The Effect of Temperature Variations on Wood’s Metal Plate Melting Simulation by Using MPS

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Abstract: Two-dimensional simulation of Wood’s Metal Plate (WMP) Melting Process has been conducted by varying the molten temperature. This simulation was performed by using Moving Particle Semi-Implicit (MPS) method which can calculate the Navier-Stokes and heat transfer equation without dividing mesh system. As a substitute, particles are selected to represent every part of simulation such as fluid, wall and dummy type. The experiment of WMP melting process has been conducted by Sudha (2018). The molten Wood’s Metal was originally set at 573 K. In this simulation, the holes formation in WMP will be investigated as a consequence of molten temperature variation. Furthermore, temperature distribution at top side of WMP and solid-liquid phase change will be analyzed for initial temperature of molten are 523 K, 473 K and 423 K. The results show that the phases change significantly in a short time when the molten temperature is increased. However, until the end of simulation which on 1.5 s just for molten temperature 573 K shows the breaching process to the WMP. This study can be implemented when the reactor nuclear severe accident happened.

1. Introduction
The molten material formation after a nuclear reactor accident occurs, can damage other components and it has to be carefully considered to elevate the safety aspect of nuclear technologies. The radioactive molten materials can be relocated to the grid plate, impinge the core catcher and the worst case is those materials can leak to the environment. Therefore, the efficient and robust design of nuclear reactor is absolutely required for preventing other accidents and radioactive leakage to the environment. The molten material can be a fragmented debris or liquid jet form, depend on the quenching process inside the reactor core. In the fast nuclear reactor, molten material can be quenched by sodium. Consequently, not much high temperature molten material is relocated to the other components [1,2]. The characteristic of molten material such as corium that can be formed when the accident happened, has been analyzed by Park (2012) using the Total Loss of Feed Water (TLFW) and the Small Break Loss of Coolant Accident (SBLOCA) without Safety Injection (SI) scenario in the Advanced Power
Reactor (APR) 1400 reactor vessel [3]. Those two scenarios of nuclear accident were referred to level 1 Probabilistic Safety Assessment (PSA). Similarly, Sudha (2018) has investigated the downward relocation of low melting point Wood’s Metal Plate (WMP) which was referred to the fast reactor nuclear accident scenario [4]. Moreover, developing the safety system for preventing the molten leakage has been done by creating the In-Vessel corium Retention (IVR) through the External Reactor Vessel Cooling (ERVC) [5].

The physical characteristic of nuclear reactor molten material has been studied through two- or three-dimensions computational code such as CORFLOW and LAVA [6,7]. However, calculating the free surface area is a little bit complex because it needs empirical equation from experiment and it cannot be used for the analysis of core melt down accident generally. On the other hand, MPS method is a new developed particle method that can solve free surface boundary condition without depending on an empirical equation [8]. It also can be used for analyzing the phase change of particle and heat transfer between materials. It does not need the grid system because of the particle orientation. The investigation of melt freezing behavior in a tube has been done by Chen (2014) by using two dimensional MPS simulation [9]. Kawahara (2012) also has simulated both two and three dimensional of in-vessel and ex-vessel molten core solidification behavior which was referred to FARO L-26S test [10,11].

In summary, the purpose of this research is to adopt and improve the two dimensional MPS method for analyzing the effect of molten temperature variations at 573 K, 523 K, 473 K and 423 K on Wood’s metal downward relocation process. The simulation result will shows the behavior of molten Wood’s metal and the heat transfer between solid and liquid form.

2. Numerical Method

The MPS method includes three equations: mass conservation, Navier-Stokes and energy conservation as shown in equation (1), (2) and (3), respectively.

\[
\frac{D\rho}{Dt} = 0 \tag{1}
\]

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

\[
\frac{Dh}{Dt} = k \nabla^2 T + Q \tag{3}
\]

The fluid density is assumed to be constant as the implementation of incompressibility condition of media, as shown in equation (1). On the right side of equation (2) of Navier-Stokes equation, there are \( \rho \), \( t \), \( \vec{u} \), \( P \), \( \nu \) and \( \vec{g} \) which fluid density, time, velocity vector, pressure, kinematic viscosity and external force, respectively. Equation (3) shows that energy conservation is composed of conduction term and heat source term. Where \( h \), \( k \), \( T \) and \( Q \) are enthalpy, thermal conductivity, temperature and heat source, respectively.

The incompressible media such as solid and liquid can be simulated by using MPS method as the first fully Lagrangian particle method [8]. Figure 1 shows the particles interaction within a radius of interaction, \( r_e \) in the MPS method. The radius of interaction is defined for limiting the influence a particle to other particle when the physical aspects such as velocity, temperature and pressure are calculated. This method does not need any computational grid. However, the weight function, \( w(r) \) is employed for implementing the influence of particle in a certain radius of interaction, as shown in equation (4).

\[
w(r) = \begin{cases} 
1 - \frac{r}{r_e} & 0 \leq r \leq r_e \\
0 & r_e \leq r
\end{cases} \tag{4}
\]
Equation (5) is the particle number density that defines the summation of all particles weight function, which \( \mathbf{r}_i \) and \( \mathbf{r}_j \) are position vectors of \( i \) and \( j \) particles, respectively. 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.

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

Equation (6) expresses the discretization of temperature calculation. It is solved explicitly after updating the particle positions. There is no temperature’s temporary value dependency for calculating the heat transfer in MPS method. Meanwhile in equation (6) and (7), velocity and pressure term will be calculated implicitly. The superscript * is the temporary values. Moreover, the \( k \) symbol is the values at the last time step.

\[
\langle \nabla^2 p \rangle_{k+1} = \frac{2d}{\lambda n^0} \sum_{j \neq i} \left( \hat{p}_{j}^{k+1} - \hat{p}_{i}^{k+1} \right) w(|\hat{r}_j^* - \hat{r}_i^*|)
\]

\[
T_{i}^{k+1} = T_{i}^{k} + \frac{k\Delta t}{\rho C_p \lambda n^0} \sum_{j \neq i} \left( T_{j}^{k} - T_{i}^{k} \right) w(|\hat{r}_j^* - \hat{r}_i^*|) + \frac{Q}{\rho C_p}
\]

Figure 1 is the MPS flowchart that used in this study. Some physical properties such as initial position, velocity, pressure and temperature of each particle will be embedded and stored in the data file. Moreover, average distance between particles, mass density, compressibility and kinematic viscosity are included in the input data. Temporal particle number density is calculated and it will affect the temporal velocity which is depended on gravity and the particle viscosity. The value of gravity is 9.81 m/s\(^2\). The temporal change that is happened before will drive some particles movement and changes the configuration of particles so that it is important to recalculate the particle number density. Poisson
equation of pressure is calculated so that the velocity and the position of each particle will be updated until the program is terminated.

3. Simulation Condition

The previous research has been conducted based on Sudha et al. experiment (2018) with the initial molten temperature at 573 K. In this study, the molten temperature has been varied at 523 K, 473 K and 423 K. The molten (Wood’s Metal) WM was released through a nozzle of 60 mm diameter. It went down to the plate which is place in a cylindrical test vessel of 950 mm diameter and height 1100 mm. The distance between nozzle and Wood’s Metal Plate (WMP) was 270 mm. The diameter and thickness of WMP are 470 mm and 7 mm, respectively. The WMP temperature was set 300 K. However, for simplifying the simulation not all of the geometry was drawn. Actually, there were 2 WMP and the test vessel was partially filled with water in the real experiment. For simulation, there was one WMP and the test vessel was not filled with water. It was chosen for focusing the downward relocation and melting process of WMP.

Figure 2. Initial condition of simulation

Figure 2 depicts the initial condition of two dimensional MPS simulation. As previously mentioned, the simulation condition was simplified. The pressure value was set same with the ambient, zero bar gauge. Moreover, not all of cylindrical test’s geometry was drawn in simulation. The particle size and total particle number were 1 mm and 15,875 particles, respectively. For the simulation requirement the WMP was defined as the first wall with green color and the SS304L was defined as the red color second wall. The blue color particles were molten WM. The initial temperature profile was given same with the experiment condition for all particles. All materials which used in this simulation and their properties are listed in Table 1.
Table 1. Material properties

| Parameter                | Wood's metal | SS304L |
|--------------------------|--------------|--------|
| Density (kg/m³)          |              |        |
| Molten                   | 9.67 x10³    | -      |
| Solid                    | 9.54 x10³    | 7.9 x10³ |
| Melting point (K)        | 345          | 1727   |
| Specific heat capacity (J/kg.K) | 168     | 500    |
| Thermal conductivity (W/m.K) | 19        | 21.5   |
| Latent heat (J/kg)       | 3.7 x10⁴     | -      |
| Viscosity (Pa.s)         | 1.5 x10⁻³    | 8.0 x10⁻³ |

Viscosity (Pa.s)* at melting point

4. Result and Discussion

Figure 3 shows the phase change between solid and liquid for each temperature variations until 1.6 s. Those graphs show the significant change for each phase. The higher molten temperature leads the sharper change of phase. It is the consequent of heat transfer between molten WM particle and WMP particle. Those results are representing the mathematical formula as written in the equation (8). Moreover, the heat transfer between those particles would affect to the holes formation as shown in the Figure 4.
Figure 4 depicts the comparison simulation result of molten temperature variation at 1.5 s. The hole was formed only at 573 K and some molten particles were relocated to the cylinder test wall. It was the consequent of high difference of temperature so the holes formation became faster. At 523 K, it is shown that there is hole formation at the top of WMP and almost reach the bottom side of the plate. However, for the molten temperature 473 K and 423 K, all molten particles still spread evenly at the top of WMP and did not occur the holes formation. It was necessary to add more simulation time for knowing the holes formation at temperature 523 K, 473 K and 423 K. The addition simulation time depended on the holes size that must same with the experimental result. It is shown on Figure 5.

Figure 5. Time requirement for holes formation each molten temperature variation

Based on Sudha’s experiment (2018), the simulation needs 1.5 s to form the holes at top and bottom of WMP for 573 K molten temperature. Apparently, for molten temperature at 523 K, 473 K and 423 K, it needs 1.8 s, 2.3 s and 3.3 s, respectively. Moreover, it can represent the correlation between time requirement for simulation and the molten temperature as shown in Figure 5. The correlation was not a linear but exponential so that with the little decrement of molten temperature will exponentially affect to the time requirement of simulation. The fitting data was good with the $R^2$ value was 0.9767.
5. Conclusion
The simulation has been conducted for analyzing the effect of molten temperature variation on Wood’s Metal downward relocation process. The improved MPS code has been used for simulating two-dimensional relocation process and heat transfer calculation between molten WM and WMP particles in the system. The volume fraction results show that the higher molten temperature leads the sharper change of phase. It will give a significant effect to the time requirement for making the same size of holes with the experiment result at the top and bottom side of WMP. Moreover, the improved MPS method can be implemented to analyze the molten material behavior inside nuclear reactor while the severe accident occurs.

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