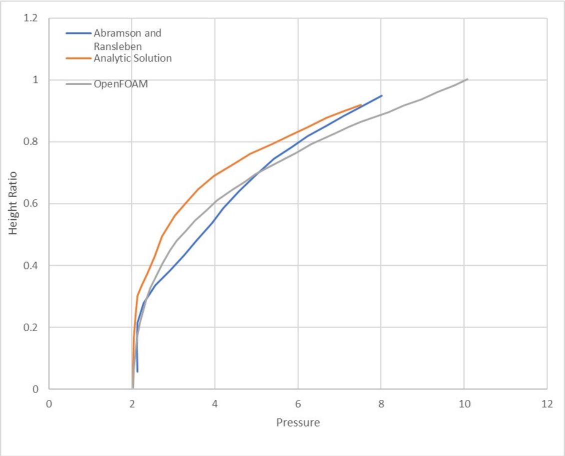

Figure 2. Comparison of maximum pressure distribution along the wall

There are some differences, but the results are well close to Abramson and Ransleben's experimental results. Therefore, it is found that the solver with preprocessed settings can be properly applied for dynamics of molten salt sloshing.

4. Result and Discussion

The dynamicmeshDict settings used in the three cylinders are as table 5.

Table 5. The dynamicmeshDict settings

Variable	oscillatingLinearMotionCoeffs
X_0	(0.01 0 0) m or (1 0 0) m
Ω	6.2832 rad/s

Pressure changes over time in the drain tank's sidewall were measured. The calculations were based on hydrostatic pressure (P_rgh), which is useful for monitoring pressure changes on walls in multiphase simulations.

When the amplitude is set at 0.01, both the average pressure on the sidewall and the pressure quartile range are illustrated in Figures 3, 4. It is observed that the average pressure does not significantly vary. However, a larger pressure range is noted in the quartile range for molten salt sloshing. This phenomenon is attributed to the higher density of molten salt. Given the small amplitude, there is no distortion of the free surface. Hence, the wall pressure stems more from the momentum itself rather than from sloshing dynamics. With molten salt's density nearly double that of water, the pressure on the wall is higher under the same lateral excitation. This aligns with previous findings, indicating that an increase in liquid density leads to higher sloshing pressure. **[4]**

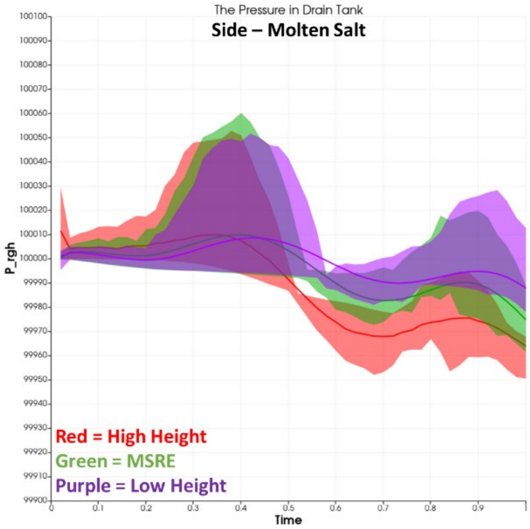

Figure 3. The simulation result at low amplitude excitation (molten salt)

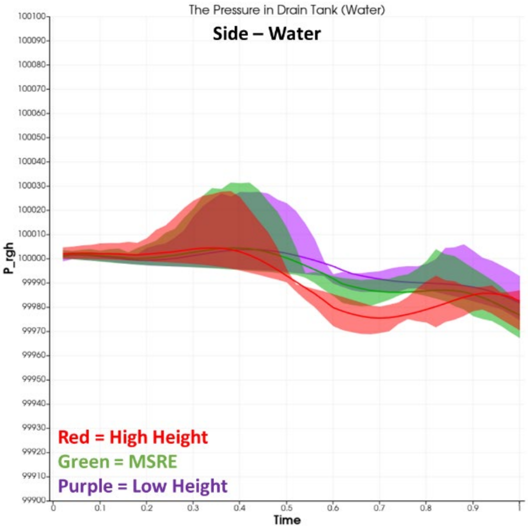

Figure 4. The simulation result at low amplitude excitation (water)

The sidewall's average pressure and pressure quartile range are both below when the amplitude is set to 1.0. The difference in pressure distribution at large aspect ratios is similar to that seen at lower amplitudes. At low aspect ratios, however, the molten salt is subjected to an overall rise in pressure. Cylinders with low aspect ratios suffer free surface breaking and splashing at higher amplitudes, leading to continuous high pressure on the ceiling and walls. Free surface breaking is shown in Figure 5. **[5]**

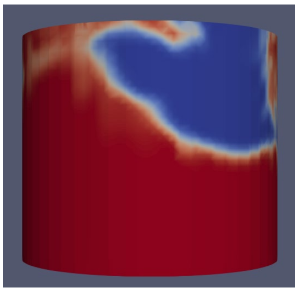

Figure 5. Free surface breaking and splashing in molten salt tank sloshing

The rising time of the impact pressure is particularly long in molten salt due to the existence of the damping effect caused by viscosity. Rising time is a duration that impacts pressure risks from zero to peak. **[5]** Eventually, as the time to apply high pressure increases, the quartile range takes place for a long time as shown in the Figure 6, 7.

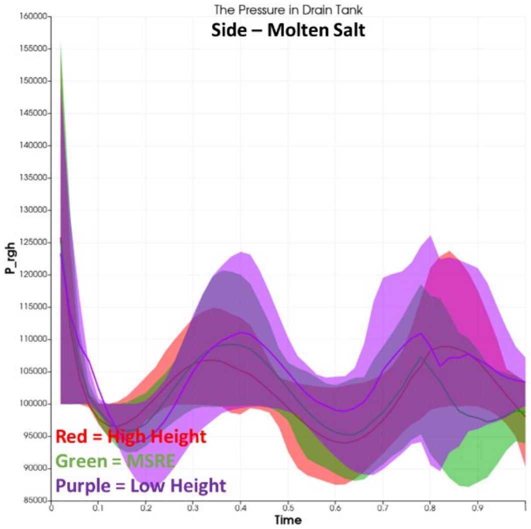

Figure 6. The simulation result at large amplitude excitation (molten salt)

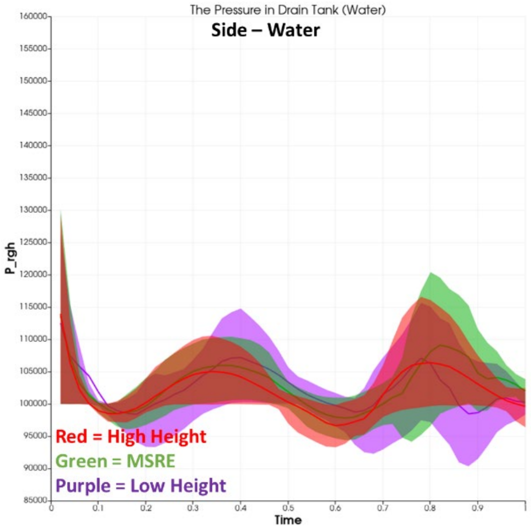

Figure 7. The simulation result at large amplitude excitation (water)

5. Conclusion and Future Work

The study shows differences in the sloshing dynamics and pressure distribution of water and molten salt within tanks with different aspect ratios. Due to their increased density and viscosity in comparison to water, molten ions demonstrate unique sloshing characteristics. When low amplitude lateral excitation occurs, the pressure distribution across all aspect ratios of dense molten salt is slightly higher than water. with high amplitude lateral excitation, the differences become significant.

Increased rising time and moderate free surface splashing are caused by the molten salt's higher viscosity. Molten salt is more resistant to free surface breaking than water, which is advantageous in low aspect ratio tanks in particular. However, the rising time is longer and the total pressure exerted is higher with smaller aspect ratios. Therefore, when the aspect ratio is lower than the maximum wave height brought on by external amplitudes, a molten salt drain tank encounters hydrodynamic load issues. Consequently, the maritime operating environment should be taken into consideration when designing a drain tank.

In this study, CFD simulations were conducted using a simplified cylindrical model; however, the actual fuel drain tank contains many internal structures including bayonet tube heat exchangers. These structures function as damping buffers, disrupting the fluid flow caused by sloshing. **[3]** Free surface resonance is effectively prevented due to the presence of baffles. As a result, the impact pressure and side pressure distribution values will be relatively small.

For future research, the disparity between CFD result and experiments must be reduced by adjusting the simulation environment of OpenFOAM. Also, it is essential to incorporate the decay heat of the fuel salt into CFD studies. Additionally, the computation of thermal loads resulting from heat transfer should be addressed in subsequent investigations.

ACKNOWLEDGEMENT

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