Transfer and pouring processes of casting by smoothed particle hydrodynamic method

†M. Kazama[1], K. Ogasawara[1], *T. Suwa[1], H. Ito[2], and Y. Maeda[2]

[1]Application development div., Next generation technical computing unit, FUJITSU Limited, Japan
[2]Department of Mechanical Engineering, Daido University, Japan

*Presenting author: suwa.tamon@jp.fujitsu.com
†Corresponding author: kazama.masaki@jp.fujitsu.com

Abstract

The casting process includes the transportation process and the pouring process. The transportation process is to carry the molten metal from the place where it is saved to the mold or the injection molding machine, and the pouring process is to pour and fill molten metal in the mold.

In the transportation process, it is undesirable to expose the surface of the molten metal to air to suppress the defect (for instance, generation of the oxidizing layer). Therefore, it is necessary to move to pour it into the mold as soon as possible after the molten metal is bailed out by the ladle. However, it is also necessary to prevent overflow of the molten metal and intervention of air or gas. So the liquid vibration by the acceleration and deceleration of the transfer machine should be suppressed.

Then, the development of the technique to control the liquid surface oscillation is needed. Computational fluid dynamics is expected to be effective as the means of the verification. The phenomenon handled here should treat the wall in the container to be a moving boundary, and the liquid surface as a free boundary.

In the pouring process, the flow of the molten metal in the mold is the target of interest. Because the quality of a final article of cast is dependent on how the molten metal flows in complex shape of the mold. Also as for this process, the use of numeric fluid analysis on the process including the fission and the fusion on a free surface is expected to be effective.

The particle-based fluid analysis methods are considered as the numerical computation technique which is applicable and useful in the treatment of these moving boundary and free boundary. However, quantitative comparative studies with the data of actual transportation and pouring process are few.

We have applied the smoothed particle hydrodynamics method to the process of transportation and pouring and validated the results with experimental data. We report on the technique and the result because we saw the experimental data and our numerical results are a good agreement.

Keywords: Casting, particle-based method, smoothed particle hydrodynamics, transfer process, pouring process,

Introduction

In computer aided engineering (CAE) of the casting process, it is necessary to simulate the flow behavior (flow analysis that solves the Navier-Stokes equation), the heat transfer phenomenon (coupled analysis of heat conduction equation and the Navier-Stokes equation), and solidification phenomena (the phase change of the liquid and the solid is indispensable) adequately. Moreover, in some cases, it is necessary to treat casting stress analysis, which is an analysis of heat transfer and the thermal stress and strain caused by solidification and is solved with the elastoplasticity and the viscoelasticity equation. Casting CAE software of the main current is adopting the numerical method for analysis of the Eulerian (grid-based) algorithms. It is not complete in generality and practical use, though these software can suitably simulate some of the casting process. There exists casting processes which are difficult to be treated by the simulators.

On the other hand, the particle-based methods are numerical analysis method of the Lagrangian algorithm, and there is an expectation that it can analyze casting processes which the numerical solution technique of Eulerian algorithms are not suitable for (e.g. Cleary (2010) [1]).

Then, we have performed the reproduction calculation that used the smoothed particle hydrodynamic (SPH) method, which is a particle-based method, simulation about the transportation of the molten metal and the experiment on the mold filling processes, compared the experimental result and the numerical computation result, and examined the possible application to the casting process of the particle method simulation.

Experiments

Transportation of liquid container

The molten metal is frequently transported in the casting process.
When transportation, because the vibration of the liquid surface generates the oxidization layer and causes the defect, it is necessary to execute it promptly with less vibration on the liquid surface. In the tilt type pouring process, the ladle is inclined and molten metal is poured to the ingate of the mold. Although it is hoped that molten metal is filled in the ingate quickly, it is also very important to suppress the vibration of the liquid surface as well as transportation. In order to shorten the lead time, the tilt motion is often begun while moving the transportation container (ladle). That is, there is a case to do transportation and tilting at the same time.

It is thought the numerical analysis of the Eulerian algorithm are not good at this type of process, which include moving container (solid wall). Therefore it is profitable if it is shown to be able to simulate it by the particle-based method.

Then, we do the numerical analysis with the particle-based method on the same condition as the experiment executed by Okatsuka et al. (2011) and Shibuya et al. (2013) [2][3]. A concise explanation of this experiment is as follows: Water is put in the liquid container of 10mm in thickness that installs the level sensor shown in Figure 1 up to the height of 140mm. The container is transported on the x axis and tilted with T shaft center. At this time, the vibration of the liquid surface is controlled by controlling the transportation speed and the tilting speed so that the wave should not occur.

Mold filling processes

Mampaey and Xu (1995) performed experiments of mold filling process in order to directly observe the molten metal flow for the model with different runner shape by arranging the heat-resistant glass in the one side of the mold[4]. The analysis of this behavior that fills the runner and the cavity is an object that cast CAE software of grid-based method analyzes enough, and the part that can be called the indispensable function of cast CAE software. Therefore, we also analyzed to attempt the utility of the cast analysis by the particle method on the same condition as the experiment and it compared it with the result of Mampaey and

Xu (1995)[4]. We reports on the results of two models shown in Figure 2 (called curved gating system and stair like gating system).

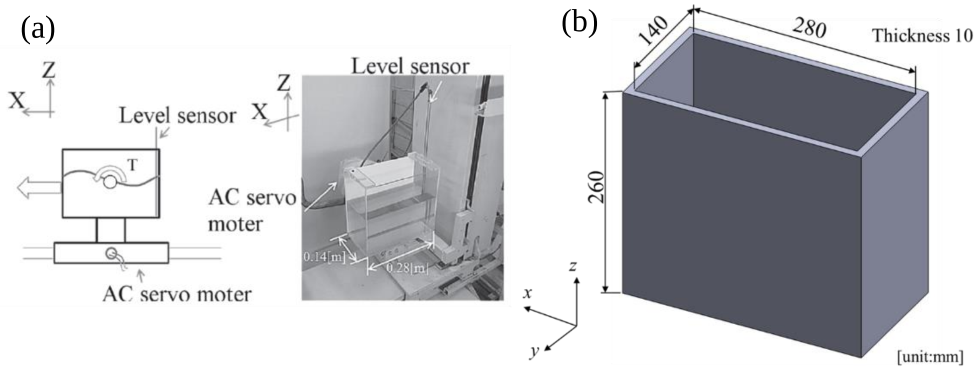

Figure 1. (a) Experimental equipment; (b) size of the container

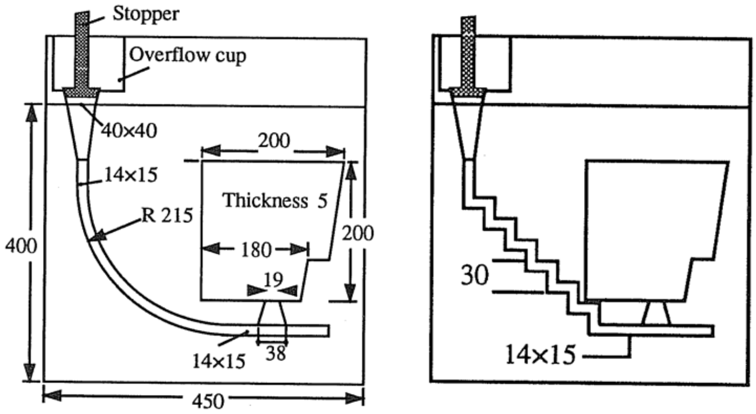

Figure 2. The plane casting systems

Numerical method

We use a form of the equation of continuity and the momentum equation of SPH method as follows (Suwa, Nakagawa, and Murakami (2013)[5]):

$$\frac{D\rho_a}{Dt} = \sum_b m_b (v_a{}^i - v_b{}^i) \frac{\partial W(\mathbf{r}_{ab}, h)}{\partial x^i} \tag{1}$$

$$\frac{D\vec{v}_a}{Dt} = -\sum_b m_b \left(\frac{p_b + p_a}{\rho_b \rho_a} \right) \frac{\partial W(\mathbf{r}_{ab}, h)}{\partial \vec{x}_a} + \vec{g} \tag{2}$$

Here, ρ, t, m, v, p, h, and $\mathbf{r}_{ab}$ are the density, the time, the mass, the velocity, the pressure, the smoothing length, and the relational position vector between the particles a and b, respectively. The constant vector $\vec{g}$ is the gravitational acceleration. The subscripts a and b are indices of the particles, and the sum is over all particles b within a radius $2h$ from the particle a. As a kernel function $W(\mathbf{r}_{ab}, h)$, we employ the quintic spline.

$$W(\mathbf{r}_{ab}, h) = \begin{cases} \alpha_d \left(1 - \frac{q}{2}\right)^4 (2q+1) & (0 \le q \le 2) \\ 0 & (2 < q) \end{cases} \tag{3}$$

Where $q=|\mathbf{r}_{ab}|/h$ and α_d, a normalization constant, is $21/(16\pi h^3)$ in 3-D.

The fluid in our SPH formalism is treated as weakly compressible. The pressure is given by the following equation of state:

$$p = \rho_0 c_s^{\ 2}\left(\frac{\rho}{\rho_0} - 1\right) \tag{4}$$

where ρ_0 and c_s are initial density and sound speed, respectively. In this study, ρ_0 and c_s are set to 1 kg m^{-3} and 50 m s^{-1}, respectively. The sound speed c_s is a numerical parameter, and a value is chosen to be extent where the density of the SPH particle with a typical kinetic energy does not come off from a standard density greatly.

Numerical results

Transportation of liquid container

The transportation of liquid container without the control and that with the control were analyzed as well as the experiment by Okatsuka et al. (2011) and Shibuya et al. (2013) [2][3]. Figure 3 shows transferring input without control. Figure 4(a) shows time series of the level of liquid under this transportation condition. The result of the SPH simulation and the result of the experiment are indicated as the blue solid line and the red broken line, respectively. The measurement point of the water level is a position of level sensor shown in Figure 1. It is shown that the shape of the first wave, which is the most important about transportation, immediately after the completion of the movement (4.1 second) is corresponding to the experiment very well. The wave attenuation occurs in the calculation since the second wave. The attenuation shows the tendency to become small when the resolution rises.

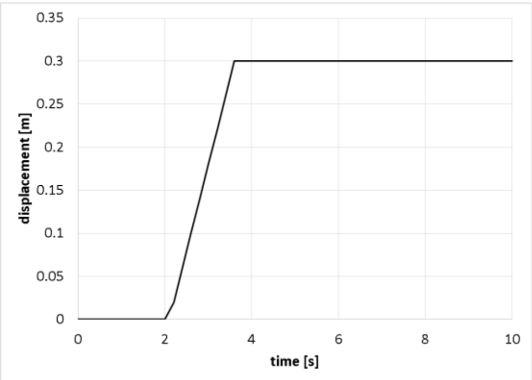

Figure 3. Transferring input without control

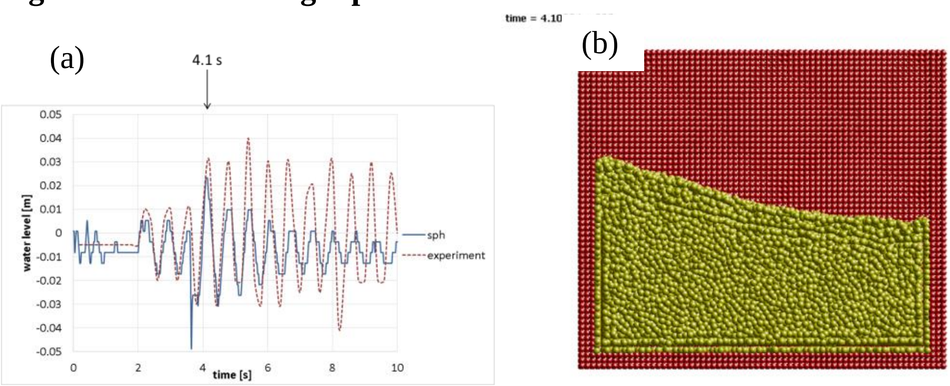

Figure 4. (a) Level of the liquid surface without control
(b) Snapshot of the liquid container without control (4.1 sec.)

Figure 5 shows transferring input with control. Figure 6(a) shows time series of the level of liquid under this transportation condition. As well as Figure 4(a), the result of the SPH simulation and the result of the experiment are indicated as the blue solid line and the red broken line, respectively. We can see that the vibration of the liquid surface becomes gentle by adding the control while the wave falls into disorder without the control of the transportation speed, and the effect is reproduced by the SPH simulation.

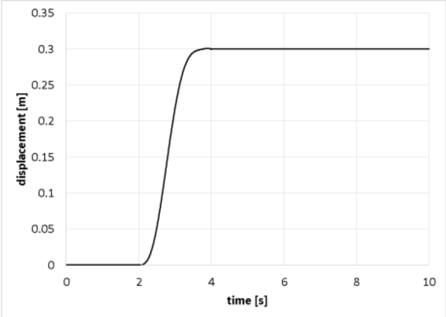

Figure 5. Transferring input with control

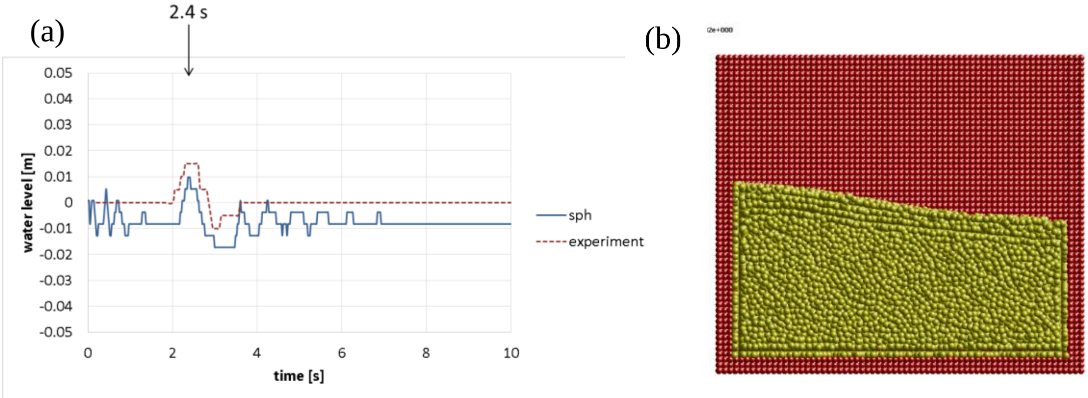

Figure 6. (a) Level of the liquid surface with control
(b) Snapshot of the liquid container with control (2.4 sec.)

Figure 7 (a) and (b) show transferring input and tilt input, respectively. The tilt input is controlled. Figure 8 is a water level history when tilting motion is input with transportation. In the situation in which the energy of the water vibration is supplied as tilting motion, the vibration of the liquid surface is kept being corresponding well since the second wave.

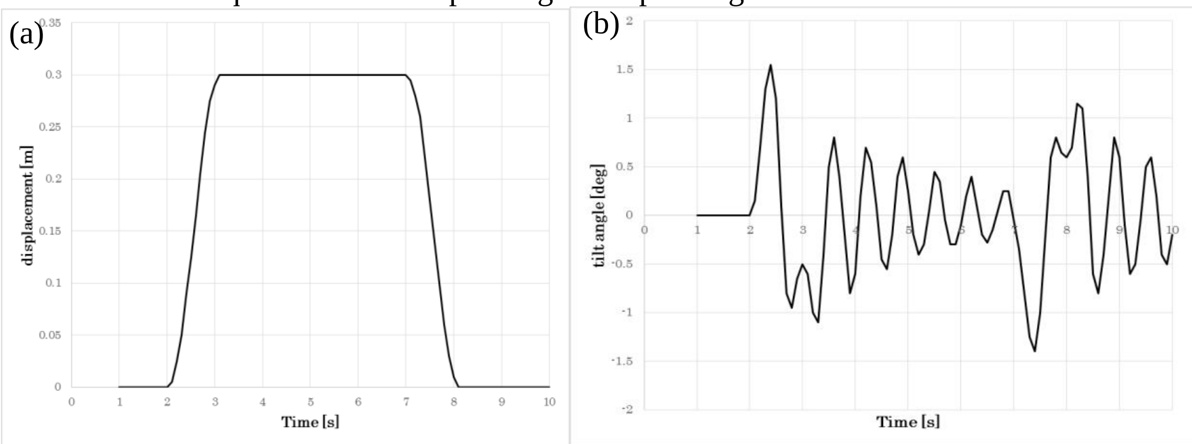

Figure 7. Transferring and tilt input with tilt control

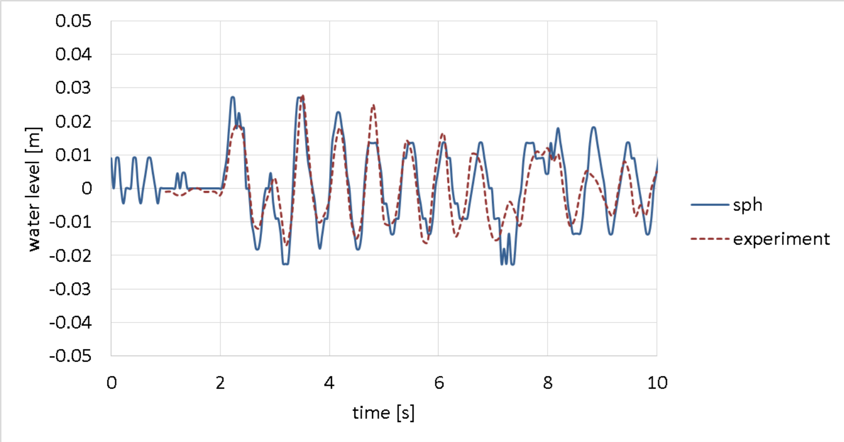

Figure 8. Height of the liquid surface with designed transfer and tilt input

Mold filling processes

The mold filling processes were analyzed with the same condition of the experiments by [4]. We have compared the results of our SPH simulations with the results of experiments and results of a CAE software employing Eulerian algorithm with volume of fluid (VOF) method as surface treatment. In SPH simulation, we put the fluid of rectangular shape (with side-lengths 6cm, 6cm, and 10cm) above the overflow cup, and the fluid has been fallen freely. In grid-based simulation, the inflow condition of the constant rate was given to the inlet. The inlet velocity was calculated to match the filling time of the experimental result (17.707 cm s^{-1} for curved gate model, and 5.646 cm s^{-1} for stair like gate model).

In Figure 8, mold filling sequences of the casting with a curved gating system are shown. The first, second, and third line indicate the results of the experiment, SPH simulation, and grid-based simulation, respectively. Any of the experiment and two simulations show that the velocity of molten metal increase at the time of 0.67s (point that the filling of the runner is completed), and we can see that the molten metal get to the top of the container. It is shown like this that a qualitative tendency is the corresponding between the simulations and the experiment.

In Figure 9, mold filling sequences of the casting with a stair like gating system are shown. As well as Figure 8, the first, second, and third line indicate the results of the experiment, SPH simulation, and grid-based simulation, respectively. It seems that the appearance to which the filling gradually progresses from the lower side is corresponding well by the simulation result and the experimental result.

As the tendency between the models, the velocity of fluid into the cavity of the curved gate model is faster than that of the stair like gate model, in which the energy loss has happened when filling it. This has been achieved by regulating the inlet velocity of the fluid in the grid base simulation. In other words, after the experimental results are known, it is necessary to adjust the input condition. On the other hand, the difference of the behavior of both models appears clearly as a result of analyzing the fluid behavior while giving the same inflow condition in the SPH simulation. This mold filling models are known well as a verification of molten metal flow analysis that has a free surface, and it is very difficult to adjust both the curved gate model and the stair like gate model. The results of the molten metal flow behavior show advantage of SPH method to reproduce a free surface behavior.

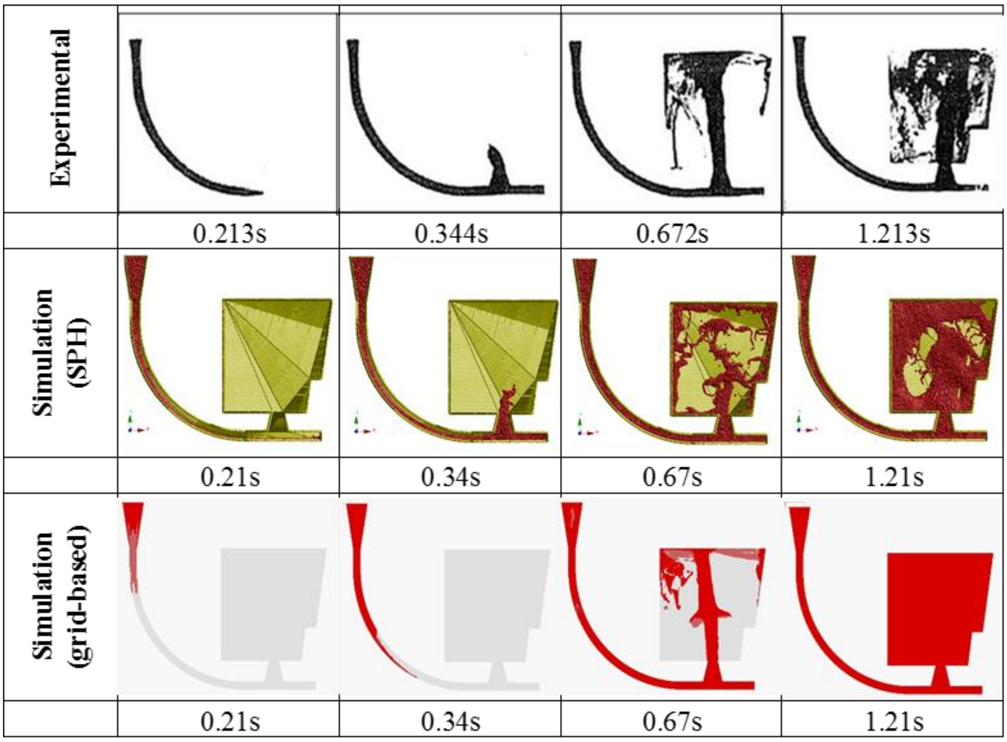

Figure 8. **Mold filling sequences of the casting with a curved gating system**

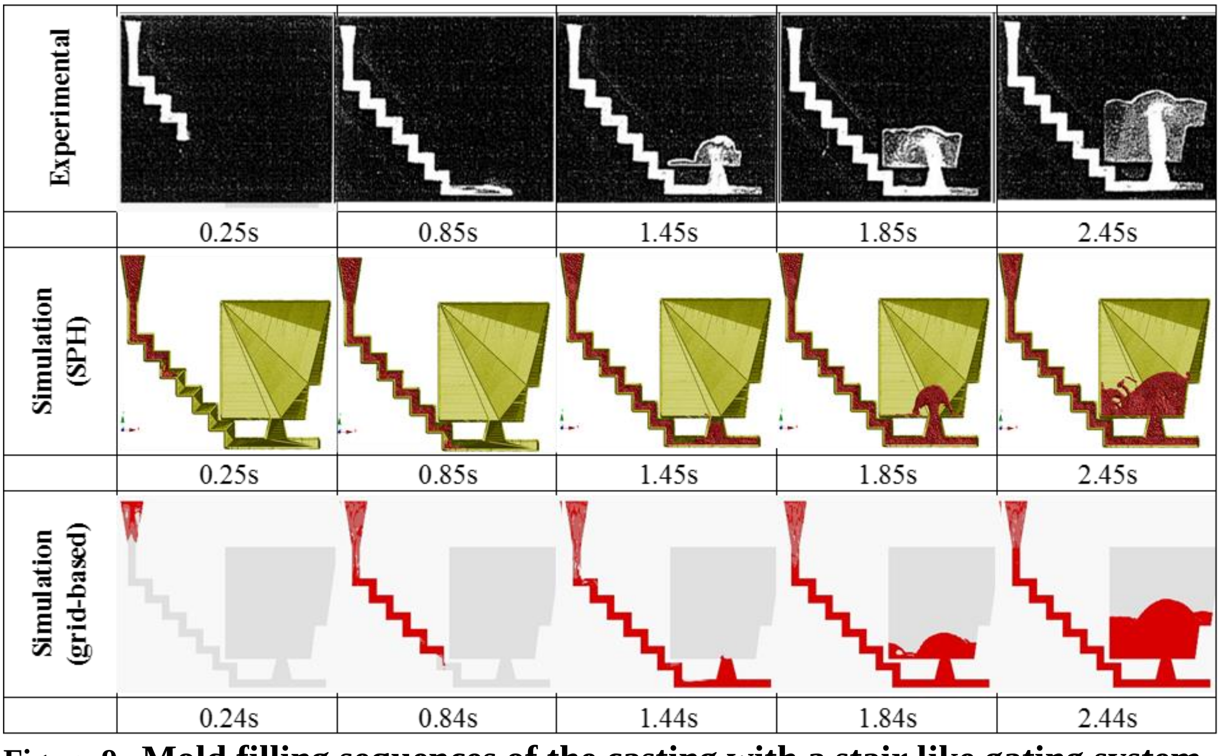

Figure 9. **Mold filling sequences of the casting with a stair like gating system**

Conclusions

The SPH method was applied to the casting process (transportation of liquid container and mold filling), and we compared them with the experimental results. In the analysis of transportation, it was shown that the result of the particle method analysis reproduced the experiment well as the liquid surface oscillation are suppressed by the presence of the sloshing control. This depends on the treatment of a solid wall, which is difficult to be taken in Eulerian analysis technics. The particle method analysis can be expected to be applied to the optimization of the carrier control. Moreover, the difference of the tendency to fill the cavity slowly in stair like gate model while spouting under the cavity in great force in curved gate model was reproduced well in the analysis of the mold filling process. It is thought that the SPH method has an enough analytic performance for the region where the solid wall moves and where the dispersion of the molten metal occur.

In the cast field, there are various processes and phenomena, and a lot of objects that should be examined of the propriety of the application of simulations exist. The processes with moving boundaries such as ladle pouring of die casting, sleeve movement, and local pressurizing process are expected to show the advantage to the particle method. We would like to examine the application of the particle method simulation to these processes in the future. It is also needed to show the applicability to heat flow and the solidification behavior that are the indispensable function as cast CAE software.

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