The molten wood’s metal initial velocity variations effect on breaching simulation by MPS method

A N Hidayati1, A Waris2, A P A Mustari2, D Irwanto2, N A Aprianti2

1Doctoral Program of Physics Department, Faculty of Mathematics and Natural Science, Bandung Institute of Technology, Jalan Ganesha 10, Bandung 40132, Indonesia
2Nuclear Physics and Biophysics Research Division, Physics Department, Faculty of Mathematics and Natural Science, Bandung Institute of Technology, Jalan Ganesha 10, Bandung 40132, Indonesia

Abstract. Series of MPS simulations have been conducted using two-dimensional geometry. The simulation was based on Sudha’s experiment (2018) about initial velocity variations on molten Wood’s Metal (WM). The molten WM would be flowed through nozzle with the diameter was 6 mm. It would impinge to the Woods Metal Plate (WMP) which 270 mm below the nozzle. The WMP diameter was 470 mm. The temperature of molten WM and WMP were set at 573 K and 300 K, respectively. The initial velocity of molten WM was varied at 0.327 m/s, 0.397 m/s, 0.498 m/s in the y-negative direction. The simulation was calculated by using 2D MPS with additional procedures such as heat transfer calculation and defining a new type of wall particle. The results showed some different spread patterns, leading edge and phase fraction change for each initial velocity. It can be concluded that with varying the initial velocity will affect on the radial spread pattern but not so much effect occurs on the phase volume fraction change.

Keywords: fluid, impinge, simulations, variation, velocity.

1. Introduction

The support system of nuclear reactor’s core is one of important part which designed for preventing the molten leakage to the environment. This preventive action must be prepared as the part of Probabilistic Safety Assessment (PSA) when nuclear severe accident happened[1]. Consequently, there are some layers that have to be sacrificed for quenching the molten material’s temperature. Moreover, those layers can be barriers for molten material to not directly contact with the Reactor Pressure Vessel (RPV).

It is important to establish some mitigation measures which can prevent the leakage of coolant and relocation of melted material into the environment. For example, some of generation IV nuclear reactors have already added grid plate and multiple barrier features in the in-vessel or ex-vessel system. The example of defense support system consists of grid plate, support structure, heat shield plate and multiple barrier plate. The main function of grid plate is the direct shielding against relocated melted material from reactor and directly contacted with the support structure. It will be a sacrificial structure for preventing the melted material leakage process to the environment. The next defense layer is multiple barriers for collecting the melt debris. Several studies have been conducted to make some formulation, optimization concept of grid plate, multiple barrier and coolant for some type of nuclear reactor. In the present study, several types of multiple barriers are including refractory coating on barrier plate, multi tray barrier, ex-vessel multiple barrier and multiple barrier plates[2]. The refractory coating on multiple barriers at least has two or three layers which must meet some
criteria such as (i) having the capability to support and restrain the relocated melted material during a severe accident; (ii) resisting the interactions with high temperature melted material for insulator coating material; (iii) preventing the oxidation process. Sharma et al., has simulated multi tray multiple barriers using SIMPLE algorithm. It was concluded that double plate or triple plate configuration of multiple barriers can accommodate the total heat load from relocated melted material of the 500 MWe Fast Breeder Reactor without exceeding the various allowable temperature limits. It can be applied in the in-vessel reactor[3].

In the previous study, some simulation based on two dimensional MPS have been carried out for knowing the grid plate melting process[4]. The Wood’s Metal was used as material for the molten and the plate. It is known for its low melting temperature and eutectic character. Variation of molten temperature has been done for 573 K, 523 K, 473 K and 423 K. In this study, the effect of molten initial velocity variation will be discussed. It will be analyzed for its relocation process, hole formation and interaction between molten particles and WMP. Giving the initial velocity is an implementation of initial pressure existing in the system especially for molten material. This study will be conducted by using two dimensional MPS simulation.

2. Numerical Method

The MPS method is a meshless simulation method that will be used in this study. This method is based on the conservative mass and Navier-Stokes equation as a representation of fluid dynamic[5]. It has been developed by Koshizuka and Oka at 1996. Mathematically, the governing equation was shown on equation 1.

\[
\begin{align*}
\frac{Dp}{Dt} &= 0 \\
\frac{D\vec{u}}{Dt} &= -\frac{1}{\rho} PP + \nu \nabla^2 \vec{u} + \vec{g} \\
\frac{Dh}{Dt} &= k \nabla^2 T + Q
\end{align*}
\]

Equation (1) is for conservative mass which applied to the Newtonian fluid. Those can briefly explain that the change of viscosity linearly happened along with the applied strain to the fluid. Equation (2) is Navier-Stokes Equation for calculating the momentum of fluid. The change of particle velocity will be affected by pressure gradient and viscosity, velocity Laplacian and gravitational vector. \( \rho, \vec{u}, P, \nu, \vec{g} \) and \( t \) are symbol for fluid density, velocity, pressure, viscosity, gravitational vector and time, respectively. Equation (3) is heat transfer equation which is added to implement the melting process of WMP by molten WM. That equation contains the enthalpy change over time, temperature Laplacian calculation and heat source. \( h, k, T \) and \( Q \) are enthalpy, thermal conductivity, temperature and constant heat source, respectively.

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

\[
n_i = \sum_{j \neq i} w(|\vec{r}_j - \vec{r}_i|)
\]

There is a specific definition for weight function, \( w(r) \), as the dynamic influence from one particle to others as shown in equation (4). Moreover, equation (5) introduces the particle number density definition which depend on weight function value each particle. The \( r, r_e, n_i, \) and \( w(r) \) are distance, limit radius, particle number density and weight function. The weight function is important for implementing the governing equation (1), (2) and (3) in the particle dynamic of MPS method. Equation (6), (7) and (8) show the formulation of discretized velocity, Laplacian of pressure and temperature each particle, respectively.
Equation (6) and (7) are implicitly calculated, which there are some temporary value applied for calculating the current physical parameters. Equation (8) is particle temperature calculation depended on MPS method discretization as shown in equation (3). The particle temperature is explicitly calculated without any dependency to the temporary value. The (*) and k in the equation (6), (7) and (8) show the temporary and the previous step value, respectively. The Symbol $u^*_k$, $\Delta t$, d, $\lambda$, $C_p$ are velocity vector of previous step, simulation delta time, simulation dimension, Laplacian coefficient and material’s specific heat coefficient, respectively. The obtaining values of those three equations will be updated until the simulation reach the equilibrium state. Other state that can define the termination of simulation is relative error value for each physical parameter does not exceed the certain value which has been set in advance.

Figure 1. Calculation procedure of MPS.

Figure 1 depicts the MPS calculation flowchart. In the initial condition, we prepare the geometry and the physical parameters which is embedded to each particle. Some data such as position, velocity, pressure and temperature are stored in the input grid data. The particle distance, compressibility, viscosity, density and margin setting are stored in input data file. Each physical parameter calculation will be initiated by updating the particle number density. Along with that, temperature, velocity and pressure of each particle will be update too until it reaches the termination time. If the relative error of calculation is less that the set value, then the simulation is finished.
3. Simulation Condition

Initial condition of two dimensional MPS simulation is shown in Figure 2. It was prepared quite similar with the experimental conditions[6]. The distance between the melt chamber’s nozzle and WMP surface was 270 mm. The diameter of melt chamber’s nozzle, WMP plate and SS304L cylindrical test were 60 mm, 470 mm and 950 mm, respectively. The molten WM and WMP initial temperature were set at 573 K and 300 K, respectively. The initial velocity of molten WM was varied at 0.327 m/s, 0.397 m/s and 0.498 m/s. Basically, the initial velocities were representing the pressure that applied by auxiliary pressure system to the molten WM before it went down and impinged to the plate (Sudha, 2018). However, the implementing to the code was not ready yet to add initial pressure in the first place. This could be happened due to some correlations in the syntax have to be set to zero pressure for initial condition. Interestingly, if the syntax was modified it could ruin the consistency of MPS algorithm itself. Therefore, implementing the initial velocities which were measured in the previous experiments is the optimal way to be done. The particles which have yellow, red, blue and green color are dummyWallType, secondWall, fluidType and wallType, respectively. DummyWallType is a particle which define as wall without giving pressure effect and heat transfer to other kind of particles. This particle is a support particle so that the pressurized particle indirectly contacts with the void condition. SecodWallType and wallType are wall particle representing SS304L and WMP, respectively. In those particles, heat transfer, pressure calculation and Navier-Stokes equation can be applied directly. FluidType is a particle type which representing the moveable particle and affected by gravitation, such as fluid. It has a certain viscosity value at a certain temperature. In this simulation, fluidType particle was used for representing the molten WM. The physical properties related to the WMP plate, molten WM and SS304L cylindrical test vessel are shown 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)         | 3.7x10⁴      | -      |
| Viscosity (Pa.s)           | 1.5x10⁻⁴     | 8.0x10⁻³ |

at melting point

4. Result and Discussion

(a)

(b)

Figure 3. Comparison of simulation results on 0.1 s (a) 0.000 m/s (b) 0.498 m/s.

Figure 3 provides the comparison of two MPS simulation condition at the 0.1 second which the (a) and (b) are result without initial velocity and with 0.498 m/s initial velocity, respectively. Those parametric surveys have been done without changing the molten WM initial temperature which was set on 573 K. It is apparent from Figure 3 that the distance between molten WM's outer surface and WMP surface is closer when the molten WM is given the initial velocity in the y-negative direction. Quantitatively, the result is shown in Figure 4.

Figure 4. The impact of initial velocity on the distance between molten WM and the WMP.
Figure 4 depicts the distance between outer surface of molten WM and WMP surface as a velocity function. It shows that with speeding the molten WM velocity up can change the distance between two surfaces. Those change linearly along with the increasing velocity. However, the minimum y-direction distance cannot be longer than the distance between nozzle and the given initial velocity indirectly shows that there is a certain pressure was given to the molten WM in advance. The bigger pressure will be resulting on the bigger initial velocity and it makes the ordinary molten WM become a jet molten. It also gives the effect to the horizontal spread pattern when the molten WM firstly contact with the WMP surface. Those have been validated to the experimental results (Sudha, 2018). The given initial velocity will change the transfer momentum between molten WM particle and WMP particle.

It can be seen that the horizontal spread patterns are different as shown in Figure 5. Along with those differences, at the beginning of simulation, the leading edge in the x-direction of non-initial velocity molten gives the longest result. It is shown in Figure 5.a. This is the consequence of y-negative direction initial velocity implementation. So that in the beginning of simulations which use initial velocity, indicate sharper of vertical spread pattern not the horizontal one. The bigger initial velocity of molten WM, resulting the sharper vertical spread above the WMP. The next step simulation results are shown in Figure 6.
The comparisons of leading edge for each molten WM initial velocity is shown in Figure 6. It depicts for non-initial velocity has longest distance among all velocity variations in the beginning of simulation. The distance is counted from the outermost particles which spread horizontally in the x-positive and x-negative direction. However, the particle’s velocity to spread on the WMP start from 0.4 s until the end of simulation becomes slower for non-initial velocity scenario. Contradictorily, the results of higher initial velocity show the molten particles will spread horizontally faster. This behavior is caused by the change of y-negative direction velocity to the transversal velocity. Consequently, more particles radially spread on the WMP and reach the maximum distance which equal to the diameter of plate, 470 mm. It can be happened before the center hole on WMP formed. The previous study has been conducted by Sudha (2018) as the experimental evidence for validating this simulation.

![Simulation result on 1.5 s when molten WM impinged the WMP (a) 0,000 m/s (b) 0,327 m/s (c) 0,397 m/s (d) 0,498 m/s.](image)

**Figure 7.** Simulation result on 1.5 s when molten WM impinged the WMP (a) 0,000 m/s (b) 0,327 m/s (c) 0,397 m/s (d) 0,498 m/s.

The spreading process of molten WM particles is fast due to higher initial velocity. It can affect to the amount of particle which reach to the cylindrical vessel test as shown in Figure 7. It depicts the comparison between all simulation results on 1.5 s. Figure 7.a shows the significant hole formation for non-initial velocity molten WM simulation. Other subfigures show the contradictory results which some molten particle reach the Stainless-steel cylindrical test. The changing of particle’s axial momentum to be the transversal form leading to faster plate ablation and reducing heat transferred to the WMP. Consequently, the heat which is transferred to the center of WMP reduced and reducing the formed hole diameter. The results have a good agreement with the experiments (Sudha, 2018).
Figure 8 depicts the volume fraction changing within the simulation time for solid phase of WMP. Implementing some initial velocity in advance does not significantly change the WMP solid volume fraction. Along with that case, for non-initial velocity simulation giving a slightly slower change of volume fraction. However, for other simulations which are given initial velocity do not have different result as shown in Figure 8 and strengthened by Figure 9.

The other volume fraction changes obtained from this MPS simulation of molten WM breaching process are presented in Figure 9. It is shown that liquid phase volume fraction as a function of time does not change significantly as well as for solid phase. However, when the solid phase decreases, the liquid phase increases linearly. It is apparent from the figure that very little difference occurs on changing liquid phase for each initial velocity conditions. Through all of those simulation results, it can be concluded that giving initial velocity to the molten WM as the representation of various pressure can greatly change the axial momentum to be transversal momentum. However, it does not change significantly for WMP melting process on the same time of simulation. Therefore, for non-initial velocity gives the biggest hole formation among all velocities.

5. Conclusion
Two dimensional MPS simulations have been conducted for analyzing the impact of varying molten WM initial velocity on WMP breaching process. The initial velocity variations are interpretations of various pressure which given to the molten WM as experiments have been done by Sudha (2018). The MPS simulations was done by initially set the molten WM’s temperature at 573 K. the initial velocity was varied at 0.327 m/s, 0.397 m/s, 0.498 m/s. The obtained results show that there is linear correlation of the distance between molten WM’s surface and WMP surface at 0.1 s. Moreover, the
molten gave some different patterns when it impinging to WMP surface. At 0.3 s of simulation, non-initial velocity molten WM gave the widest horizontal spread pattern on WMP surface. However, the next step of simulation results showed other patterns. It showed that the higher initial velocity would be resulting faster spread pattern above WMP surface as the consequence of changing the momentum from axial to transversal form. Along with that cases, qualitatively more molten WM particles reached to the SS304L cylindrical test when the higher initial velocity was enforced to the molten particles even the hole formation was less than for non-initial velocity condition. Other results were about the volume fraction which change within the simulation time. Those did not show a significant change either for solid or liquid phase of WMP even there are some heat transfer calculations. In summary, these result show that initial velocity will affect on momentum changing and number of molten particles which reach to the cylindrical test. However, the hole formation only significantly occurs for non-initial velocity condition. Those MPS simulations are having a good agreement with the experimental results which have been done before (Sudha, 2018).

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