Study on Fluid Descends Vertically on Static Fluid Using Moving Particle Semi-Implicit Method

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Abstract. The process of fluid descend vertically on static fluid has been studied through experiment and simulation by using Moving Particle Semi-Implicit (MPS) method. MPS has been developed by Koshizuka and Oka (1996). MPS method is a particle method based on the Lagrangian calculation for incompressible medium and does not rely on grid system. This study has been done by doing simulation first then validated by experiment. Water and cooking oil were used in the experiment. This study was carried out to analyze distance and density influence in the height of static fluid bursting process. The experiments were conducted in an acrylic box with the dimension 150 mm x 40 mm x 30 mm and a bottle with height of 100 mm and the nozzle of bottle was 26 mm. The distance between nozzle and surface of fluid inside box is varied for 100 mm and 200 mm. The results show that in the same height, water will be more difficult to be moved than cooking oil because water has bigger density. The distance between nozzle and fluid surface inside the box will affect at the pressure which is received by the fluid. Higher distance will create higher pressure so that fluid inside the box will be moved easier and more fluid will split out to the box. It also gives some influence in the final condition of remaining fluid in the acrylic box.

I. Introduction

The strategy for preventing the accidents in the nuclear reactor and its environmental impact have been required to take into account by several countries that develop nuclear technology. So that nuclear reactor safety is an important aspect that has to be considered carefully. One of safety aspect is about melting behavior of core material when the accident is happened and how it interact with other material inside the reactor core. It will be good if the condition inside the reactor can be imitated in the lab-scale. Because it can be predicted easily for any accidents-like in the future so that it can be prevented early. But it is quite difficult and insufficient to be done and also the conventional simulation methods have their own difficulty to analyze several melted core phenomena. One of them is free-surface flows that have to be calculated thoroughly by using empirical equations but some of code packages have a problem with the general versatility [1]. Other difficulty is the phase transition when it comes to some heat transfer between two or more material in the calculation.
One of the methods that can be used for simulating the inside-core phenomena is Moving Particle Semi-Implicit (MPS) method, developed by Koshizuka and Oka (1996). MPS method has been developed based on fully Lagrangian and particle dynamics are not in a grid system anymore or it can be called grid-less method [2]. MPS can calculate the incompressible mediums such as liquid and solid. The particles are distributed only in the area where the fluid presents and it calculates the diffusion phenomena. Other particle methods are Particle-and-Force (PAF) method developed by Darly (1965) and Smoothed Particle Hydrodynamics (SPH) method developed by Gingold and Monaghan (1977) for calculating the compressible medium [3]. Free surface and multiphase flow phenomena can be calculated by using MPS such as study about breaking waves by Koshizuka [4] and droplet breakup behavior by Nomura [5]. Other studies that can be implemented by using MPS are heat transfer prediction in pool boiling without relying on empirical correlation by Yoon [6] and analyzing bubble rising in a stagnant liquid pool [7, 8].

Recently a study about melting penetration of Armco Iron and Fe-U by using modified MPS has been done by Mustari [9,10] for predicting the penetration rate of both material inside the high temperature system. In this study, the modified MPS code has been used to simulate the fluid that descends vertically on static fluid from a certain height. Experiment has been done for validating the simulation data using water and cooking oil. The effects of both density of liquids and height have also been investigated by using simulation.

II. Model and Numerical Simulation

Governing equation

Analyzing the incompressible medium such as water and solid can use any of numerical method. MPS method is one of those numerical methods that have advantages in treating fluid free surface and interface. MPS method has a robust approach and effectiveness for analyzing the physical phenomena. The fundamental equations for expressing the incompressible flows are in the following form:

\[
\frac{D\rho}{Dt} = 0
\]

\[
\frac{D\vec{u}}{Dt} = -\frac{1}{\rho} \nabla P + \nu \nabla^2 \vec{u} + \vec{g}
\]

Where \(\rho\), \(t\), \(\vec{u}\), \(P\), \(\nu\) and \(\vec{g}\) are fluid density, time, velocity vector, pressure, kinematic viscosity and external force, respectively. Equation (1) is written about mass conservation while equation (2) is written about Navier-Stokes equation. The left side in the equation (2) is the momentum conservation that directly calculated by moving particles. Particles will move because of some influences from pressure gradient term, viscous term and gravity as an external force term as shown in the right side of equation (2).

Particle interaction models

MPS method introduces the interactions of one particle with other particles within the range of a \(r_e\), as a cutoff radius respectively. Those interactions are represented by a weight function \(w(r)\), as shown in equation (3).

\[
w(r) = \begin{cases} 
1 - \frac{r}{r_e} & 0 \leq r \leq r_e \\
0 & r_e \leq r 
\end{cases}
\]

\[
n_i = \sum_{j=1} w(|\vec{r}_j - \vec{r}_i|)
\]
Figure 1. Interaction model of MPS method

The summation of all particles weight function is called particle number density, as shown in equation (4), which $r_i$ and $r_j$ are position vectors of $i$ and $j$ particles. This particle number density is used to represent how particle can give some influence to other particle inside the system along with the mass and momentum conservation equation. All the differential operators in the mass and momentum conservation equations that represent the particle interaction should be substituted with the following form:

$$
\langle \nabla \phi \rangle_i = \frac{d}{n^0} \sum_{j \neq i} \frac{\phi_j - \hat{\phi}_i}{|r_j - \hat{r}_i|^2} w(|r_j - \hat{r}_i|)
$$

(5)

$$
\langle \nabla \cdot \vec{\varphi} \rangle_i = \frac{d}{n^0} \sum_{j \neq i} \frac{\varphi_j - \varphi_i}{|r_j - \hat{r}_i|^2} (r_j - \hat{r}_i) w(|r_j - \hat{r}_i|)
$$

(6)

$$
\langle \nabla^2 \phi \rangle_i = \frac{2d}{\lambda n^0} \sum_{j \neq i} (\phi_j - \phi_i) w(|r_j - \hat{r}_i|)
$$

(7)

Where $d$, $n^0$, $\phi_i$, $\hat{\phi}_i$ are the number of spatial dimensions, initial particle number density, scalar value of the $j$-particle at $r_j$, and the $i$-target particle’s minimum scalar value, respectively. The $\lambda$ value can be approximated by equation (8) so that the Laplacian model can be proportional to the analytical solution.

$$
\lambda = \frac{\sum_{j \neq i} w(|r_j - \hat{r}_i|)|r_j - \hat{r}_i|^2}{\sum_{j \neq i} w(|r_j - \hat{r}_i|)} \approx \frac{\int_V w(r) r^2 dV}{\int_V w(r) dV}
$$

(8)

The incompressible conditions can be preserved by divining a constant number density for non-free surface particles. While for free-surface particles have the number density less than other particles which is divined by equation (9), where $\beta$ is the constant value which less than unity.

$$
n_i < \beta n^0
$$

(9)

All of the previous numerical formulation will be used for calculating the particle dynamic that related with the viscosity and external force such as gravity. The viscosity and gravity will be calculated explicitly. External force and viscosity term will affect the particle movement. Thus it is necessary to calculate the temporal velocity, as shown in equation (10). Meanwhile the pressure term will be calculated implicitly, as shown in equation (11).

$$
\vec{u}_k = \vec{u}^k_t + v \Delta t \frac{2d}{\lambda n^0} \sum_{j \neq i} (\vec{u}_j^k - \vec{u}_i^k) w(|\vec{u}_j^k - \vec{u}_i^k|)
$$

(10)

$$
\langle \nabla^2 p \rangle_{k+1}^t = \frac{2d}{\lambda n^0} \sum_{j \neq i} (p_{j}^{k+1} - \bar{p}_i^{k+1}) w(|\vec{r}_j^* - \vec{r}_i^*|)
$$

(11)
Where the superscript * and k are the temporary values and the values at the last time step, respectively. Temporal position will be updated as result of the change of velocity.

$$\vec{u}^{**} = \vec{u}^* + \Delta t \vec{g}$$  \hfill (12)$$

$$\vec{r}^{**} = \vec{r}^k + \Delta t \vec{u}^{**}$$  \hfill (13)$$

$$\vec{u}^{k+1} = \vec{u}^{**} + \Delta t \left( -\frac{1}{\rho^0} \nabla P \right)$$  \hfill (14)$$

$$\vec{r}^{k+1} = \vec{r}^{**} + (\Delta t)^2 \left( -\frac{1}{\rho^0} \nabla P \right)$$  \hfill (15)$$

Figure 2. Flowchart of MPS method

Figure 2 depicts the MPS flowchart for incompressible flow that used in this study. The calculation will be started by preparing the initial conditions. Each particle is given some physical properties such as initial position, velocity, pressure and temperature that will be stored in the grid data file. Moreover, average distance between particles, mass density, compressibility and kinematic viscosity are included in the input data. As previously mentioned in the equation 4, temporal particle number density is calculated, and it will affect the computed velocity which depends on gravity and the particle viscosity. In this calculation, 9.81 m/s^2 is used for the value of gravity. With all of temporal change that is happened before, it will drive some particles movement and changes the configuration of particles. So that, it is important to recalculate the particle number density as the cutoff radius function. In the second step, Poisson equation of pressure is calculated so that the velocity and the position of each particle will be updated until the program is terminated.

III. Experiment and simulation

The experiments were conducted in an acrylic box with the dimension 150 mm x 40 mm x 30 mm and a bottle with height of 100 mm and the nozzle of bottle was 26 mm, respectively. In this study water and oil was used for analyzing the bursting process of a liquid which was moved by other liquid from a certain height. The distance between fluid surface in the acrylic box and the nozzle was set to 100 mm and 200 mm. All of the experiments processes were taken by a certain camera so that not all of the height profile could be seen in this case.
Figure 3 and 4 depict the initial condition of simulation and experiment of water-water and water-cooking oil bursting process. In the simulation, the blue liquid represented as water, while the green one represented as cooking oil and the rest was wall and the dummy wall. Moreover, one millimeter particle size was used in this simulation, so the total of particle was 13,341. Physical parameter of fluid that was used in this simulation and experiment can be seen in the table 1.

Table 1. Physical Properties of Cooking Oil and Water

| Physical Properties                      | Cooking oil | Water  |
|------------------------------------------|-------------|--------|
| Density (kg/m³)                          | 890.13      | 1,000.00 |
| Kinematic viscosity (mm²/s)              | 53.146      | 1.004  |

In the initial condition of simulation and experiment were slightly different. In the simulation, the bottle was given a lid on its top. Meanwhile in the experiment, there was no lid on the top for keeping laminar flow of water. The difference of both left no impact to the result.

IV. Result and Discussion

The experiments were done after doing some simulation as a validation data of liquid bursting profile. From figure 4, it can be seen 2 dimensional view of both experiment and simulation of water that descend vertically to water at 100 mm. Water from bottle descend and interact with water inside the acrylic box at 0.11 s, approximately. The exact time of the first interaction between those two fluids cannot be determined because of unclear picture. However, the final states of both, experiment and simulation, are quite similar, that there is water split out of box and systems are being stable at 1.00 s.
Figure 4. Experiment and simulation results of water-water 100 mm bursting process (a) 0.11 s (b) 0.23 s (c) 1.00 s

Figure 5. Experiment and simulation results of water-water 200 mm bursting process (a) 0.16 s (b) 0.26 s (c) 1.00 s

Figure 5 shows the result of experiment and simulation with the difference height from surface of water in the box is 200 mm. The water stream down and interact with water inside the box at 0.16 s. It takes longer time both in the experiment and simulation than the previous one at 100 mm. With the difference of height, there is some impact that can be seen in the figure 6. It shows that the height of burst during the simulation is different each other. For the height of 200 mm, it gives higher result of burst because higher surface can give higher pressure to the water inside the box. However, the pattern of those two results was similar as shows in the figure 7. At first, the height is goes up for a while then goes down. After that it goes up again because of the water that is being moved before go back to the box and give other pressure to the water which left in the box.
Figure 7 and 8 depict the experiment and simulation result of water-cooking oil bursting with height 100 mm and 200 mm, respectively. Figure 8 shows that the time of first interaction between water and cooking oil is 0.11 s, it is same with the water-water bursting process at 100 mm. The patterns of burst profile that are shown in figure 7 is quite similar compare to the previous one, but the differences are about the height of burst itself and the final condition. Cooking oil has density lighter than water so it can be moved vertically easier than water. After being moved by water, cooking oil will spilt out of box and hardly comes back so that at the final condition (Figure 7.c) it shows just a little amount of oil that still in the box.
Figure 9 depicts other simulation and experiment result when it comes to water-cooking oil bursting process at 200 mm. The height of burst profile shows that height of 200 mm gives the highest result among all of the experiment and simulation. This can be happened because of two reasons. First, because of the height of water that can impact to the pressure which is received by cooking oil inside the box. Moreover, cooking oil is lighter than water so that with higher pressure water can pushes cooking oil easily. However, the burst profile is slightly different between water-water and water-cooking oil, because there is no going up process of the height again when it comes to the water-cooking oil bursting process. Final condition that is reached in the water-cooking oil 200 mm bursting process is 1.40 s. It is little bit longer than other simulation.

| Condition            | Experiment ( ± 0.5 mm) | Simulation ( ± 0.5 mm) |
|----------------------|------------------------|------------------------|
| Water-Water          | 100 mm                 | 34                     | 36                     |
|                      | 200 mm                 | 30                     | 39                     |
| Water-Cooking Oil    | 100 mm                 | 33                     | 32                     |
|                      | 200 mm                 | 26                     | 29                     |

Table 2 shows the final height condition of liquid inside the box for experiment and simulation. It was measured from the bottom side of box. It can be seen that the result shows there is no a significant difference between experiment and simulation. The experiment final results are having same pattern both of water-water and water-cooking oil which higher the height or distance between nozzle and the fluid inside the box will give smaller height in the final condition.

V. Conclusion
The experiment and simulation have been conducted for analyzing the bursting process between two different fluids at the different height. Modified MPS code has been used for simulating the two dimensional bursting process between water-water and water-cooking oil. The distance between fluid in the acrylic box and nozzle of bottle has been varied at 100 mm and 200 mm. In this study, density and the height influence have been investigated through simulation by using the MPS method. The simulation results have been validated by using experiments, where the simulation results are quite similar to the experiment results. The results show that in the same height, water will be more difficult to be moved than cooking oil because water has bigger density. Other result which can be concluded that the distance between nozzle and the surface of fluid inside the box will affect at the pressure which is received by the fluid. Higher distance will create higher pressure so that fluid inside the box will be moved easier and more fluid will split out to the box. It also gives some influence in the final condition of remaining fluid in the acrylic box. The two dimensional simulation shows a good agreement with the
experiment, which shows that the modified MPS code has the ability to analyze the phenomenon of bursting process between two fluids. It also can be implemented for analyzing the safety aspect inside nuclear reactor. For the improvement, it will be better if we can add height data from experiments. Thus it is important to make sure that all of the experimental processes are recorded well. The future works will be analyzing the core melt-down accident inside the nuclear reactor using MPS with some additional code for heat transfer process.

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