Simulation of Fluid Sloshing in Core Catcher for Nuclear Accident Using Moving Particle Semi-Implicit Method

Asril Pramutadi Andi Mustari[1] (✉), Stefany Imanuel Sihombing[2] and Anni Nuril Hidayati

[1]Nuclear and Biophysics Research Division, Physics Department, Faculty of Mathematics and Natural Sciences, Bandung Institute of Technology, Bandung, Indonesia
pramutadi@itb.ac.id

[2]Advanced Nuclear Laboratory, Physics Department, Faculty of Mathematics and Natural Sciences, Bandung, Indonesia

Abstract. Fluid sloshing simulations and tests were performed in a nuclear reactor scheme, especially core meltdown, using the moving particle semi-implicit (MPS) method. The MPS method is a method for analyzing the interactions between incompressible particles. In this method, the fluid is represented by particles, and each particle carries physical information such as position, velocity, pressure, and temperature. The fluid sloshing experiment was carried out using a glass bowl with dimensions of 11 cm x 20 cm x 9 cm and a glass cup with a diameter of 7 cm. The fluids used are water and cooking oil. The results of experiments and simulations with MPS show that the sloshing of the water in the bowl's middle and outer wall is higher than oil due to the greater water viscosity. The fluid becomes thinner and easier to move as the viscosity increases. In addition, the fluid's sloshing peak at the bowl's wall is always greater than in the center of the bowl due to the forces acting on the fluid. The sloshing height from the experiment is greater than the simulation results due to the lifting process of the glass. This study conducted experiments and simulations to determine the fluid dynamics and the effect of fluid differences during fluid sloshing on a representative surface with a core catcher.

Keywords: Fluid Sloshing, Core Catcher, Nuclear Accident, Moving Particle, Semi-Implicit Method

1 Introduction

In the nuclear energy fields, there were three major accidents that, within its disaster, many things can become the object of improvement. The accidents start with an increase in the temperature of the fuel rod above its melting point [1,2]. Since the melting point of the fuel rod is the highest among material structures inside the reactor, when the fuel rod, including cladding, becomes molten other structural material will also melt and mix with the molten fuel, the so- called molten corium. Without any further cooling

M. Setiyo et al. (eds.), *Proceedings of the 4th Borobudur International Symposium on Science and Technology 2022 (BIS-STE 2022)*, Advances in Engineering Research 225,
https://doi.org/10.2991/978-94-6463-284-2_70

approach, the temperature of molten corium will increase continuously due to decay heat. Based on that phenomenon, the viscosity of the molten will decreases due to high temperature and act like a viscous fluid.

Some researchers have studied the relocation of the molten corium inside the reactor. Fukano et al., conducted the CAFÉ experiment to study the flow and the erosion [3,4]. MPS is a particle method fluid dynamic simulation that can easily simulate surface deformation cases. Regarding severe accident phenomena, MPS has been utilized and agreed well with some experiments devoted to imitating the accident. MPS have been used to calculate melting in the reactor lower plenum [5–7]. The MPS also calculates the molten outside vessel [8]. Research about the relocation of molten corium has been made to improve the MPS method to calculate eutectic phenomena [9–12].

The objective of this study is to simulate the sloshing experiment using by MPS method. This is the first step to evaluate its capability to simulate severe accident mechanisms, especially molten relocation in the core catcher where sloshing can happen.

2 Method

2.1 Sloshing experiment

The sloshing experiment was conducted using a bowl made of glass and glass, see Fig. 1. The lower diameter of the bowl was about 11 cm, and the upper diameter was about 20 cm. The height of the bowl was 11 cm. The glass diameter was about 7 cm. The fluids for the sloshing were water and oil with detail density, and kinematic viscosity shown in Table 1.

(a) (b)

Fig. 1. Initial condition of experiment (a) water (b) oil

Table 1. Characteristics of the fluid used in the simulation

Material	Fluids	
	Water	Oil
Density (kg.m^{-3})	1000.00	890.13
Kinematic viscosity (mm^2/s)	1.004	54.89

2.2 MPS method

The governing equation of the Newtonian incompressible fluid are the continuity and momentum equations, as equations 1 and 2, respectively.

$$\frac{D\rho}{Dt} = 0 \quad (1)$$

$$\frac{D\vec{u}}{Dt} = -\frac{1}{\rho}\nabla + \nu\nabla^2\vec{u} + \vec{g} \quad (2)$$

Where u is the velocity vector, t is time, ρ is the fluid density, P is pressure, υ is kinematic viscosity, and g is the gravitational acceleration.

As for the MPS calculation, the initial mechanism is explicit location modification of particles, and then the number density is renewed [13]. The next mechanism is an implicit modification where the particle number density is modified to the initial number to keep the fluid incompressible.

The MPS method draws the fluid as a group of fluids interacting. However, even though it is assumed as a particle, there is no volume decrease since one particle has a volume equal to a cube with a side length equal to the particle diameter. The re is the cutoff radius of particle interaction. The force between particles is defined according to the kernel function, weight function in the calculation of the number density model, Laplacian model, and gradient model. Equation 3 is the weight function of this calculation.

$$w(r) = \begin{cases} 1 - \frac{r}{r^e}, 0 \le r \le r_e \\ 0,\ r_e \le r \end{cases} \quad (3)$$

All the interaction parameters will affect the calculated particle as long as the neighboring particle is inside the cutoff radius. Those interactions are represented by a weight function w(r), as shown in equation (3). For comparison of MPS calculated results with experiment results, the geometry used in the calculation is similar to the sloshing experiment in the previous section with some simplifications, see Fig. *2*. The simulation was conducted in 2D system.

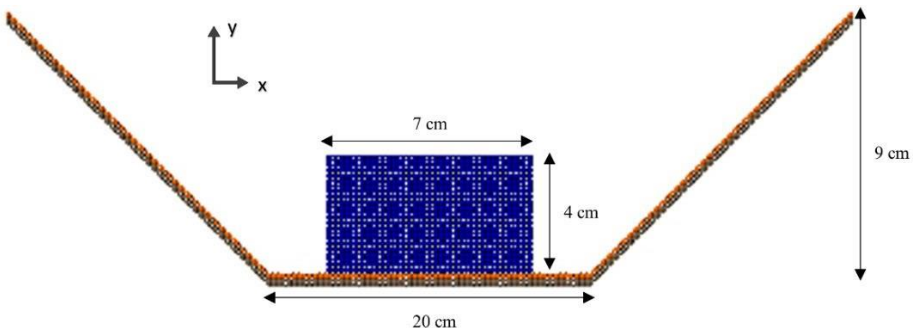

Fig. 2. Initial condition of simulation

3 Result and Discussion

3.1 Water experiment

Fig. 3 shows the sloshing process for both experiment and MPS simulation using water. In the initial process, a small disagreement occurs between the experiment and simulation due to the raising process of the glass. Some water seems to attach to the glass and then, at some height, start to fall. The reason for the phenomena is air pressure and surface tension. The air pressure outside the glass is greater than the pressure inside, and the gravity force is acting on the water. This time adjustment is needed between the experiment and simulation. Time of 0.04 s in the simulation is the condition where the front edge of the water reaches the bottom part of the wall, while that condition is at 0.04 s of the experiment. After that, the qualitative figure is presented with the same time interval between the experiment and simulation. Qualitatively, the results of both methods were similar. However, at t = 0.44 s of simulation, the experimental result shows a higher peak than the simulation—mainly due to the simulation of 2D dimension. In addition, increasing the number of particles may improve the agreement.

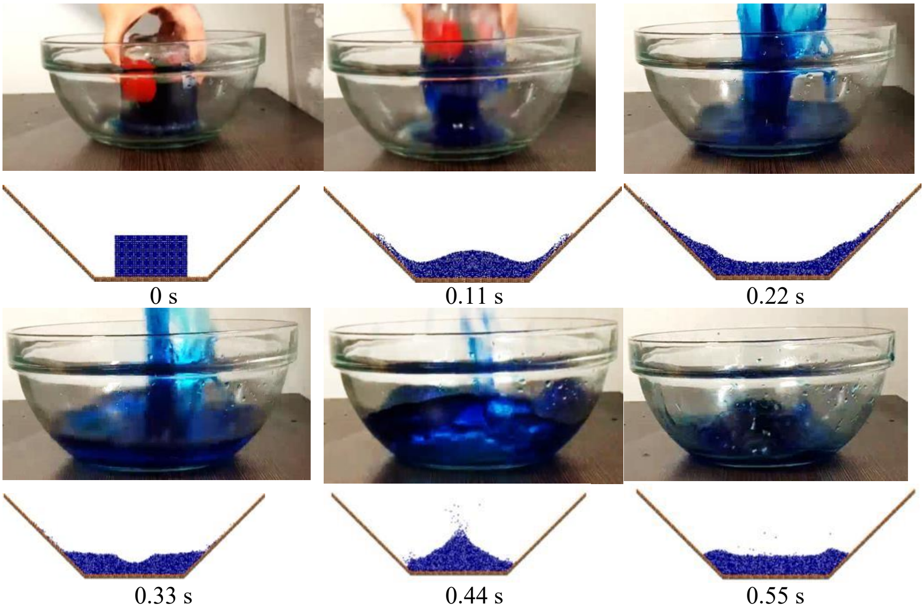

Fig. 3. Comparison of experimental and simulation results of water

Fig. 4 shows the MPS simulation result of the pressure profile of water. In the beginning, it can be seen that high pressure is focused in the bottom-middle, then as it proceeds to the wall, the pressure decreases when the water climbs the wall and the high-pressure shift to the corner between the wall and the floor.

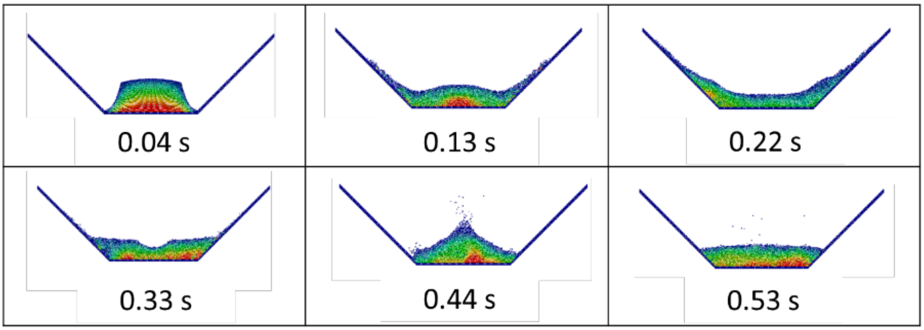

Fig. 4. simulated pressure profile of water

Fig. 5 compares the experimental and MPS simulation of height profile versus time. Fig. 5a shows the height profile of the middle point of the bowl. Experimentally, the water height falls from 4 cm to 3.2 cm at 0.11 s; however, below that time, some water attached to the glass then falls. The simulation shows that the height falls below 3 cm at 0.11 s. Fig. 5b shows the water height on the wall of the bowl. It shows that the simulation value increases earlier than the experiment, and the peak of the simulation is higher than the experiment. This may be due to the early attachment of the water with the glass that delays the peak formation. Another reason for the delay was the geometry of the wall between the simulation and the experiment, where the wall of the experiment was steeper.

3.2 Oil experiment

Fig. 6 shows the sloshing process for both experiment and MPS simulation using oil. Fig. 6 shows good agreement between the experiment and simulation of MPS. Unlike the case of water, this time, less oil is attached to the glass. However, air pressure is still affected at the beginning of the experiment. At 0.05 s, the fluid started to climbthe wall. The fluid reaches the maximum wall height between 0.17 s and 0.39 s. The peak of sloshing formed at 0.39 s. After the peak formation, oil starts to become stable.

Fig. 7 shows the MPS simulation result of the pressure profile of the oil. The pressure profile is like what happened to the water case. The pressure was high at the fluid's bottom-middle and started to spread as time passed when the peak of the sloshing formed the pressure slightly higher in the bottom-middle of the fluid.

Fig. 8 compares the experimental and MPS simulation of height profile versus time. Fig. 8a presents a profile of the fluid height from the middle of the bowl. In the experiment, the oil height starts at 4 cm and rises following the glass, then falls and spreads. On the other hand, simulation without such effect slowly decreases in height. For example, Fig. 8b shows that the oil starts climbing the wall at 0.05 s, while the experiment at 0.11 s. This is highly due to the initial raising process that did not calculate in the simulation. However, overall, the trend shows a similar profile.

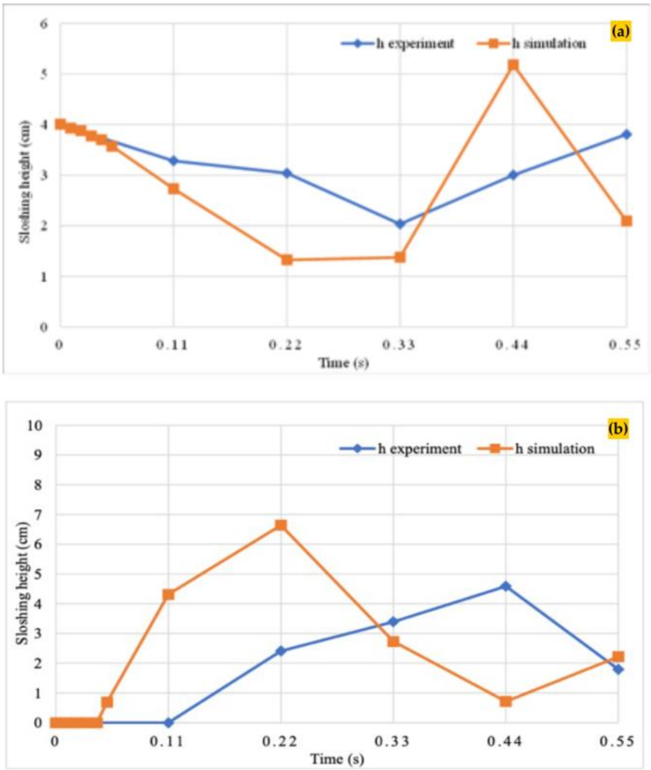

Fig. 5. Sloshing height of water at (a) the center and (b) the wall

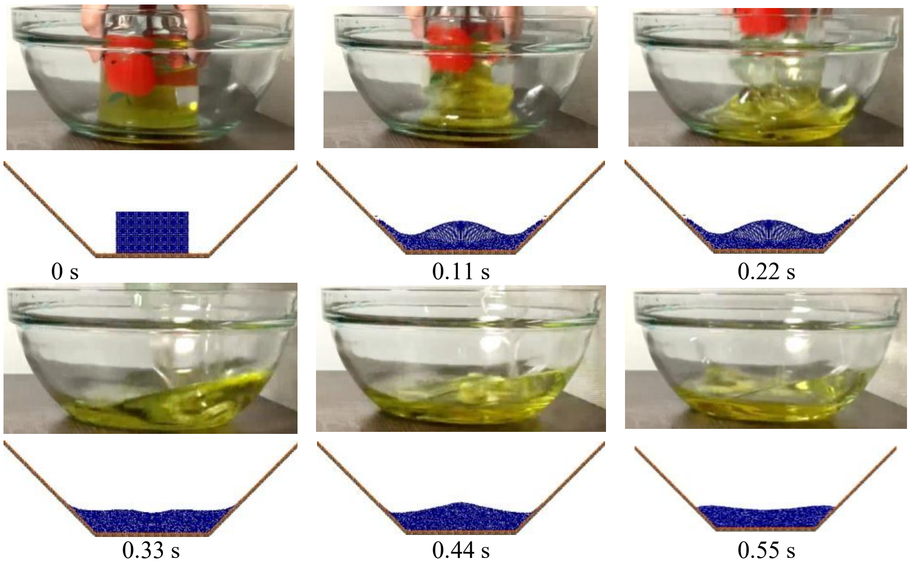

Fig. 6. Comparison of experimental and simulation results of oil

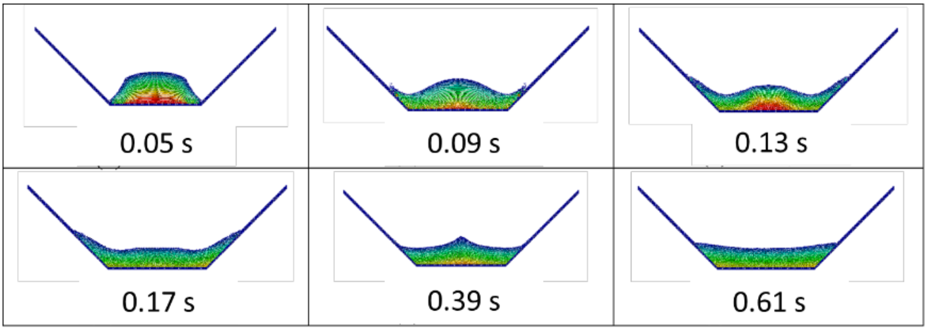

Fig. 7. Simulated pressure profile of oil

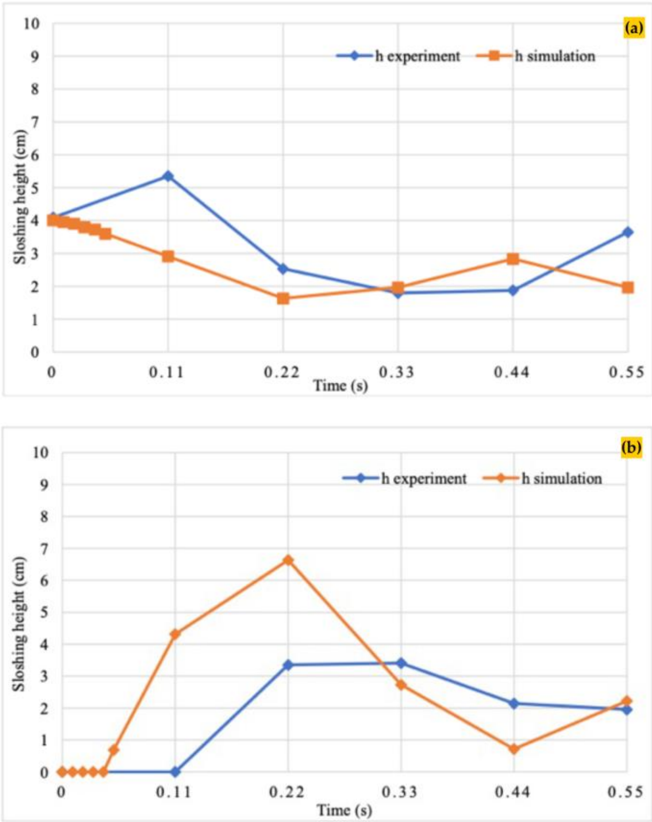

Fig. 8. Sloshing height of oil at (a) the center and (b) the wall

The experiment showed that the fluid did not spread out when the glass was lifted—part of the fluid was attached to the glass for some height before falling and spreading. The phenomenon was similar to the upside-down glass of water experiment [14]. It was air pressure from outside against pressure inside the glass. As the fluid leak out due to an opening at the tip of the glass and bowl surface, outside air can penetrate, then the fluid continues to flow out or fall after a certain height.

Fig. 5 and Fig. 8 show the sloshing wave formation after the fluid climbed the wall and reflected. The experiment shows that the oil case has a lower peak than the water case, which is affected by its viscosity [15,16]. The viscosity resists the movement of fluid climbing the wall; thus, higher viscosity fluid may affect more even though the oil has more kinetic energy at the beginning.

4 Conclusion

An experimental and simulation study was presented for the sloshing phenomena utilizing water and oil. The two- dimensional sloshing simulation was conducted using the MPS method. Experimentally, the two fluids showed a similar process of spreading at the beginning of the process, including raising the fluid following the glass due to the air pressure effect. The fluid climbs the wall before being reflected and forming a sloshing peak. Both experimental and calculational results show a similar phenomenon in that the fluid spread in the beginning, climbed the wall, and then reflected to form a sloshing peak. Based on the simulation results, the pressure profile shows similar results for both fluids. Therefore, it is important to conduct a future experiment using a transparent pipe, i.e., without a closing end cap, to hinder the effect of air pressure.

Acknowledgments. This study is fully funded by PPMI ITB 2022. The source code of the simulation is adopted from the works of Prof. Koshizuka, Prof. Sakai, and Dr. Shibata.

References

1. Pellegrini, M.; Suzuki, H.; Mizouchi, H.; Naitoh, M. Early Phase Accident Progression Analysis of Fukushima Daiichi Unit 3 By the Sampson Code. **2014**, *109*, 1–12, doi:10.13182/NT13-107.
2. Sehgal, B.R. Chapter 1 - Light Water Reactor Safety: A Historical Review. **2012**, 1–88, doi:http://dx.doi.org/10.1016/B978-0-12-388446-6.00001-0.
3. Fukano, Y.; Kawada, K.; Sato, I.; Wright, A.E.; Kilsdonk, D.J.; Aeschlimann, R.W. CAFÉ Experiments on the Flow and Freezing of Metal Fuel and Cladding -Test Conditions and Overview of the Results-. In Proceedings of the International conference on fast reactors and related fuel cycles (FR09): Challenges and opportunities; kyoto (Japan), 2009; pp. 1–10.
4. Wright, A.E.; Bauer, T.H.; Kilsdonk, D.J.; Aeschlimann, R.W.; Fukano, Y.; Sato, I. CAFÉ Experiments on the Flow and Freezing of Metal Fuel and Cladding. In Proceedings of the International conference on fast reactors and related fuel cycles (FR09): Challenges and opportunities; kyoto (Japan), 2009; pp. 1–9.
5. Li, G.; Oka, Y. Sensitivity Study of Melt Behavior of Fukushima Daiichi Unit 1 Type Accident with MELCOR Code and MPS Method. *J. Nucl. Sci. Technol.* **2015**, *52*, 109–121, doi:10.1080/00223131.2014.933136.

6. Hidayati, A.N.; Waris, A.; Mustari, A.P.A.; Irwanto, D.; Aprianti, N.A. Moving Particle Semi-Implicit Simulation on the Molten Wood's Metal Downward Relocation Process. *Nucl. Sci. Tech.* **2021**, *32*, 1–12, doi:10.1007/s41365-021-00922-x.
7. Yanti, N.J.; Mustari, A.P.A.; Hidayati, A.N.; Aprianti, N.A. The Effect of Copper Utilization on MSFR's Safety Plug Performance Simulation by Using MPS. *J. Phys. Conf. Ser.* **2022**, *2243*, 012059, doi:10.1088/1742-6596/2243/1/012059.
8. Kawahara, T.; Oka, Y. Ex-Vessel Molten Core Solidification Behavior by Moving Particle Semi-Implicit Method. *J. Nucl. Sci. Technol.* **2012**, *49*, 1156–1164, doi:10.1080/00223131.2012.740944.
9. Mustari, A.P.A.; Iksal; Sumiati; Syeilendra; Irwanto, D.; Aprianti, N.A. Prediction of Melting Penetration of Armco Iron by Liquid Uranium Using MPS-LER. *J. Phys. Conf. Ser.* **2017**, *799*, doi:10.1088/1742- 6596/799/1/012019.
10. Mustari, A.P.A.; Oka, Y. Molten Uranium Eutectic Interaction on Iron-Alloy by MPS Method. *Nucl. Eng. Des.* **2014**, *278*, 387–394, doi:10.1016/j.nucengdes.2014.07.028.
11. Mustari, A.P.A.; Oka, Y.; Furuya, M.; Takeo, W.; Chen, R. 3D Simulation of Eutectic Interaction of Pb-Sn System Using Moving Particle Semi-Implicit (MPS) Method. *Ann. Nucl. Energy* **2015**, *81*, 26–33, doi:10.1016/j.anucene.2015.03.031.
12. Mustari, A.P.A.; Iksal, I.; Sumiati, S. MPS Simulation on Melt Penetration of CAFÉ Experiment at 1200 C. *Indones. J. Phys.* **2012**, *23*, 23–25.
13. Koshizuka, S.; Oka, Y. Moving-Particle Semi-Implicit Method for Fragmentation of Incompressible Fluid. *Nucl. Sci. Eng.* 1996, *123*, 421–434.
14. Lindén, J. Upside down Glass of Water Experiment Revisited. *Phys. Educ.* **2020**, *55*, doi:10.1088/1361- 6552/ab9dbb.
15. Nguyen-Thi, L.-Q.; Nguyen, V.-D.; Pierens, X.; Coorevits, P. An Experimental and Numerical Study of the Influence of Viscosity on the Behavior of Dam-Break Flow. *Theor. Comput. Fluid Dyn.* **2021**, *35*, 345–362, doi:10.1007/s00162-021-00562-2.
16. Ozmen-Cagatay, H.; Turhan, E.; Kocaman, S. An Experimental Investigation of Dam-Break Induced Flood Waves for Different Density Fluids. *Ocean Eng.* **2022**, *243*, 110227, doi:10.1016/j.oceaneng.2021.110227.