Direct Observation and simulation of ladle pouring behaviour in die casting sleeve

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Abstract

The ladle pouring process is one part of die casting which has the advantages of high speed, good quality and mass production. The molten metal is quickly poured into the sleeve by tilting the ladle, and immediately injected into the die cavity with high speed and high pressure by advancing the plunger. Since the entrapment of air and the generation of solidified layer in the ladle pouring may cause the defects of cast products, it is necessary to simulate the ladle pouring behavior.

In the present study, the pouring experiment into the sleeve using water and die casting aluminum alloy JIS-ADC12 are carried out to observe the flow behavior by tilting the ladle. The temperature of the dissolved metal is measured using a thermocouple to investigate heat transfer behavior. The flow behaviors in ladle pouring of water and molten aluminum alloy are simulated using Particleworks^{TM} of MPS software. The simulation results, when using water are almost the same actual wave behavior. It is difficult to simulate the wave behavior of molten aluminum alloy because there is a difference in wave behavior between water and molten aluminum alloy. On the other hands, it is clear that the molten aluminum alloy is not solidified during wave behavior in the early stage of pouring by the experiments. Therefore, we try to adjust the kinematic viscosity of molten metal and the thermal conductivity of sleeve die. As the result, the wave behavior and temperature of molten aluminum alloy after adjusting the parameters are almost agreed with the actual phenomena. Flow and heat transfer simulation using the MPS method is effective method that ladle pouring of molten aluminum alloy with free surface flow can be simulated accurately.

Keywords: Ladle pouring, Wave behavior, Molten metal, Aluminum alloy, Solidification

1. Introduction

Since the molten metal in die casting process injects to the cavity with high speed and high pressure, it has the advantage of good quality and mass production.[1][2] However, defects are caused by the solidified layer in the sleeve [3][4], air entrainment, the oxide film of the aluminum alloy.[5]-[7] So, it is desirable to suppress the sleeve air entrainment and generation of oxide film in the pouring process [5]-[8].

In this study, the influence of the tilting ladle conditions on the flow behavior in the sleeve is investigated using water and die casting aluminum alloy. The temperature of molten metal is measured using thermocouple in order to investigate the heat transfer behavior. The conditions are three tilting speed and three angle between ladle and sleeve. Also, in recent years, attempts have been made to apply the particle method to the casting field. Mochida et al. Use the SPH method to simulate the die casting process by adopting a model in which the viscosity is changed according to the solid content of the molten metal.[2] Hasuno et.al. is simulated pouring process to sleeve from ladle using MPS method.[5] Kazama et al. Have used the SPH method to reproduce the vibration of the surface of the molten metal during conveyance of the molten metal and to develop an oxide film model of the aluminum alloy, and also obtained good results in analysis.[6][7] Suwa et al. Investigated the validity of the oxide film model when changed the angle and pouring speed of the ladle.[8] There, simulated ladle pouring behavior using by lagrangian MPS particle method software. Further, the flow behaviors in ladle pouring of water and molten aluminum alloy are simulated using Particleworks^{TM} of MPS software.[9]

2. Pouring experiment by tilting ladle

2.1 Experimental apparatus

Experimental apparatus consists of tilting ladle, sleeve, automatic pouring machine, recorder and video camera, as shown in Fig.1. The sleeve shape is the rectangular container 300×60×35mm and the front side is the heat-resistant glass wall in order to observe the pouring behavior directlly. It is possible to change the tilting speed and the angle between ladle and sleeve.

The tilting speeds are 0.45,0.37 and 0.28[rad/s]. The angles are 0°, 20° and 40° , as shown in Fig.2. The temperature of molten metal is measured using K-type (Chromel-Alumel) thermocouple in order to investigate the heat transfer behavior.
The measurement points P1, P2, P3 and P4 are located at 1mm from the bottom and at 100,150,200, 250mm from right wall, and P5 is located at 10mm from bottom and on the left wall, as shown Fig.3.

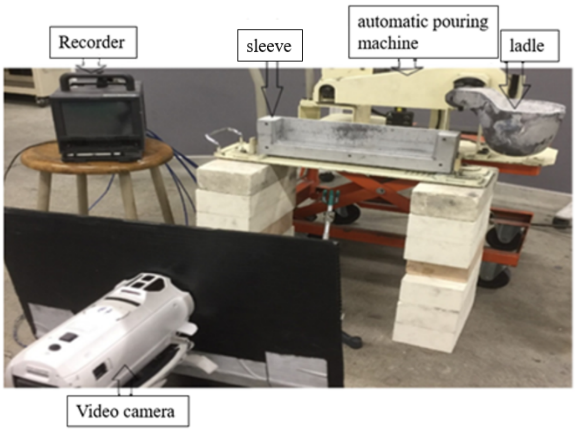

Fig.1 Experimental apparatus.

Fig.2 The angle between ladle and sleeve

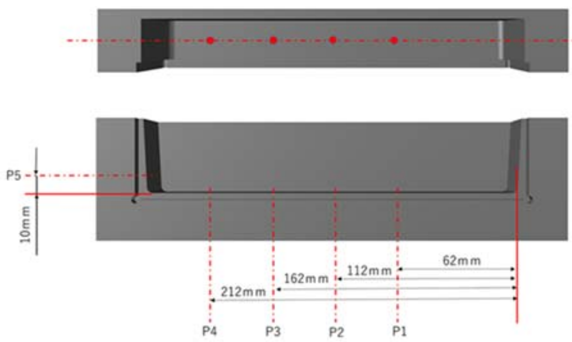

Fig.3 Measurement points for molten metal.

2.2 Experimental procedure

The pouring experiment into the sleeve using water and die casting aluminum alloy JIS-ADC12 are carried out to observe the wave behavior by tilting ladle. The flow behavior is observed using by video camera with 60fps. Table 1 shows the experimental conditions of ladle pouring. Mass of water and aluminum alloy are 250g and 675g, respectively. Those values mean about volume of 250cm^3.

In the experiments, the aluminum alloy are melt in the Muffle furnace, and the sleeve and the ladle are pre-heated at 300℃. When the temperature of molten metal aluminum alloy reaches 700℃, the ladle is tilted by the automatic pouring machine, then the molten aluminum alloy is poured into the sleeve. Number of repetition times is 3 or more taking consideration of reproduciblity.

Table 1 Experimental conditions of ladle pouring.

Material	Water	JIS-ADC12
Pouring temp. [℃]	Room temp.	700
Mass of sample [g]	250	675
Ladle angle [°]	0,20,40	
Tilting speed [rad/s]	0.45,0.37,0.28	
Initial temp. of ladle and sleeve [℃]	Room temp.	300

2.3 Experimental results and discussion

The wave behaviors of water and molten aluminum alloy obtained by experiment in the case of tilting speed 0.45rad/s are shown in Fig.4 to Fig.7, respectively. The first column shows front view in the case of the ladle angle 0° and the second and third columns show the front and top view in the case of ladle angle 40°. In the case of water, the liquid height rises by bouncing back when the water hits the bottom of the sleeve. Even if the ladle angle varies, the wave behavior of water not almost changed. This tendency is the same in other tilting speeds. The liquid height of molten aluminum alloy is not become high like water. This result is the same trend in other tilting speeds. Further, in the case of water, the tip reaches the left wall at about 2.5 [s], whereas it does not reach in the case of the molten aluminum alloy. Although the kinematic viscosity of molten aluminum alloy is almost the same with water, it is clarified the different wave behaviors. Please refer to Table 3 and Table 4. Also, in the case of molten aluminum alloy of top view, molten metal is found meandered from Fig.7.

As an example, the temperature cooling curve at P1 in the case of tilting speed 0.45rad/s is shown in Fig.8. Although the result of ladle angle of 20° is a little lower than others, the cooling behavior of molten metal are almost the same tendency. In the case of high tilting speed of 0.45rad/s, the temperatures go down to liquidus temperature about at 5s. From the wave behavior of Fig.5, the flow front of molten metal collides with the left wall at 2.9s, and reaches the front go back to the right wall at 4.2s, and then the wave movement is stopped before the temperature of molten metal reaches the liquidus temperature. Therefore, the solidified layer is not large influenced on the wave movement and is not involved to stop it.

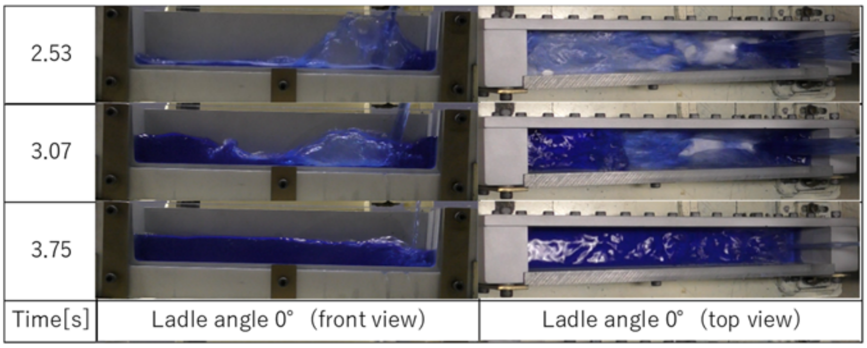

Fig.4 Wave behavior of water obtained by experiment in the case of tilting speed of 0.45rad/s of ladle angle 0°.

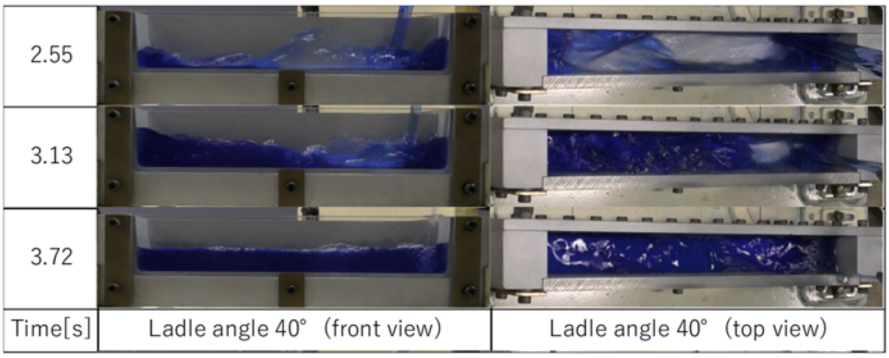

Fig.5 Wave behavior of water obtained by experiment in the case of tilting speed of 0.45rad/s of ladle angle 40°.

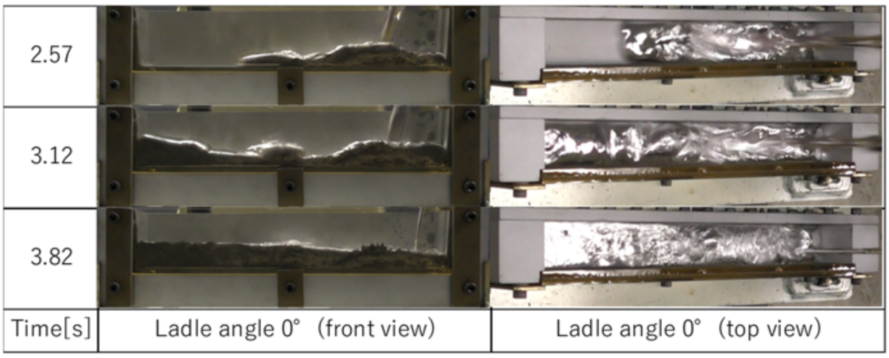

Fig.6 Wave behavior of molten aluminum alloy obtained by experiment in the case of tilting speed of 0.45rad/s of ladle angle 0°.

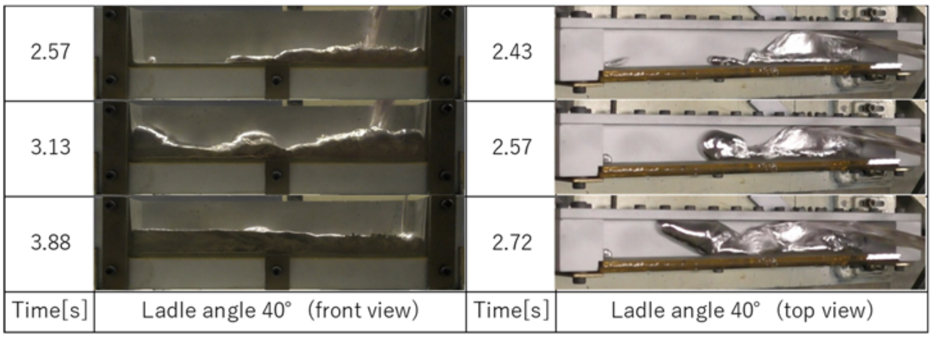

Fig.7 Wave behavior of molten aluminum alloy obtained by experiment in the case of tilting speed of 0.45rad/s of ladle angle 40°.

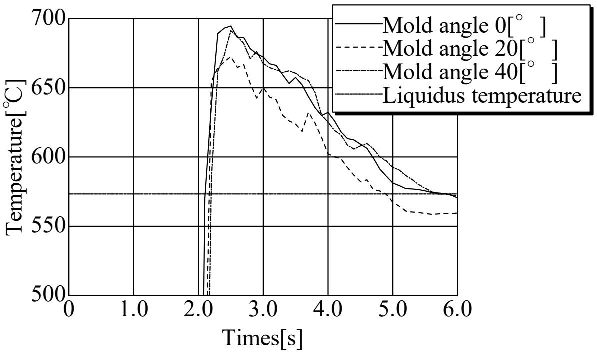

Fig.8 Temperature cooling curve at P1 in the case of tilting speed 0.45rad/s.

3. Particle-based Simulation

It is difficult to simulate the pouring behavior of tilting ladle because the process has the moving boundary of the ladle and free surface boundary of molten metal. [4] Further, in the die casting process, the molten metal is injected from sleeve to the cavity by pushing of plunger. So, the particle-based methods are suitable for the numerical simulation for the die casting process. [5]-[8] In the present study, the ladle pouring behavior is simulated using by the Particleworks^{TM} of MPS software.

3.1 Wave behavior of water

The calculation conditions of present study are shown in Table 2. This speed of sound is not physical property value but also calculation parameter. The physical properties of water shown in Table 3 are used in simulation.

The comparisons of wave behavior between experiment and simulation in the case of the water, the tilting speed of 0.45rad/s and ladle angle of 0° are shown in Fig.9. In the simulation of Fig.9, the color of the fluid is changed by the velocity. Blue indicates that the speed is almost 0m/s, and the speed becomes faster as the color approaches light green. The wave behaviors obtained by simulation are almost agreed with experiments. Fig.8 shows the front view of wave behavior in the case of ladle angle of 40°. Also, Fig.11 shows the flow of top view of water obtained by in the case of ladle angle 40°. The difference in color in the simulation of Fig. 9 is the same as Fig. 10. The

Table 2 Calculation conditions.

Software	Particleworks 6.1.2
Pressure Eq. Scheme	Explicit
Speed of sound [m/s]	7.37
Viscosity condition	Explicit
Surface tension condition	CSF model
Surface tension coefficient	0.90
Particle size [mm]	1.0
Analysis time [s]	6.0
Initial time step [s]	1.25×10^{-4}
Courant number	0.2
Collision distance	0.90
Influence radius	3.1
Interparticle distance	1.0

Table 3 Physical properties of water.

Density [kg/m^3]	1000
Kinematic viscosity coefficient [m^2/s]	1.0×10^{-6}
Surface tension coefficient [N/m]	0.072

wave behavior of water can be reproduced even if the angle is changed from Fig.11. The flow front of water obtained by simulation in the case of ladle angle 40° meander like real phenomena. Even if the ladle angle and tilting speed are varied, it possible to simulate in the case of the water the wave behavior reasonably.

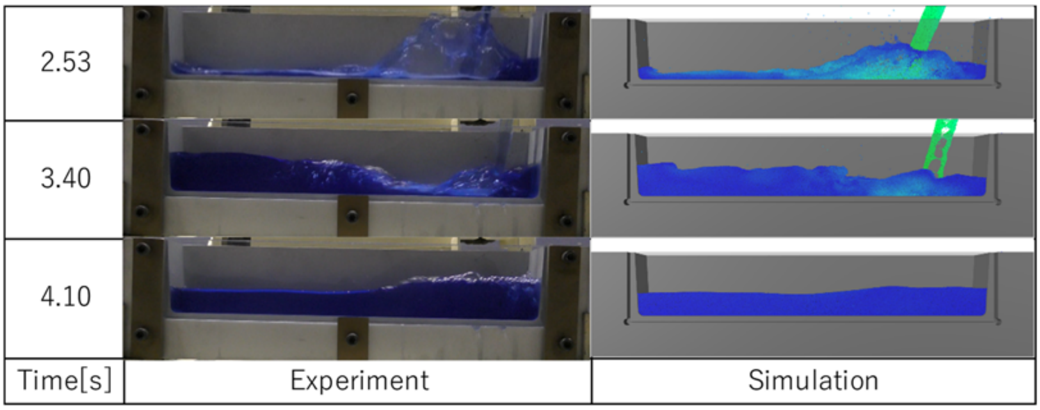

Fig.9 Comparison of front view of wave behavior between experiment and simulation in case of water, tilting speed of 0.45rad/s and ladle angle of 0°.

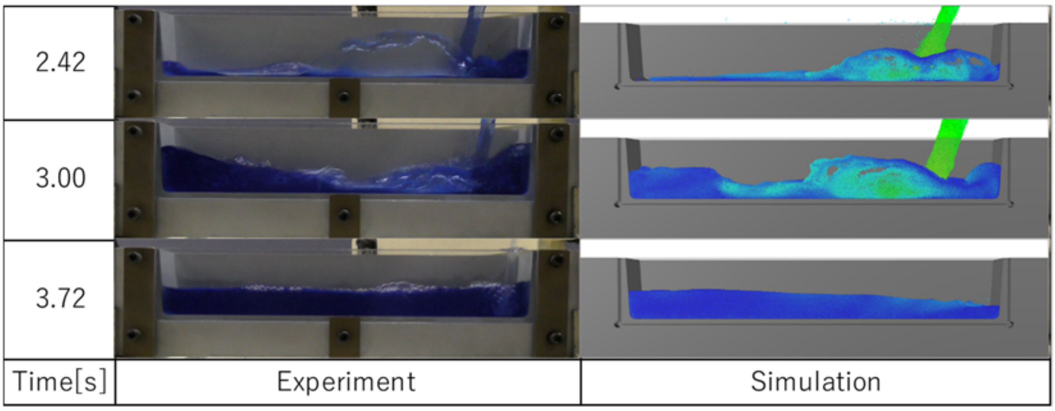

Fig.10 Comparison of front view of wave behavior between experiment and simulation in case of water, tilting speed of 0.45rad/s and ladle angle of 40°.

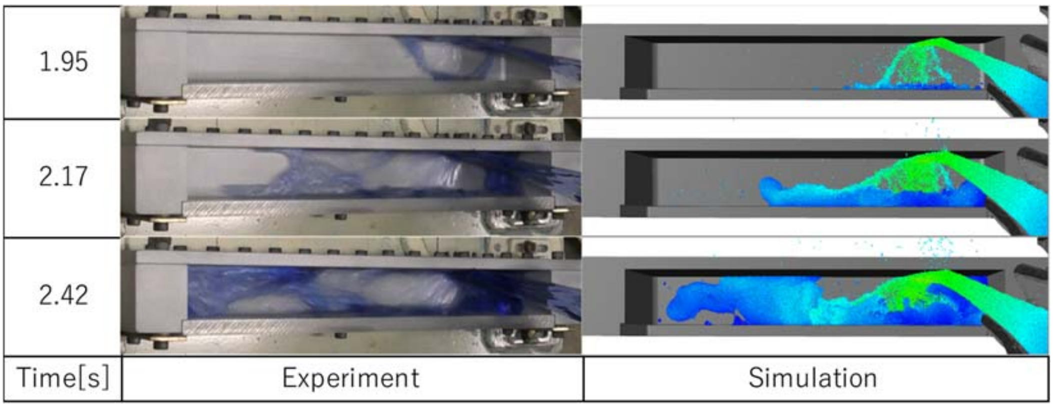

Fig.11 Comparison of top view of wave behavior between experiment and simulation in case of water, tilting speed of 0.45rad/s and ladle angle of 40°.

3.2 Wave behavior of molten aluminum alloy

The physical properties of die casting aluminum alloy JIS-ADC12 are shown in Table 4. The calculation conditions of aluminum alloy are the same of water shown in Table 2 other than the surface tension coefficient for molten aluminum alloy is 0.97. Table 5 shows the physical properties of sleeve made by steel (JIS-SS400).

Table 4 Physical property of aluminum alloy.

Density [kg/m^3]	2700
Kinematic viscosity coefficient [m^2/s]	1.1×10^{-6}
Surface tension coefficient [N/m^2]	0.886
Specific heat [J/(kg·K)]	960
Thermal conductivity [W/(m·K)]	96

Table 5 Physical property of sleeve.

Density [kg/m^3]	7850
Specific heat [J/(kg·K)]	4730
Thermal conductivity [W/(m·K)]	51.6

Fig.10 shows the comparison of wave behavior between experiment and simulation in the case of molten aluminum alloy, the tilting speed of 0.45rad/s and ladle angle of 0°. In the simulation, the temperature is changed the color of the fluid. Red indicates the liquidus temperature, blue indicates the solidus temperature, and the other colors indicate the temperature between the liquidus temperature and the solidus temperature. The simulation reproduces the phenomenon close to water and cannot explain the actual wave phenomenon. The reason is considered that it does not taken consideration of specific oxide film of aluminum alloy. Fig.11 shows the comparison of temperature at P1 between experiment and simulation in the case of the molten aluminum alloy, tilting speed of 0.45rad/s and ladle angle of 0°. The calculated temperature decreases rapidly unlike the experiment. The software has not the functions of temperature calculation by heat transfer coefficient and by solidification phenomena.

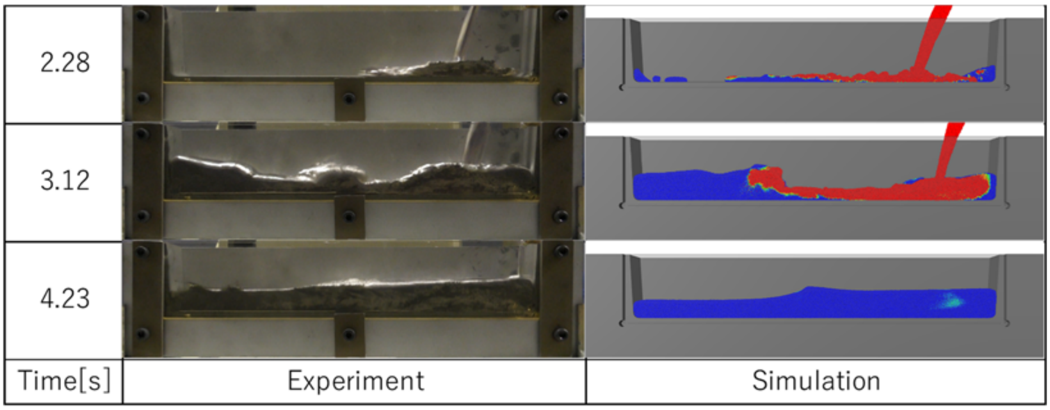

Fig.12 Comparison of wave behavior between experiment and simulation in case of molten aluminum alloy, tilting speed of 0.45rad/s and ladle angle of 0°

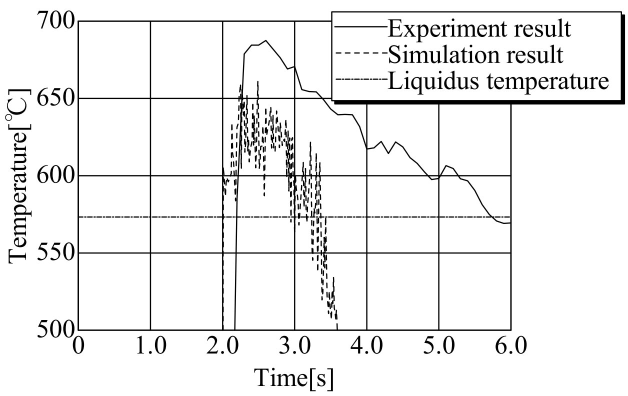

Fig.13 Comparison of temperature at P1 between experiment and simulation in the case of the molten aluminum alloy, tilting speed of 0.45rad/s and ladle angle of 0°

3.3 Wave behavior of molten aluminum alloy using adjusted physical properties

Hasuno et.al [5] is adjusted kinematic viscosity coefficient in order to take into consideration of oxide film of aluminum alloy molten. In the present study as well, we tried to adjust kinematic viscosity coefficient unite flow behavior. Regarding heat transfer, the thermal conductivity of sleeve metal is adjusted to match heat transfer behavior.

Fig.14 shows the comparison of wave behavior between experiment and simulation using adjusted parameter in case of molten aluminum alloy, the tilting speed of 0.45rad/s and the ladle angle of 0°. The results in the case of the ladle angle of 40° are shown in Fig.15 and Fig.16. Fig.16 shows the top view of wave behavior. About the difference in the color of the simulation of Fig.14, Fig.15 and Fig.16, it is the same as Fig.12. Fig.17 shows the comparison of temperature at P1 between experiment and simulation using adjusted parameters in the case of the molten aluminum alloy, tilting speed of 0.45rad/s and ladle angle of 0°. From Fig.14 and Fig.15, the simulated result obtained by using adjusted parameters are almost agreed with the experiments. Thermal conductivity behavior obtained by using adjusted parameters as shown in Fig.17 are also the same tendency to the experiment. Although the flow front of molten metal in experiments as shown in Fig.16 goes like a meander, these phenomena cannot simulate in the present study. Because it is considered that the flow front of molten metal goes advance while meandering by repeating of generation and tearing of oxide film. This phenomenon will be simulated in the future study.

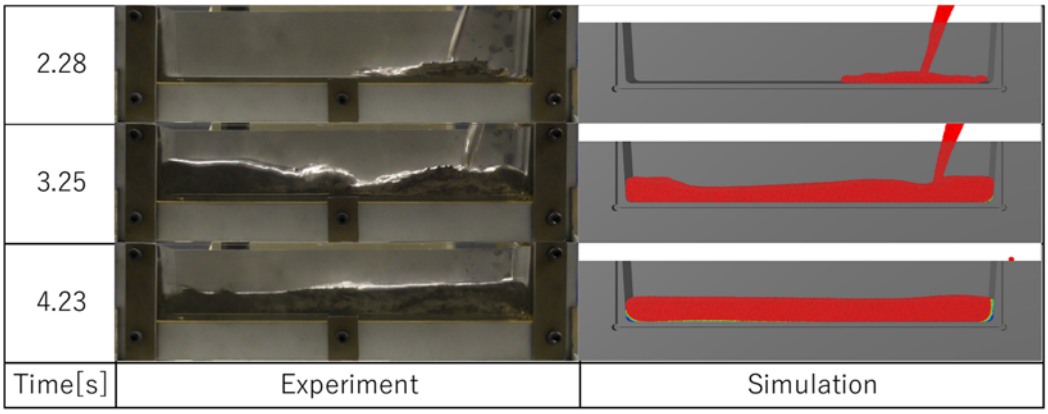

Fig.14 Comparison of wave behavior between experiment and simulation using adjusted parameters in case of molten aluminum alloy, tilting speed of 0.45rad/s and ladle angle of 0°.

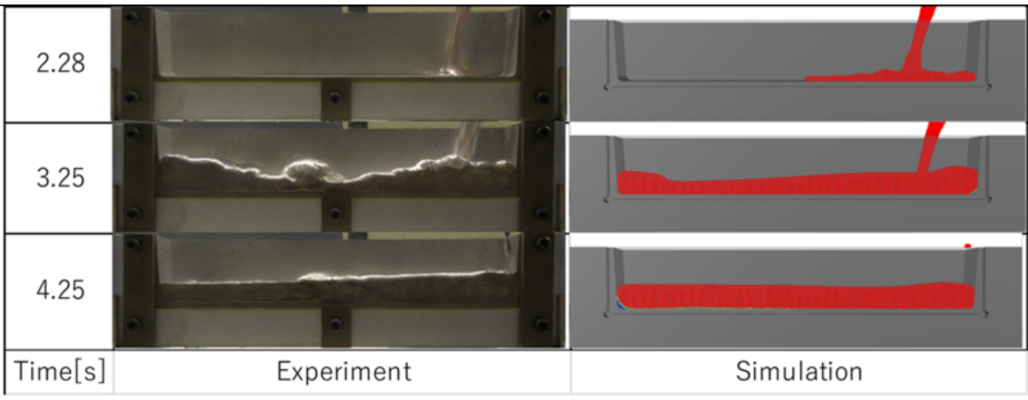

Fig.15 Comparison of wave behavior between experiment and simulation using adjusted parameters in case of molten aluminum alloy, tilting speed of 0.45rad/s and ladle angle of 40°.

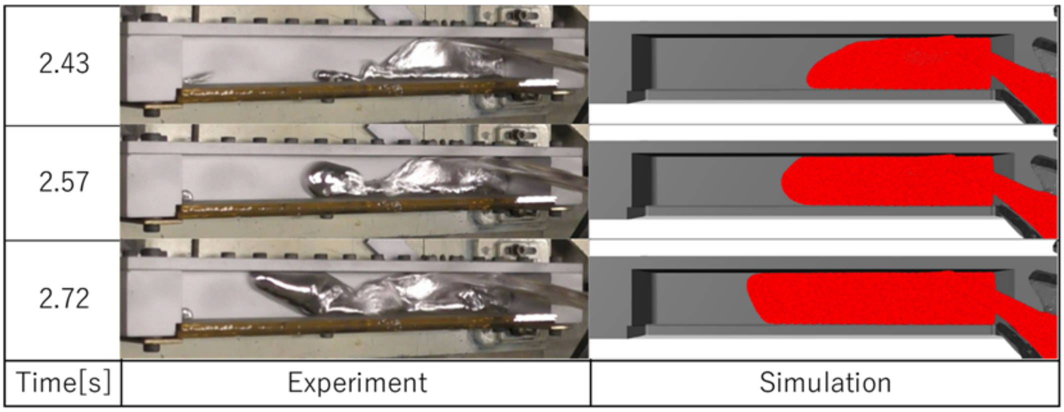

Fig.16 Comparison of top view of wave behavior between experiment and simulation using adjusted parameters in the case of molten aluminum alloy, tilting speed of 0.45rad/s and ladle angle of 40°

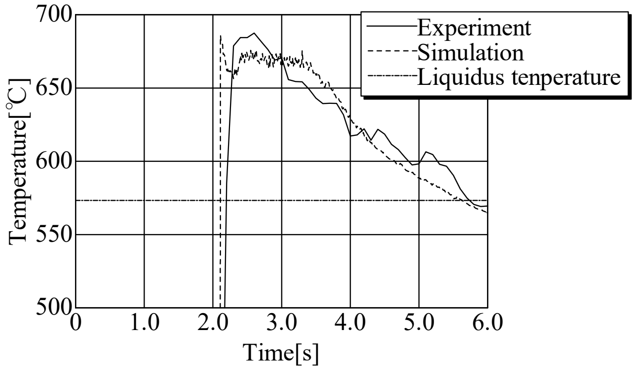

Fig.17 Comparison of temperature at P1 between experiment and simulation using adjusted parameters in the case of the molten aluminum alloy, tilting speed of 0.45rad/s and ladle angle of 0°

4. Conclusion

The pouring experiment of water and molten aluminum alloy by tilting ladle is carried out to observe the wave buhavior in the sleeve and temperature measurement is done. Further, the numerical simulation using MPS software executed to simulate the real phenomena. The following results are obtained.

(1) It is clear that the molten aluminum alloy is not solidified during wave behavior in the early stage of pouring by the experiments in the case of pouring temperature of 700°C.

(2) The ladle pouring simulation used MPS software is good match to experiment result in the case of water.

(3) The simulation result of molten aluminum alloy is not agreed with experimental result. Adjusting the parameters which are the kiematic viscosity of molten metal and the thermal cinductivity of sleeve metal we can get the results coresponding to the real phenomena.

(4) The flow behavior of molten aluminum alloy in the case with ladle angle is observed like a meanber. From the experiment, the flow front of molten metal goes advance while meandering by repeating of generation and tearing of oxide film.

(5) The parameter adjustment is not useful operation for casting CAE. To simulate the real phenomena, it is necessary to develop the new funtional algorithm. There are the oxide film model, heat transfer analysis, solidification analysis and taking into consideration of air gap between mold and melt.

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