

MPS SIMULATION ON THE CORIUM MELT FLOW IN CASE OF REACTOR ACCIDENT

SIMULASI MPS PADA ALIRAN LELEHAN CORIUM DALAM KASUS KECELAKAAN REAKTOR

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ABSTRACT

MPS SIMULATION ON THE CORIUM MELT FLOW IN CASE OF REACTOR ACCIDENT. A model of liquid corium in a nuclear reactor has been simulated using the Moving Particle Semi-Implicit (MPS) method. Simulations were conducted to display the pressure and flow velocity profiles of the corium fluid falling from the reactor pressure vessel (RPV) to the plenum by adjusting the dynamic viscosity values and corium temperatures. The first simulation observed the corium pressure and velocity profiles in the plenum, while the second simulation determined the relation between the required time of the corium to reach the plenum due to the variation of the viscosity and temperature. The simulation results show that the required time is proportional to the increase in corium viscosity. In contrast to the effect of temperature, the increase in corium temperature will further reduce the movement time.

Keywords: Corium, melt, MPS, plenum, viscosity

ABSTRAK

SIMULASI MPS PADA ALIRAN LELEHAN CORIUM DALAM KASUS KECELAKAAN REAKTOR. Telah dibuat model simulasi corium cair dalam reaktor nuklir dengan menggunakan metode Moving Particle Semi-Implicit (MPS). Simulasi dilakukan untuk menampilkan profil tekanan dan kecepatan aliran fluida corium yang jatuh dari reaktor pressure vessel (RPV) ke plenum dengan mengatur nilai viskositas dinamis dan temperatur corium. Simulasi pertama mengamati profil tekanan dan kecepatan corium dalam plenum dan simulasi kedua mencari hubungan antara waktu yang dibutuhkan corium untuk mencapai plenum terhadap variasi viskositas dan temperatur. Hasil simulasi menunjukkan bahwa waktu yang diperlukan dalam pergerakan corium sebanding dengan peningkatan nilai viskositas corium. Berbeda dengan pengaruh suhu, kenaikan suhu corium akan memperkecil waktu pergerakan.

Kata kunci: Corium, lelehan, MPS, plenum, viskositas

INTRODUCTION

Although it has a small probability, safety studies are necessary to observe the various factors causing accidents during nuclear reactor operation. One of the accidents that may occur in the operation is the failed cooling system of the reactor core, causing the reactor core to overheat and resulting in the degradation of the core. The degradation of the reactor core due to overheating can be in the form of corium melting. Corium is an alloy material between fuel, cladding, and other components in the core that melts to form a fluid material. The interaction of molten corium with the surface of the reactor pressure vessel (RPV) can damage the material and cause leaks. If there is a leak in the RPV, the corium fluid will move, fall, and fill the plenum space. The movement phenomenon of molten corium in the RPV until it falls and fills the plenum cannot be observed during actual events but can be observed through simulation models.

In modeling, fluid flow can be done with the grid and the particle methods. Modeling with the conventional mesh simulation method has several obstacles, one of which is the problem of using empirical equations to calculate the flow from the free surface. The moving particle semi-implicit (MPS) method is an alternative to model the phenomenon of molten material in the reactor core. MPS was developed in 1996 by S. Koshizuka and K. Shibata from Tokyo University, who applied a meshless particle method to analyze incompressible flows to increase numerical stability and computational speed significantly. The MPS method is used for incompressible fluid fragmentation modeling. MPS applications in nuclear engineering including stability and illusion, limits conditions,

surface tension, multiphase flow, fluid-structure interaction, and multi-resolution techniques were discussed by Li et al. [1]. The equation for incompressible flow commonly used is the Navier-Stokes equation which is mathematically shown in the following equations.

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

$$\frac{Du}{Dt} = -\frac{1}{\rho}\nabla P + \nu\Delta^2\mathbf{u} + \mathbf{g} \quad (2)$$

$$\frac{Dh}{Dt} = k\nabla^2 T + Q \quad (3)$$

where ρ , u , P , ν , g , h , and Q represent density, velocity, pressure, kinematic viscosity, gravity, enthalpy, thermal conductivity, and heat source, respectively. Equation (1) states the conservation of mass, while Equation (2) expresses the Navier-Stokes equation which is affected by particle displacement, and Equation (3) declares the conservation of energy. The interactions between particles in each radius are considered in the MPS method.

To solve fluid mechanics problems apart from the MPS approach by Koshizuka and Oka [2], particle methods such as Smoothed Particle Hydrodynamics (SPH) by Monaghan [3], and the consistent particle method (CPM) for large amplitude free surface motions [2] are developed. In existing particle methods such as SPH and MPS, the partial differential operator approach requires a predefined kernel function, so in particular, this particle method tends to give false and severe pressure fluctuations. However, some researchers have tried to make modifications to solve the problem of pressure fluctuations in MPS, SPH, and I-MPS [2] methods.

In recent years, the MPS method has been applied in the analysis of severe reactor accidents, for example, simulating the behavior of corium in Boiling Water Reactor (BWR) instrument tubes [3], melt flow and compaction in BWR fuel support sections [4], the dissolution behavior of UO_2 [5] and ZrO_2 [6] by liquid zircaloy [7, 8]. Gen Li et al. conducted a similar study that simulated the thermal erosion behavior of the lower head RPV wall by relocating molten corium, including SS, Zr, ZrO_2 , and UO_2 , analyzed in two dimensions [9]. In this study, simulation modeling of the corium melts in the reactor core that falls into the plenum through the leak gap in the reactor pressure vessel was carried out by entering the value of corium viscosity and corium temperature at a certain value. In this study, the model of the initial condition was an empty plenum. Therefore, the pressure and velocity profiles of the melt movement will be observed from the empty plenum to the filled plenum by molten corium.

METHODOLOGY

A simulation model with MPS was carried out to observe the molten corium movement from the RPV to the plenum. This simulation model was only done in 2 dimensions, as shown in Figure 1. The simulation parameters of molten corium have a density of 5180 kg/m^3 , area dimension of $1.2 \text{ m} \times 0.5 \text{ m}$, RPV tank dimension of $1.4 \text{ m} \times 0.8 \text{ m}$, and thickness of 0.1 m . There are 3 leakage gaps in the RPV with a gap width of 0.1 m , and each spaced 0.1 m . The RPV tank is placed in a plenum with a dimension of $1.8 \text{ m} \times 1.9 \text{ m}$ and a thickness of 0.1 m . The distance between the RPV and the inner surface of the plenum is 0.8 m . The simulated fluid is corium material with UO_2 composition with the thermophysical properties of liquid UO_2 and corium referring to the dynamic model and predictions of Kim et al. [10] and Kuala et al. [11].

The simulation results will display the pressure and velocity profiles of the corium fluid as a function of time. This work simulates the corium fluid with 3152 particles with pre-determined corium viscosity and temperature parameters. Simulations were carried out using the MPS computer program, and Paraview was used to display the pressure and velocity profiles. The simulation used a personal computer with an i9 2.5 GHz processor, 8 cores, 16 GB RAM, and a 64-bit Windows 10 operating system.

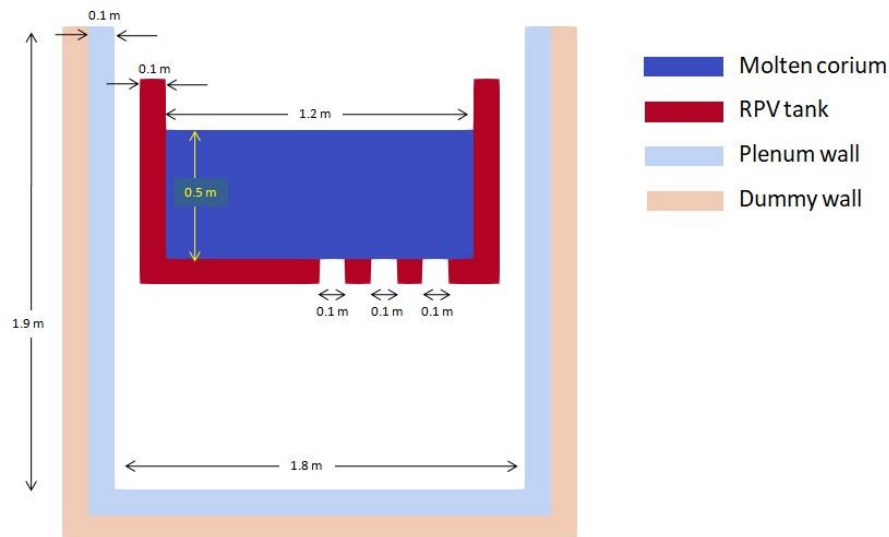


Figure 1. Simulation model of corium melt flow.

Simulations will also be carried out to plot the relation between the dynamic viscosity and temperature of the corium with the required time for melting until it reaches the surface of the plenum. To observe the effect of the dynamic viscosity of corium on the time required for the melt to fall to the surface of the plenum, the dynamic viscosity was varied from 2 mPa.s to 4 mPa.s and then simulated for 2 s with an interval of 1 ms. To see the effect of corium temperature on the time required for the melt to fall and flow to meet the surface of the plenum, the temperature was varied from 1000 K to 3000 K, then simulated for 2 s with an interval of 1 ms. Temperature variations are based on the changes in dynamic viscosity and corium density values based on the modeling results of Kim et al. [10]. In the first MPS simulation, the dynamic viscosity value was varied with a corium density of 5180 kg/m³. The second simulation is to vary the corium temperature using dynamic viscosity and density data obtained from t Equations (4) and (5) [10].

$$\rho(T) = 4.40 - 8.31 \times 10^{-4}(T - 3120) \quad (4)$$

$$\mu(T) = 0.520e^{8.26 \times \frac{10^3}{T}} \quad (5)$$

RESULT AND DISCUSSIONS

The effect of variations in dynamic viscosity and temperature of corium on the pressure profile and melt rate is shown in Figure 2-5. Based on the corium pressure profile with a dynamic viscosity of 2 mPa.s, 3 mPa.s, and 4 mPa.s, it shows that there is a slight difference between the empty plenum.

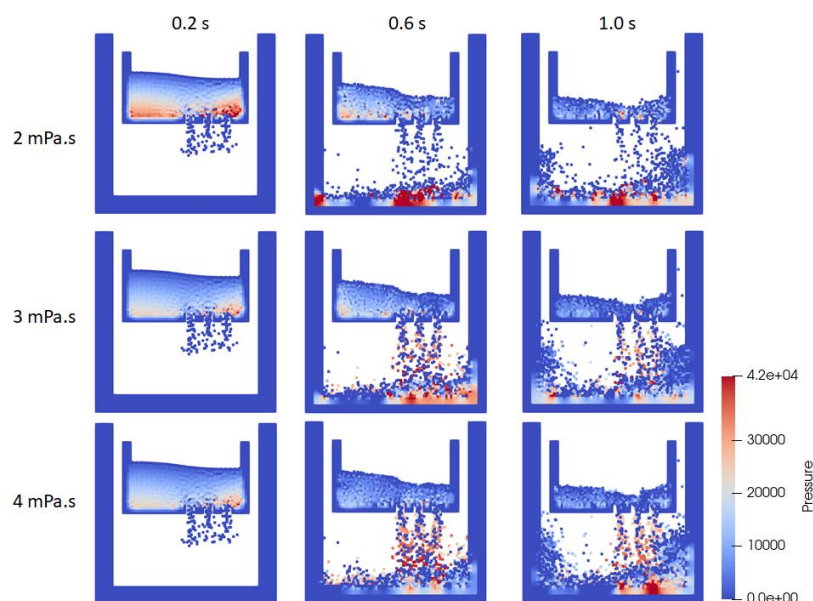


Figure 2. Pressure profile on dynamic viscosity variation

In addition, the velocity profile in which the plenum in a filled condition with corium fluid gets a faster deceleration. This is due to the interaction between the falling corium fluid and the corium in the plenum. The research of Jubaidah et al. showed that the difference in dispersion was not much influenced by melt heat loss to different substrates [12]. The pressure that arises due to the impact of waves in the simulation results needs to be clearly observed. It is because the MPS method has several drawbacks including non-conservation of momentum and false pressure fluctuations, despite its wide applications. To solve this problem, Khayyer et al. modified the MPS using the Poisson pressure equation [7].

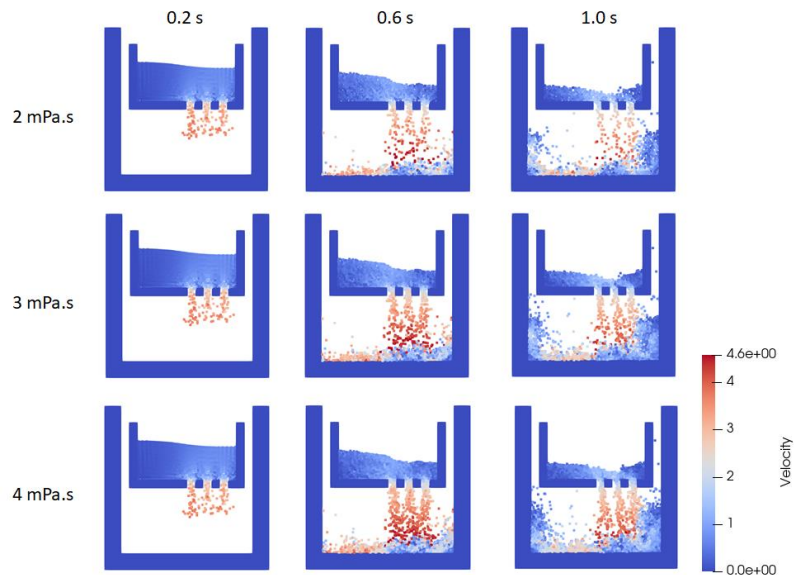


Figure 3. Velocity profile on dynamic viscosity variation

Regarding the effect of temperature on the pressure and velocity profile, it can be concluded that the greater temperature of the corium, the smaller pressure received by the plenum but was more evenly distributed. Corium with a lower temperature will exert greater pressure on the plenum in the drop position but with a less even distribution. The effect of velocity shows that the higher temperature of corium will have a faster fluid flow rate than the lower temperature. Minor differences in the display of the pressure and velocity profiles are less obvious due to the low resolution. To increase the resolution, it can be conducted using multiple-size particles [3,4].

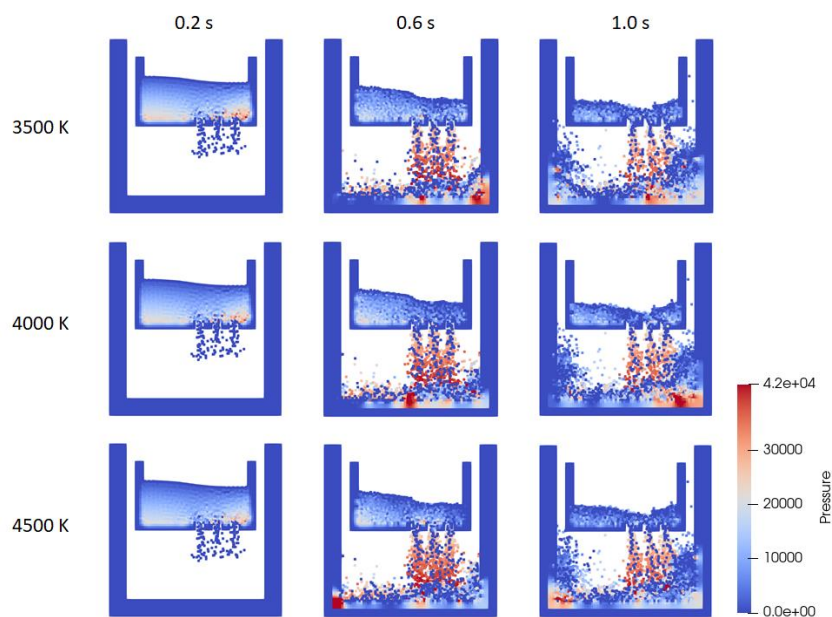


Figure 4. Pressure profile on temperature variation

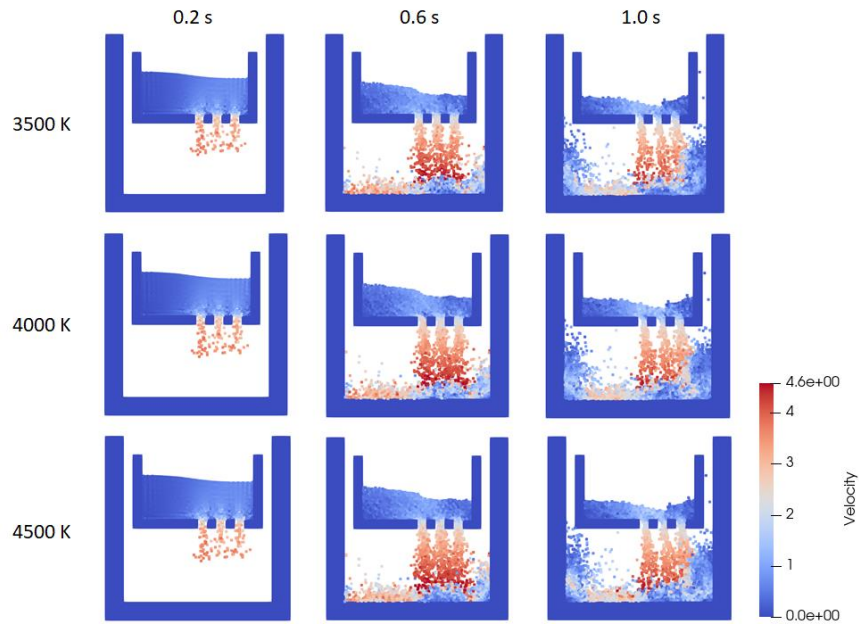


Figure 5. Velocity profile on temperature variation

The greater dynamic viscosity of corium can produce a greater pressure and a smaller velocity. To observe the effect of the dynamic viscosity on the required time for melting, the dynamic viscosity was varied from 0.5 mPa.s to 50 Pa.s and then simulated for 1 s with an interval of 1 ms. The MPS simulation result in Figure 6 shows that the required time for molten corium to reach the plenum surface varies as a function of its dynamic viscosity. The molten corium with a dynamic viscosity difference greater than 10 Pa.s has a significant difference in flow time in the order of seconds. Meanwhile, the dynamic viscosity of less than 10 Pa.s will have an insignificant difference in flow time, which is below the order of milliseconds.

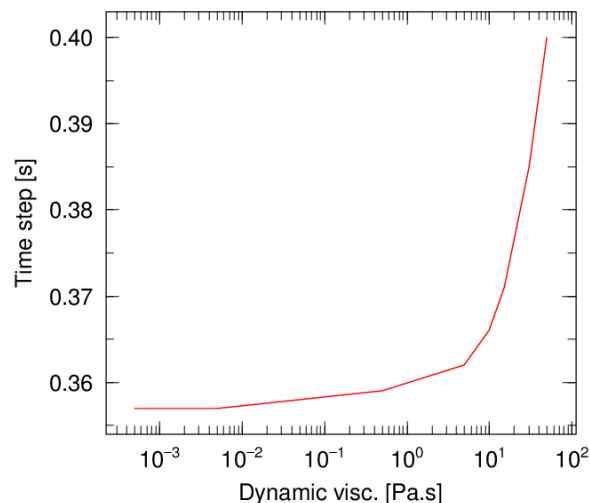


Figure 6. Effect of dynamic viscosity on corium flow time

The lower corium temperature, the greater pressure received by the plenum, and vice versa, the smaller velocity. To see the effect of corium temperature on the required time, the temperature was varied from 1000 K to 3000 K, then simulated for 1 s with an interval of 1 ms. The MPS simulation result in Figure 7 shows that the flow time significantly decreases as a function of temperature. The effect of leak hole size was not obtained in this finding, contrary to the simulation by Hidayati et al., which concluded that the hole size significantly affected the required displacement time [15]. However, these results are similar to the results of Gen Li, et al. which showed that at high temperatures the melt transfer of ZrO_2 and UO_2 becomes faster [9]. In addition, Schiano et al. also obtained a significant change in corium flow velocity at lower temperatures, which displayed the temperature profile and confirmed the rapid flow of several millimeters occurring at the start of the corium temperature rise during dispersion [16].

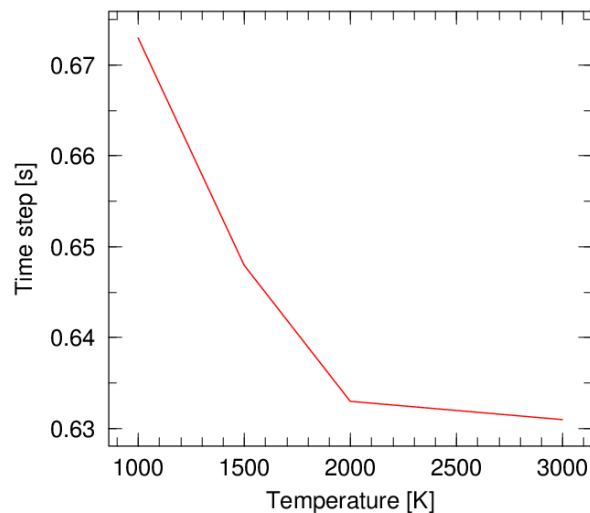


Figure 7. Effect of temperature on corium flow time

CONCLUSION

The corium viscosity affects the pressure and velocity profiles; the greater corium viscosity, the greater pressure exerted on the plenum. On the other hand, the corium temperature is related to the pressure and velocity profiles. The higher corium temperature, the lower pressure is applied to the plenum but results in a higher flow rate. The required time-movement for corium fluid will increase the corium viscosities and decrease the corium temperatures.

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