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NUMERICAL SIMULATION ON DEPOSITION PHENOMENA OF MOLTEN DROPLET

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Abstract. Deposition is a phenomenon where melting particles passing through a combustion chamber are cooled and adhere to the surfaces of a turbine vane and endwalls. Though previous studies have investigated the effect on cooling efficiency after deposition, the deposition mechanism remains unclear. Since it is difficult to carry out the detailed measurement, numerical studies on the deposition mechanism are expected. In the present study, we consider the case where a high-temperature molten droplet impacts on a cold substrate. The temperature change and behavior of a droplet are reproduced, using a MPS-AS method[1]. Furthermore, the deposition phenomena in three cases with different impact speeds and four cases with different substrate temperatures are numerically investigated. We numerically investigate the deposition mechanism on the cooled substrate and describe in detail how the solidification process varies with the impact velocity and the temperature changes.

1 INTRODUCTION

Deposition is a phenomenon where melting particles such as sand and dust passing through a combustion chamber are cooled and adhere to the surfaces of a turbine vane and endwalls. The adhered material is not only the entered particle with air from an engine intake but also the ash generated by fuel burning. Deposition occurs when aircrafts fly in a cloud of volcanic ash. When a volcano erupts, aircrafts have to change the route and detour. Deposition generates disturbances of the coolant flow in the turbine and degrades the engine performance. Moreover, partial or complete blockage of film-cooling holes occurs. As the result, the blockage decreases the cooling efficiency and degrades safety and life time of the turbine. There is also some possibility of leading to the loss of the engine power. Additionally, frequent maintenance works for the turbine vane are required, and thus the engine operation cost becomes high.

An example of the airplane accidents due to deposition is British Airways Flight 9 on 24 June 1982. This accident was that the airplane flew into a cloud of volcanic ash thrown up by the eruption of Mt. Galunggung, and resulted in the failure of all four engines. Furthermore, a cloud of the volcanic ash generated by the volcanic eruption in Eijafjallajokull caused enormous disruption to air traffic across western from northern Europe in April 2010. This eruption was also in danger of the deposition on an aircraft. Simultaneously, it is indicated that the deposition phenomenon is the serious problem even in these days.

In the previous studies, the effect on cooling efficiency after deposition such as deposition effect on film cooling in the channel flow and blade passages has been investigated [2] [3]. It is also suggested that the deposition depends on the temperature [4]. However, the deposition mechanism including temperature change of a single molten droplet remains unclear. If this mechanism can be clarified, it is possible to improve the predictive performance of the deposition phenomena in turbines. Since it is too difficult to carry out the detailed experimental measurements, numerical studies on the deposition mechanism are expected.

Taking into account these backgrounds, in this study, we consider the phenomenon where a high-temperature molten droplet impacts on a cold substrate. The temperature change and the behavior of a droplet are simulated, using a MPS-AS method[1]. Additionally, the deposition with different impact speeds and substrate temperatures are numerically investigated. Through this study, it is indicated that both the impact speed and the substrate temperature strongly affect the deposition process.

2 NUMERICAL METHOD

2.1 Governing equation

In this study, we simulate a molten particle behavior when it impacts on a cold substrate with the MPS-AS method, which was developed by Arai et al. in 2009[1]. This numerical method can consider compressibility of fluid unlike an early MPS method. Governing equations are continuity and Navier-stokes equations as follows:

$$\frac{1}{\rho}\frac{D\rho}{Dt} + \nabla\cdot\mathbf{u} = 0 \tag{1}$$

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\mathbf{u} + \mathbf{g} + \frac{1}{\rho}\sigma\kappa\delta\mathbf{n} \tag{2}$$

where ρ, P, ν, σ, κ, δ and $\mathbf{n}$ are the density, the pressure, the kinematic viscosity, the surface tension coefficient, the curvature, the delta function and the unit vector perpendicular to the surface, respectively. The left side of Equation (2) is Lagragian differential of velocity vector. The first term of the right side is the pressure term, the second term is the viscous term, the third term is the gravity term and the forth term is the surface tension term. Additionally, the energy transport equation and the Poisson equation of pressure are expressed as:

$$\frac{DT}{Dt} = \frac{k}{\rho C_P}\nabla^2 T + \frac{1}{\rho C_P}Q \tag{3}$$

$$\nabla\cdot\left(\frac{1}{\rho}\nabla P^{x+1}\right) = \frac{P^{x+1} - P^{x}}{\rho C_s^2 \Delta t^2} + \frac{1}{\Delta t}\nabla\cdot\mathbf{u} \tag{4}$$

where T, C_p, k, Q and C_s are the temperature, the specific heat, the heat conductivity, the heat source and the sonic velocity, respectively. The movement of the particle is obtained from interactions between neighboring particles. The weight function defined in the MPS-AS method is followed as:

$$w_{ij} = \begin{cases} \ln r_e / \left|\mathbf{r}_{ij}\right| & \left|\mathbf{r}_{ij}\right| < r_e \\ 0 & \left|\mathbf{r}_{ij}\right| \geq r_e \end{cases} \tag{5}$$

where $r_{i,j}$ is the distance between *i* and *j* particle and r_e is the radius of the interaction range. If the distance between two particles is significantly far, the interaction can be neglected. Thus, a finite number of neighboring particles are related to the interaction.

Governing equations are deicretized using the gradient and Laplacian operators, which are defined as:

$$\left\langle \nabla\phi \right\rangle_i = \frac{d}{n_i} \sum_j \frac{\phi_j - \phi_i}{\left|\vec{r}_{ij}\right|^2} \mathbf{r}_{ij} w_{ij} \frac{n_i}{n_j} \tag{6}$$

$$\left\langle \nabla^2\phi \right\rangle_i = \frac{2d}{\lambda n_i} \sum_j \left(\phi_j - \phi_i\right) w_{ij} \tag{7}$$

where ϕ is the physical quantity and *d* is the number of space dimensions. Equation (6) represents that the gradient between two adjacent particles are summed with considering the weight function. Equation (7) represents the physical property of the target particle is distributed by the particles of its neighborhood. λ and n_{i} are a model parameter and a particle number density as follow:

$$\lambda = \frac{1}{n_i} \sum_{j \neq i} \left(\left|\mathbf{r}_{ij}\right|^2 w_{ij} \right) \tag{8}$$

$$n_i = \sum_j w_{ij} \tag{9}$$

In this model, the velocity change due to the gravity and the viscosity, the temperature and the phase change are solved explicitly. The pressure term is estimated implicitly.

3.2 Phase change condition

The phase transition is simply simulated by two types of particles, i.e., fluid particle and solid particle. The deposition is reproduced by metamorphoses from liquid to solid, when the droplet temperature *T* approaches the solidifying temperature T_{liquid}. The particle metamorphosed from liquid to solid is treated as a wall particle. This condition is defined as:

$$\begin{array}{lll} Solid & if & T < T_{liquid} \\ Liquid & if & T > T_{liquid} \end{array} \tag{10}$$

Since the viscosity increases as the temperature of the fluid is close to the melting point, the viscosity is calculated by using the exponential function of temperature.

3 COMPUTATIONAL CONDITION

Figure 1 shows the computational configuration where a high-temperature molten droplet impacts on a cold substrate. First we simulate the deposition phenomenon in three different impact speed cases, in which the specified speeds are 4, 10, and 20 m/s, and the temperature is fixed at 1100 K. Second, four cases with different substrate temperatures of 1100, 1300, 1500 and 1700 K on the impact speed of 10 m/s are numerically investigated. A SiO_2 droplet is used in this study. This is one of the major materials of the deposition in a jet engine. The droplet diameter is 1.1 mm and the initial temperature is 1928 K. The droplet is composed of 4205 particles and the substrate is composed of 6186 particles. The droplet perpendicularly impacts on the substrate surface. Table 1 shows the material properties adopted in this study.

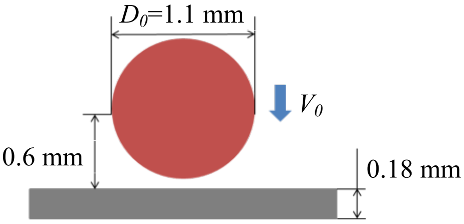

Figure 1: Comp. Configuration

Table 1: Material Properties

k	[W/mK]	1.1
C_P	[J/kgK]	830
ρ_{liquid}	[kg/m^3]	2200
ρ_{solid}	[kg/m^3]	2320
T_{liquid}	[K]	1923

4 RESULTS AND DISCUTION

4.1 Behavior of impacting droplet

The behavior of a droplet impacting on the cold substrate in the case of 10 m/s is shown in Fig. 2. The particle impacts on the surface, it deforms and it begins to spread outwards. The protuberance is generated on both ends of a droplet in Fig 2 (b). This phenomenon is often seen and it is a general characteristic for a molten metal droplet whose viscosity is relatively high. It is caused by the surface tension acting on both ends of the droplet and the increased viscosity with increased temperature near the wall surface. In Fig 2 (c), the droplet particles near the wall are solidified as the temperature decreases. As shown in Figs 2 (d) and (e), the inside of the droplet is cooled with the progress of time and solidification propagates to the whole area of the droplet. These trends are in reasonable agreement with the experiment by Tabbara et al.[5].

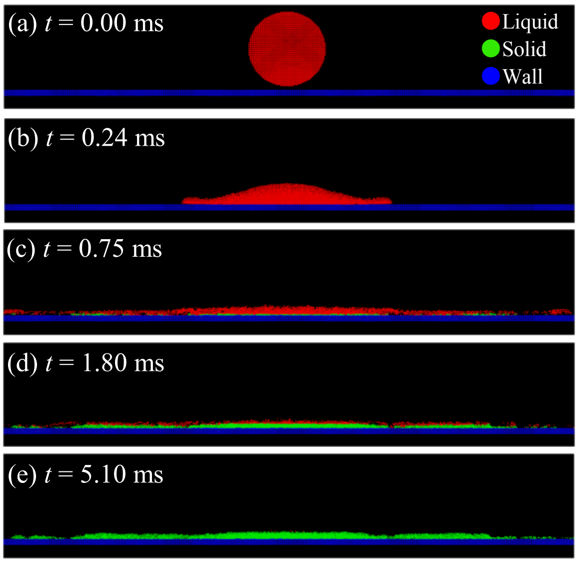

Figure 2 Distribution of Splat Formation (V_0=10 m/s)

4.2 Spreading and deposition rate

The time history of spread factor (D/D_0) for each impact speed is exhibited in Fig. 3. Here, D is the span and D_0 is the initial particle diameter. Apparently, D/D_0 increases as the impact speed becomes faster. It is caused from the increase of the velocity in the horizontal direction as the impact speed of droplet is larger. Additionally, the gradient of D/D_0 saturated with time in all cases and converges to the constant value. It is caused by surface tension acting on both ends of the droplet and the increased viscosity with increased temperature near the wall surface as mentioned in section 4.1.

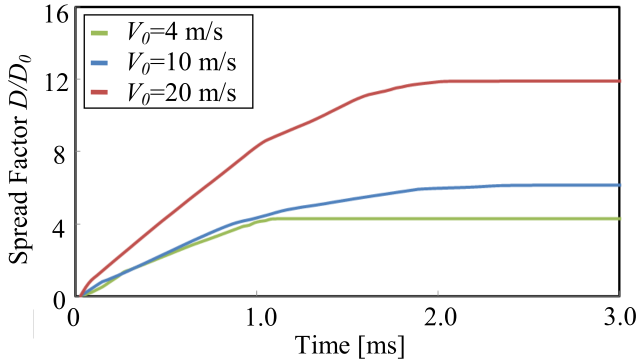

Figure 3 Time History of Droplet Spread Factor

Figure 4 indicates the time history of the deposition rate. The deposition rate means the ratio of the solidified particle number to the total particle number of a droplet. The variation of the deposition rate is low with time in all cases. The particles cooled near the wall surface run into the solidifying state immediately. On the other hand, the upper droplets are not affected by the substrate temperature due to the slow heat transfer through the solidified particles. Therefore, the temperature change of the liquid phase particle is small, and the change of the deposition rate is also low. When the impact speed is 20 m/s, the gradient of deposition rate is extremely low around 0.3 ms. As shown in Fig. 5, the particles rebound on the surface with the increasing impact velocity. This caused that the temperature change of a droplet becomes small due to the decrease of heat transfer between the rebound particles. As the result, the change of the deposition rate decreases. Although the rebound of particles was also slightly confirmed at 4 and 10 m/s, it was remarkable in the case of 20 m/s.

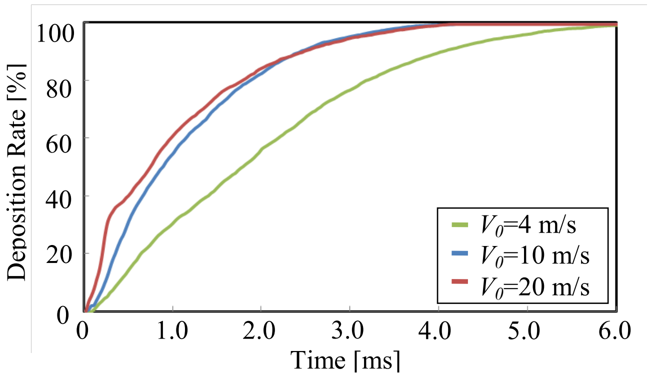

Figure 4 Time History of Deposition Rate

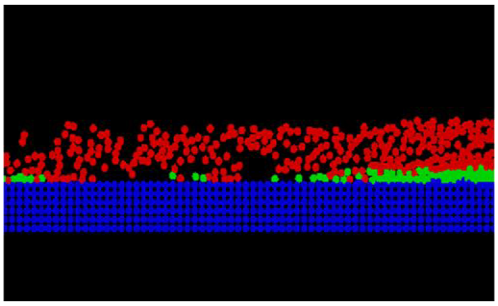

Figure 5 Distribution of Splat Formation (V_0=20 m/s, t=0.3 ms)

The time history of the deposition rate for the temperature change of the cooling substrate in the case of the impact speed 10 m/s is shown in Fig. 6. The time of the starting deposition does not depend on the temperature of the surface. Additionally, the increase of the deposition rate is early as the temperature of the substrate is low. This tendency accords with the observation result of the deposition phenomenon in the jet engine turbine [4].

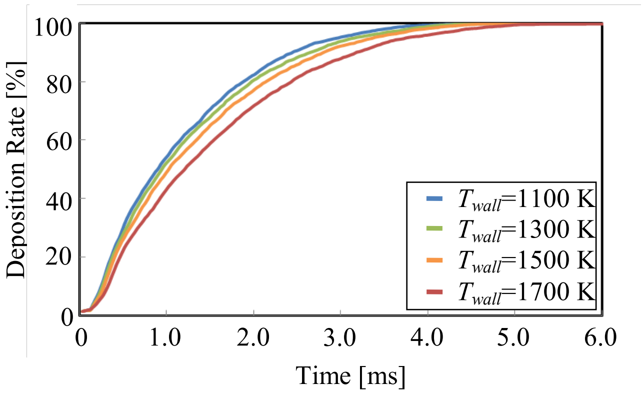

Figure 6 Time History of Deposition Rate

5 CONCLUSIONS

The behavior of a molten droplet impacted on the cooled substrate was numerically investigated, using the MPS-AS method proposed by Arai et al. [1].

Through the present study, we confirmed that the larger the impact velocity is, the wider spread of a droplet is and the larger deposition rate is. However, the deposition rate decreases by bouncing off the wall if impact velocity is high. Moreover, it was showed that the lower the substrate temperature is, the larger deposition rate is. These trends agree well with the experiments. Therefore, we conclude that the MPS-AS method can reasonably reproduce the deposition of a molten metal droplet.

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