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Optimization of Pouring Velocity for Aluminium Gravity Casting

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1. Introduction

In current casting factories, tilting type automatic pouring machines are often used to pour the molten metal into the mold, with the operator relying on experience, perception and repeated testing to manually determine the pouring velocity. However, seeking an optimum multistep pouring velocity through trial and error results in an enormous number of combinations and is very difficult. For this reason, it cannot be said that suitable casting that realizes a high-quality cast is being carried out, inviting a decline in the yield rate due to product defects.
Furthermore, the extension of the production preparatory phase and increase in costs due to this kind of trial operation also become a significant problem.
Until now, much research relating to product defects in aluminum gravity molding has been conducted (Yutaka et al., 2001)(Takuya, 2004). Meanwhile, research applying casting CAE for the purpose of improving the quality of castings and production efficiency is coming to attention (Itsuo, 2006). Furthermore, in recent years, optimization of the casting problem has begun to be carried out in accompaniment with developments in computers (Takuya et al., 2007)(Ken'ichi et al., 2008). However, these all target comparatively short calculation time die-casting and adoption of optimization technology in sand mold casting and gravity casting is lagging.
Accordingly, in this research, the objective is to stabilize the fluid speed in the mold gate and derive an optimum pouring velocity to realize a mitigation of defects such as pin holes and blow holes in aluminum gravity casting through invoking a fluid behavior simulator, swiftly filling the sprue cup and controlling the liquid level at a fixed high level of liquid. For the automatic pouring machine, the multistep velocity input is designed for actual product of an intake manifold. The effectiveness of this research is shown by a fluid analysis simulation and an actual test.

2. Experimental apparatus

An overview of the automatic pouring machine is shown in Fig. 1. It is a tilting type automatic pouring machine with one degree of freedom in the forward and back direction of the ladle.
In the pouring machine, the tilting angular velocity and velocity switching angle are configured by teaching pendant and the pouring velocity is determined. The setup enables

four steps of tilting angle velocity and three of switching angle for a total of seven variables as shown in Fig.2. The tilting angular velocity command is assigned in the form of raised trapezoidal shapes as shown in Fig.3.

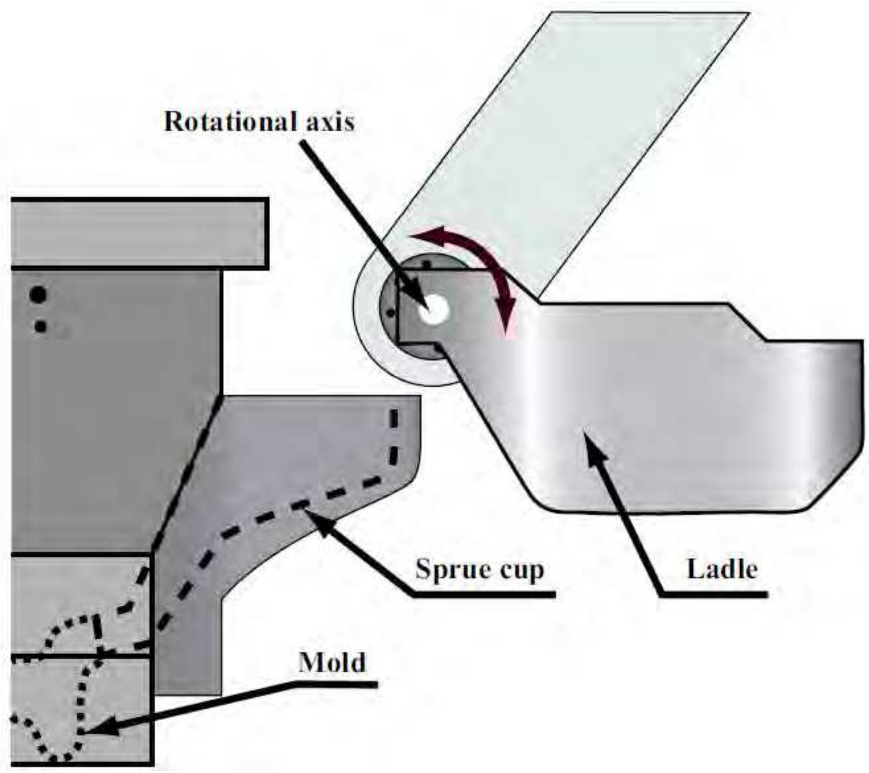

Fig. 1. Overview of the pouring machine

Switching angle [deg]	Pouring speed [%]
10	
	v_1 : 1st speed
θ_1: Switching angle 1	
	v_2 : 2nd speed
θ_2: Switching angle 2	
	v_3 : 3rd speed
θ_3: Switching angle 3	
	v_4 : 4th speed
63	
10 ~ 63	**1 ~ 100**

Fig. 2. Input setting of the automatic pouring machine.

As the tilting angular velocity setting is displayed as a percentage, each step of tilting angular velocity is displayed by the following formula using the maximum angular velocity.

$$V_n = \frac{v_n}{100} V_{max} \tag{1}$$

Here, it is necessary to carry out parameter identification, since maximum angular velocity V_{max} and the angular acceleration a are unknown parameters.

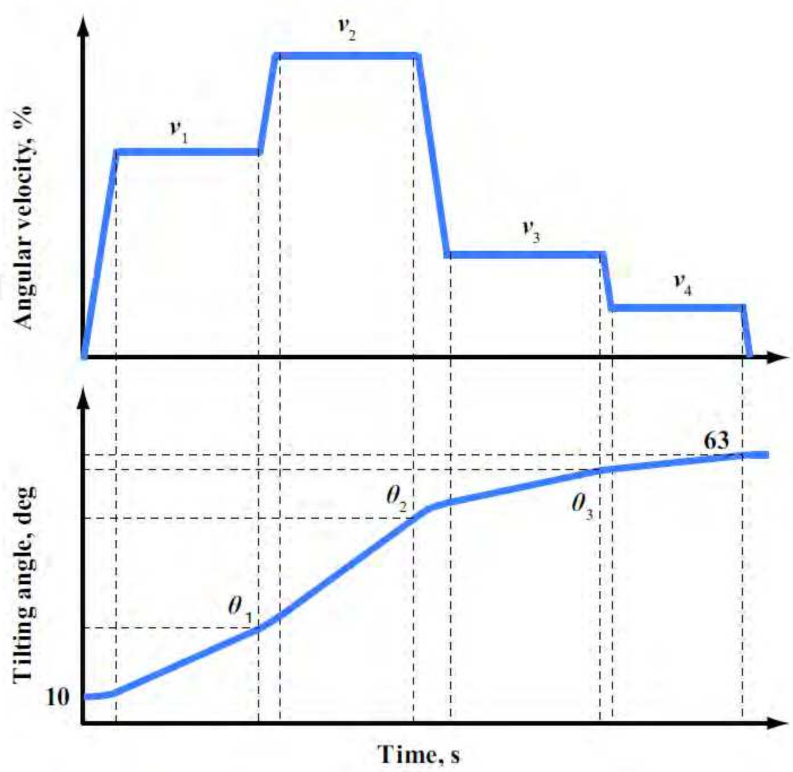

Fig. 3. Tilting velocity of pouring machine.

3. Identification the motion of the pouring machine

In this pouring machine, the tilting movement to input is unknown because the machine doesn't have the output device for the angular velocity or the angle. At the simulation of the fluid of molten metal, the identification of the tilting movement to input is needed. Thus, to get the unknown parameter of V_{max} and a, the movement to input of the actual poring machine is filmed with the motion capture system. Table 1 shows the input of the pouring machine using analysis the motion.

	Switching angle (deg)	Pouring velocity (%)
1	22	10
2	32	30
3	42	50
4	--	30

Table 1. Setting of the tilting input for identification the motion.

The unknown parameter of V_{max} and a, is identified by using the data of the angular velocity from the motion capture. The angular acceleration and maximum angular velocity are a=200 (deg/s^2), V_{max} =51.9 (deg/s) respectively. Fig.4 shows the result of identification of actual pouring machine, where the solid line is the path of actual pouring machine and the broken line is the path of plant model.

From the Fig.4, it can be seen the motion is accorded very well. In this result, the plant model can be recreated the motion of the actual movement.

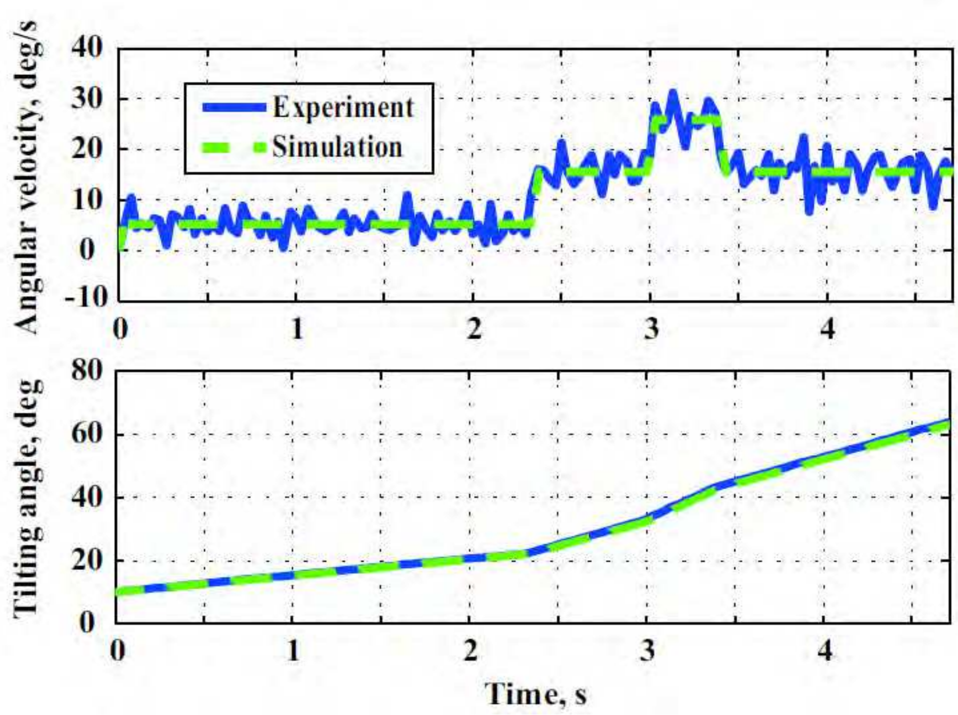

Fig. 4. Result of identification of actual pouring machine.

4. Construction of fluid behavior simulator and flow evaluation

The fluid analysis software FLOW-3D was used in this research. AC2B is taken as the subject fluid. The cast quantity is 1.863×10^{-3}(m^3) and the product part volume is 1.429×10^{-3} (m^3). The physical values of AC2B for the analysis were set as in Table 2. An outline map of the mesh in the simulation domain is shown in Fig. 5 and the mesh parameters are shown in Table 3.

Fluid parameters	AC2B aluminum alloy
Density	2550 kg/m^2
Viscosity	0.00125 Pa•s
Temperature of fluid	993 K
Specific heat	1071 J/(kg•K)
Thermal conductivity	100 W/(m•K)

Table 2. Fluid parameters

Mesh block	Cell size (m)	Number of cell
X-direction	0.004~0.080	108
Y-direction	0.005	54
Z-direction	0.004~0.080	65
Total number of cell		379080

Table 3. Mesh parameters

In an actual plant, a molten metal filter (wire mesh) is installed in the sprue runner with the purpose of removing slag as shown in Fig. 5. The thickness of the wires in the mesh is 0.5×10^{-3}

(m) and the number of wires is 50 in the vertical and 55 in the horizontal. In this research a porous baffle (hereinafter, baffle) was used to reproduce this filter in the CFD simulator.
The air porosity b_p, the linear velocity drop coefficient b_l and the two-dimensional velocity drop coefficient b_q are assigned as setting parameters for the baffle. b_l and b_q are defined by an equation for baffle flow loss shown by Eq. (2).

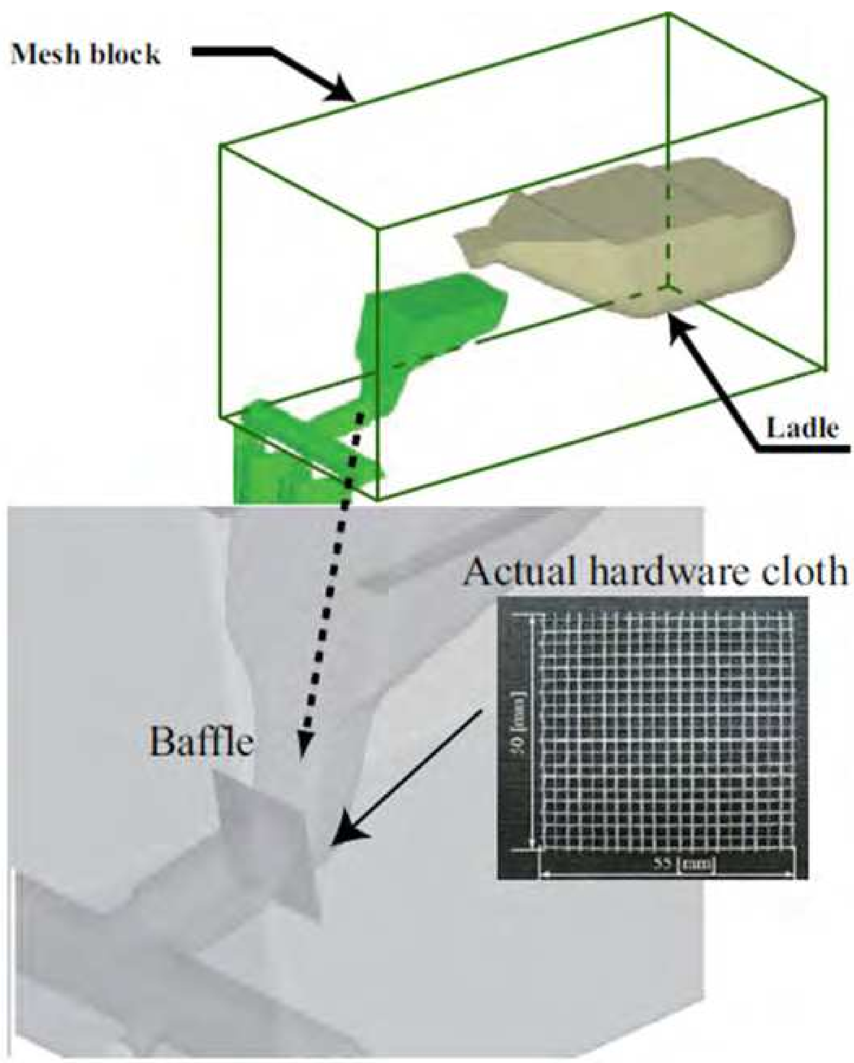

Fig. 5. Mesh setting of CFD

$$B = \frac{1}{L}\left(b_l u + 0.5 b_q u|u|\right) \tag{2}$$

Here, B denotes the baffle flow loss, u the flow speed within the baffle and L the length in which the flow loss is produced. The air porosity of the wire mesh can be calculated from the area ratio of the metal wires and opening between them. As the linear velocity drop is dominant for the baffle flow loss, the 2-D velocity drop coefficient is set at b_q=0 and the results of searching for the linear velocity drop coefficient b_l are shown in Table 4. Furthermore, the search range was carried out in 0.05 increments over b_l=0.00–1.50. Simulation results considering the baffle loss are shown in Fig. 6.

Void	0.655
Linear loss coefficient : b_l	0.90
Quadratic loss coefficient : b_q	0.00

Table 4. Parameters of porous baffle

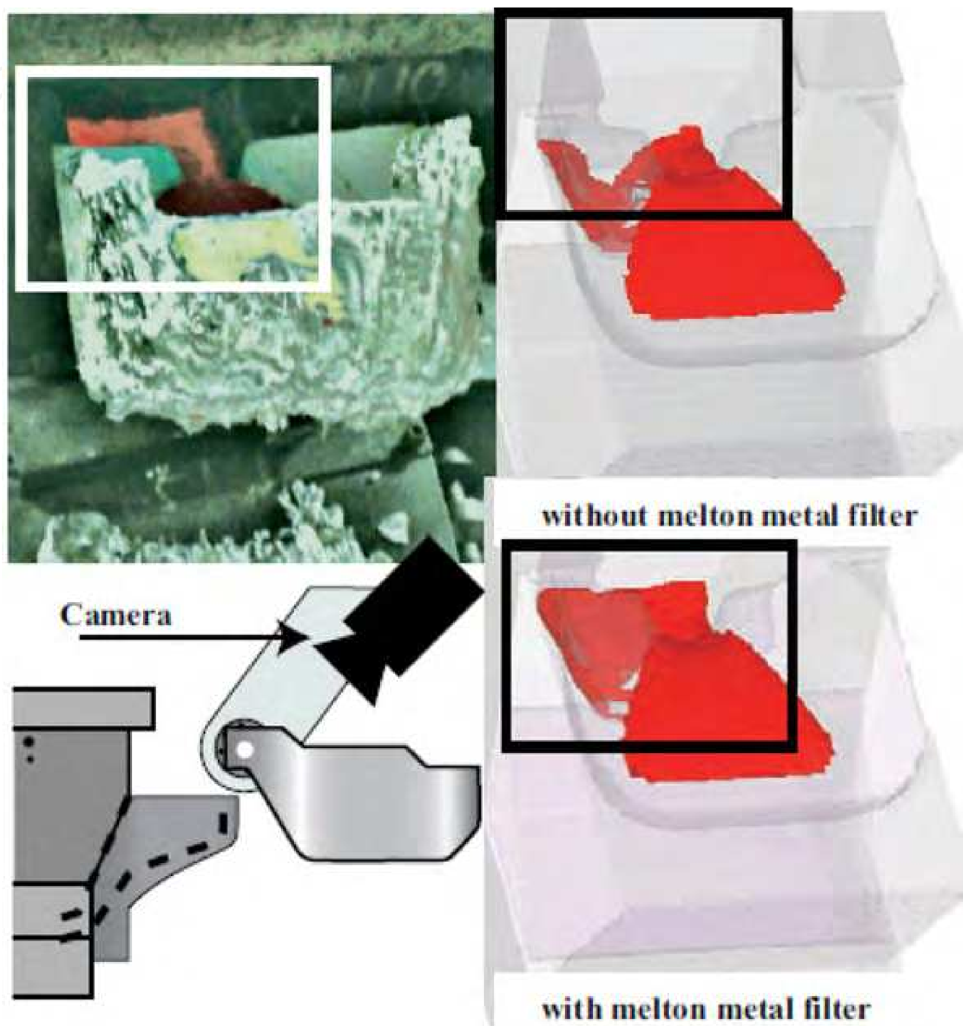

Fig. 6. Comparison of flow in sprue cup between simulation with molten metal filter and without molten metal filter.

Comparing these with the pouring test results, it can be seen that a satisfactory reproduction of the molten metal behavior inside the sprue is achieved.

5. Derivation of optimum pouring input using a genetic algorithm

Through swiftly filling the inside of the sprue cup with molten metal and controlling the liquid level to preserve a liquid level with high uniformity, the flow velocity in the mold gate is made constant.

This is regarded as making possible the production of high-quality casting that mitigates product defects. However, in the case the pouring velocity is determined by operator trial and error, problems occur such as the overflowing of molten metal from the melt due to

improper velocity setting and unstable liquid levels inside the sprue cup etc. Accordingly, in this research, liquid level control is realized through optimizing the pouring input using a genetic algorithm (GA) (Thomas et al., 1993).
GA is an algorithm that models natural selection and mutation in the processes of inheritance and evolution in biological groups in the processes of evolution and inheritance for populations in the natural world and is a probabilistic optimization method.
The three steps of switching angle and four steps of pouring velocity for a total of seven set parameters are taken as variables that are the settings input for the pouring machine, and an optimum tilting velocity pattern is calculated within the limitations of the real machine. In order to swiftly fill the sprue cup and stabilize the liquid surface at a uniform level, the tilting end time is taken as a performance function and the optimization problem is expressed by Eq. (3) with the liquid level inside the sprue as a limiting condition. Through taking the tilting end time as a performance function, the filling time is reduced and through already taking the liquid level as a limiting condition, liquid level control becomes possible.

$$\text{minimize}: J = t_{\mathrm{p}} + J_{\mathrm{p}} \qquad h \geq 0.025 \tag{3}$$

Here, t_{p} denotes the tilting end time, J_{p} a penalty function denoted by Eq. (4), and h the displacement from the sprue exterior to the molten metal.

$$J_{\mathrm{p}} = w_1 + w_2 \tag{4}$$

In Eq. (4), the penalty clause w_1,w_2=100 is imposed in the case the displacement from the sprue exterior to the sprue interior liquid level drops to below 0.025(m) ($h < 0.025$).

6. Optimization with CFD simulator

6.1 Optimization result and melt flow analysis

Optimization by GA was carried out using the calculation parameters shown in Table 5 Forty-eight hours was required for optimization with 41st generation using an Intel Core2 Quad CPU equipped PC.

Number of variable	7
Number of population	10
Number of elite preservation	1
Mutation fraction	0.01
Crossover fraction	0.80

Table 5. Parameters of genetic algorithms

At that time the evaluation value was J=4.668. The tilting angles and velocities obtained from the optimum parameters are shown in Fig. 7. And the simulation results of the liquid level control is shown in Fig. 8.
As a result, it can be seen that the objective liquid level is not reached in the case of any control and a satisfactory liquid surface is not maintained. Conversely, it can be seen that a satisfactory liquid level control that swiftly fills the sprue cup is realized through the optimization of pouring control input.

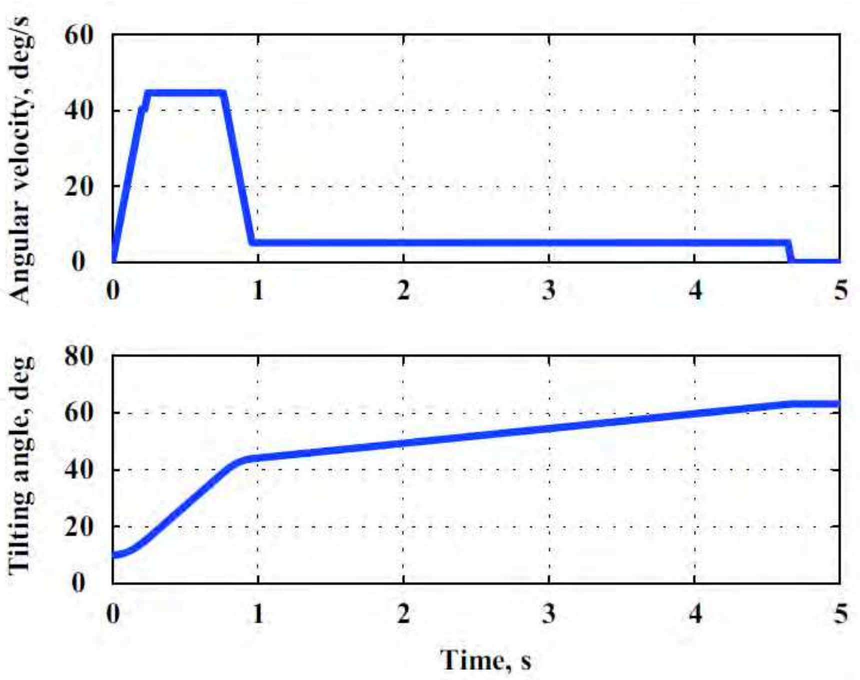

Fig. 7. Tilting input of optimization result.

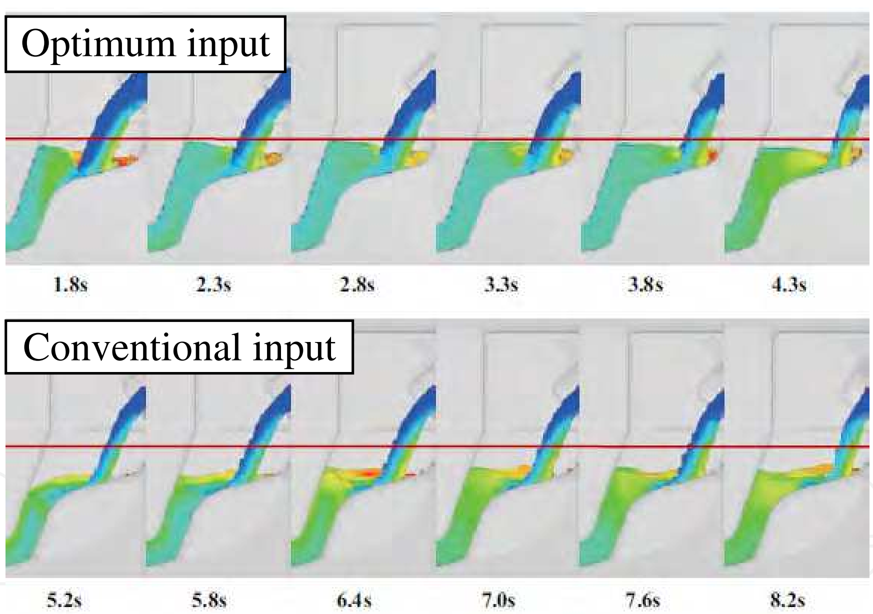

Fig. 8. Tilting input of optimization result.

6.2 Evaluation of the optimum input

Air entrainment is one of the defect origins of such as pin holes and blow holes as shown in Fig.9. Thus, using the evaluation function of air entrainment which is one of the functions of *Flow-3D*, the optimum input is evaluated.

The air entrainment at the liquid surface is based on the concept that turbulent eddies raise small liquid elements above the free surface that may trap air and carry it back into the body of the liquid. The extent to which liquid elements can be lifted above the free surface depends on whether or not the intensity of the turbulence is enough to overcome the surface-stabilizing forces of gravity and surface tension as shown in Fig. 10.

Fig. 9. Photograph of blow hole

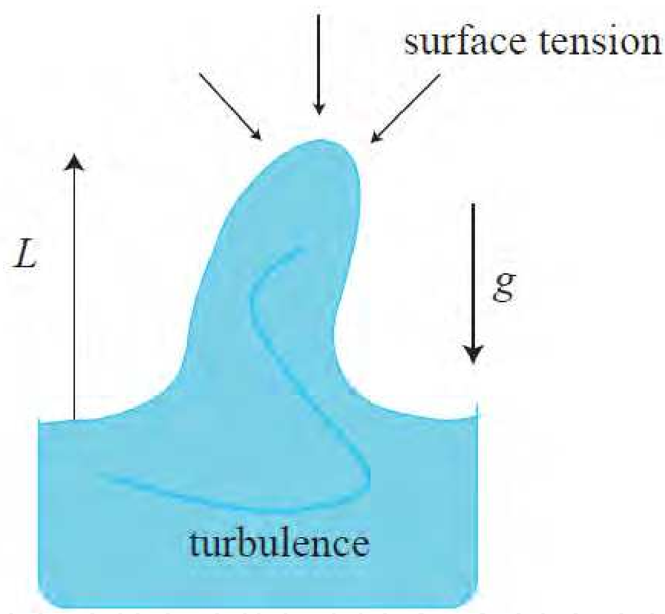

Fig. 10. Model of air entrainment

Turbulence transport models characterize turbulence by a specific turbulent kinetic energy Q and a dissipation function D. The characteristic size of turbulence eddies is then given by Eq. (5).

$$L = 0.1\frac{\sqrt{Q^3}}{D} \tag{5}$$

This scale is used to characterize surface disturbances. The disturbance kinetic energy per unit volume (i.e., pressure) associated with a fluid element raised to a height L, and with surface tension energy based on a curvature of L is given by Eq. (6).

$$P_d = pgL + \frac{\sigma}{L} \tag{6}$$

where ρ is the liquid density, σ is the coefficient of surface tension, and g is the component of gravity normal to the free surface.
For air entrainment to occur, the turbulent kinetic energy per unit volume, P_t=ρQ, must be larger than P_d; i.e., the turbulent disturbances must be large enough to overcome the surface-stabilizing forces. The volume of air entrained per unit time, V_a, is given as Eq.(7).

$$\frac{\partial V_a}{\partial_t} + \nabla V_a = Rt(1 - V_a) \tag{7}$$

where $R = C_{air}\sqrt{2(P_t - P_d)/\rho}$, u is fluid velocity, t is time, and C_{air} is a coefficient of proportionality : C_{air} =0.5; i.e., assume on average that air will be trapped over about half the surface area. If P_t is less than P_d then V_a is zero. Futhermore, Fig.11 is shown the meaasurement point of out flow rate and V_a.

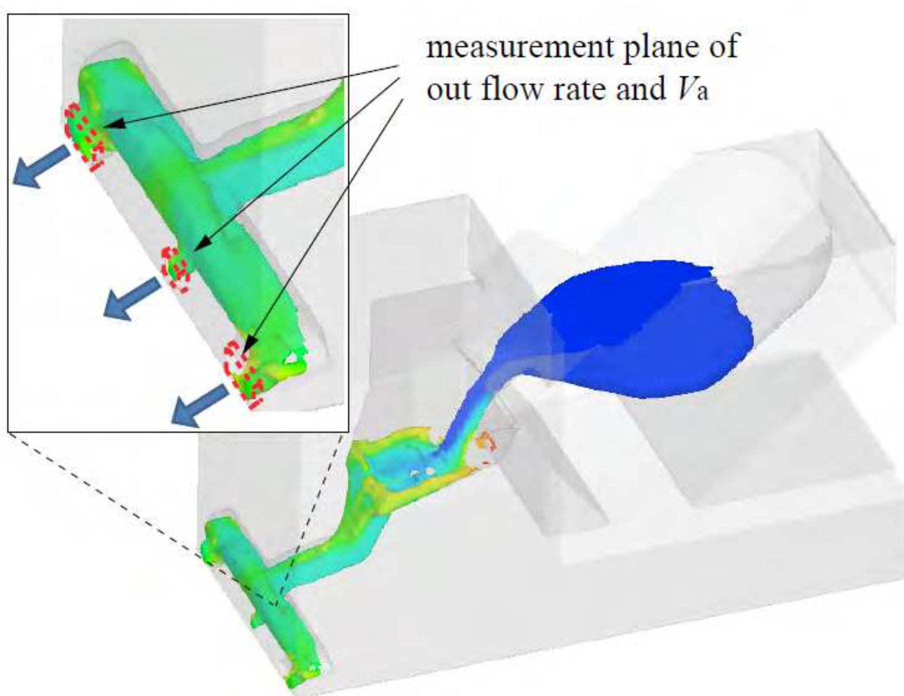

Fig. 11. Measurment plane of out flow rate and V_a

The air entrainment is expressed in Eq.(8).

$$A = \sum_{k=1}^{n} V_{ak} F_{fk} V_{fk} V_{ck} \tag{8}$$

where A is the quantity of air entrainment, V_a is the volume of air entrained per unit time, F_f is the fluid fraction, V_f is the volume fraction, V_c is the volume of the mesh cell, and n is the aggregate number of mesh cells.
Fig.12 shows the flow of molten metal with the mold. It can also be seen the satisfactory liquid level control that swiftly fills the sprue cup is realized. Fig.13 shows the air entrainment at the maching surface. Upper figure shows using the conventional input,

lower figure shows the optimum input, where the color of this figure is indicated the value of the air entrapment, and red color is the most air entarinment point. From the figure, the optimum input can be decrease the air entrainment, and it can be expect to realize a mitigation of defects such as pin holes and blow holes in experiment.

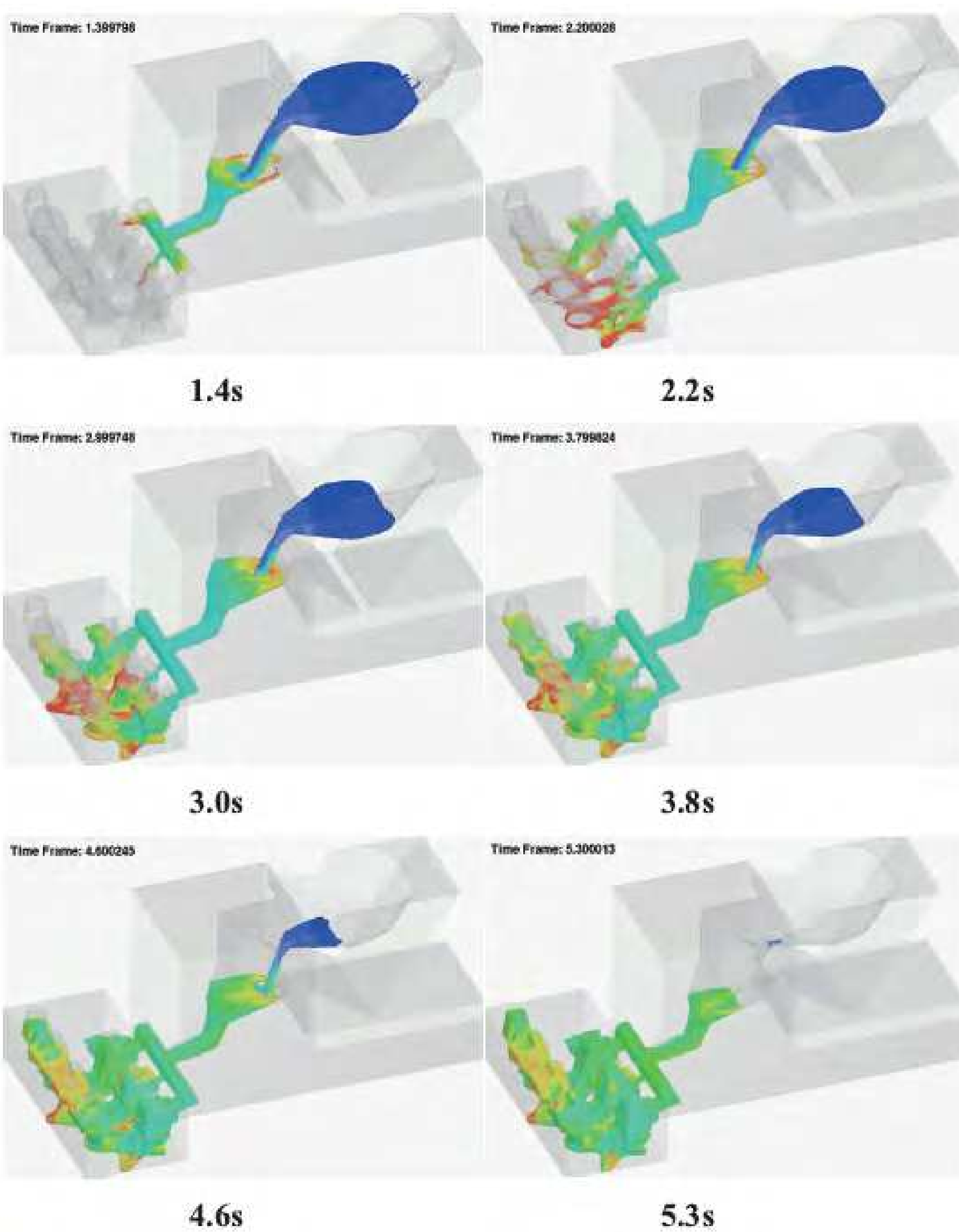

Fig. 12. Flow of molten metal with the mold

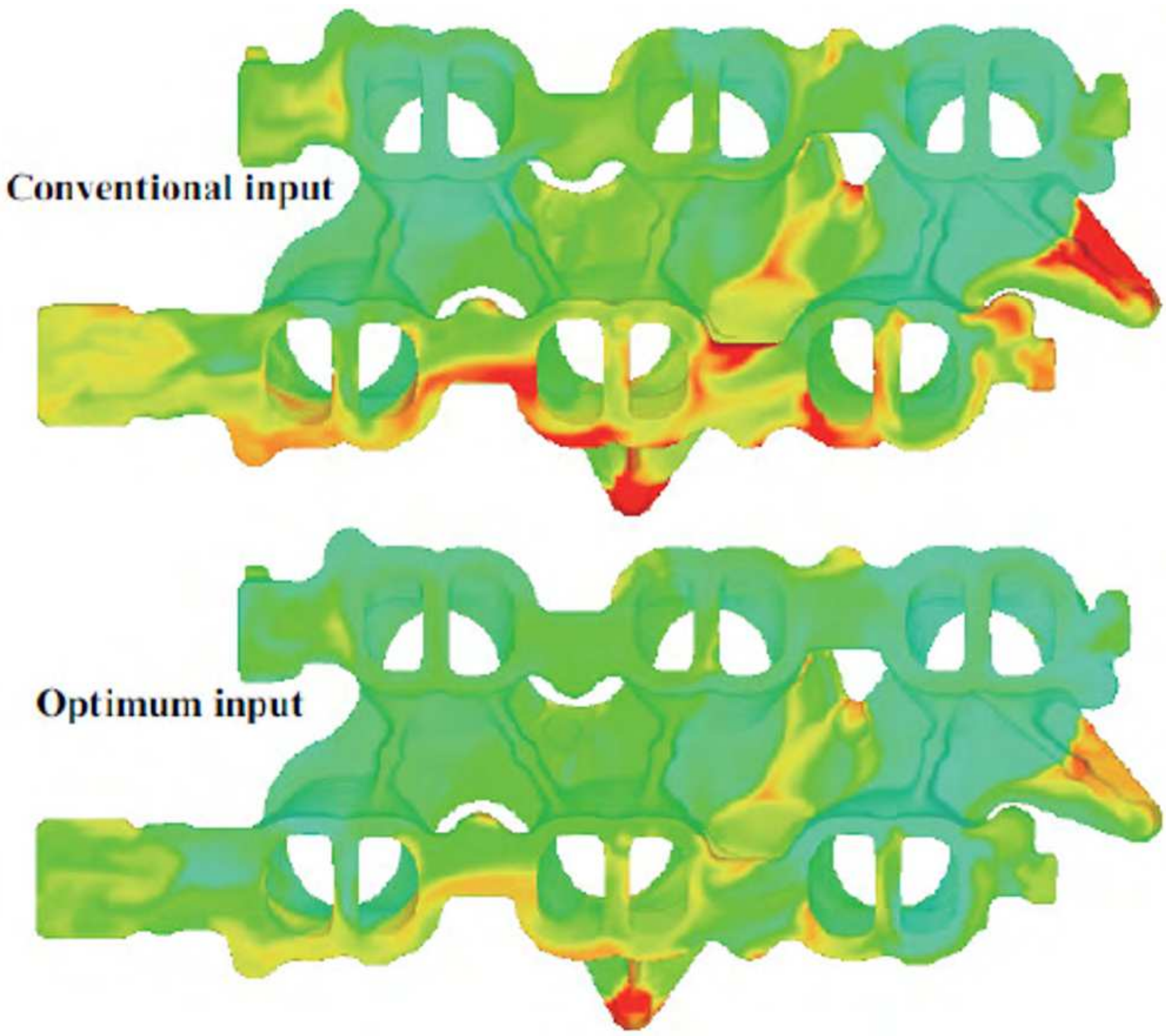

Fig. 13. Air entrainment at machining surface

7. Pouring control experiment using optimum velocity input

The desired optimum velocity input was applied to an actual machine and a pouring experiment was conducted. The conventional inputs were used to compare the optimal solution. Eleven trial runs were carried out and the frequency of defects appearing in the machined surface was evaluated after machining the product part from which the sprue, gating system and gate riser part had been removed. Fig. 14 shows the experiment results using each input and Fig. 15 shows the defect frequency for each.

As a result, it was possible to reduce the manufacturing defect to 1/6 rate by using an optimum pouring velocity as shown in Fig. 14 and Fig. 15. From this it was seen that the optimum input parameter derived using the proposed technique was valid for mitigating the occurrence of product defects.

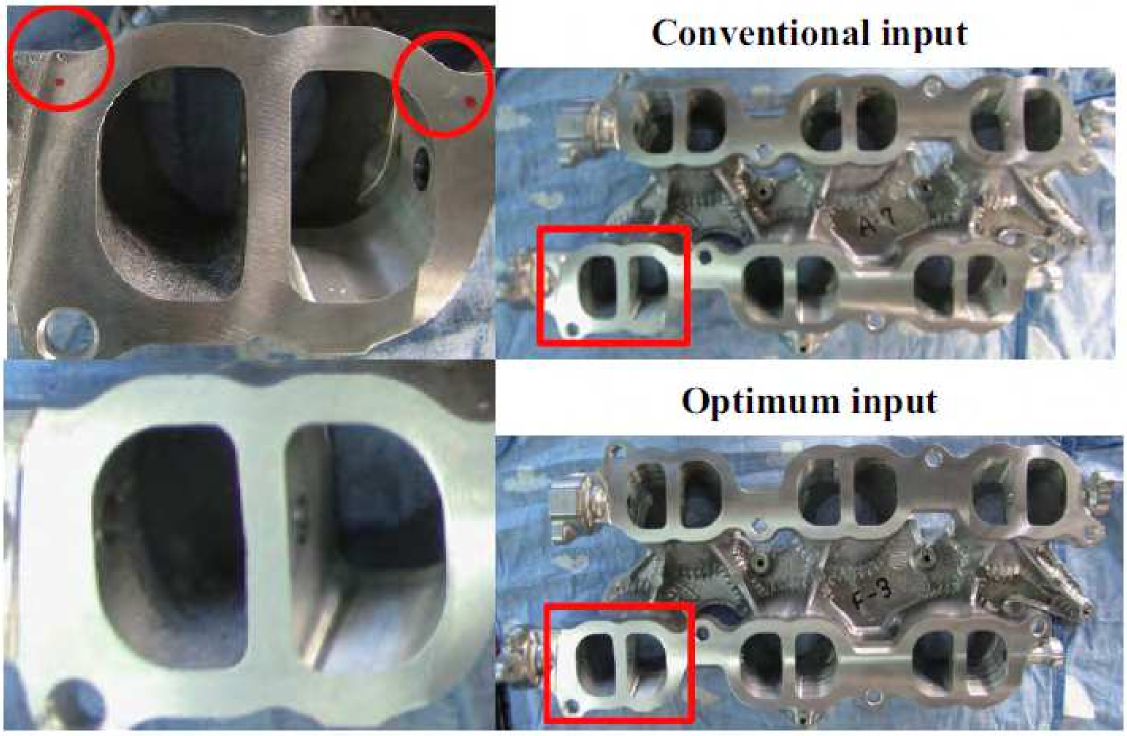

Fig. 14. Experimental results with conventional input and optimum input

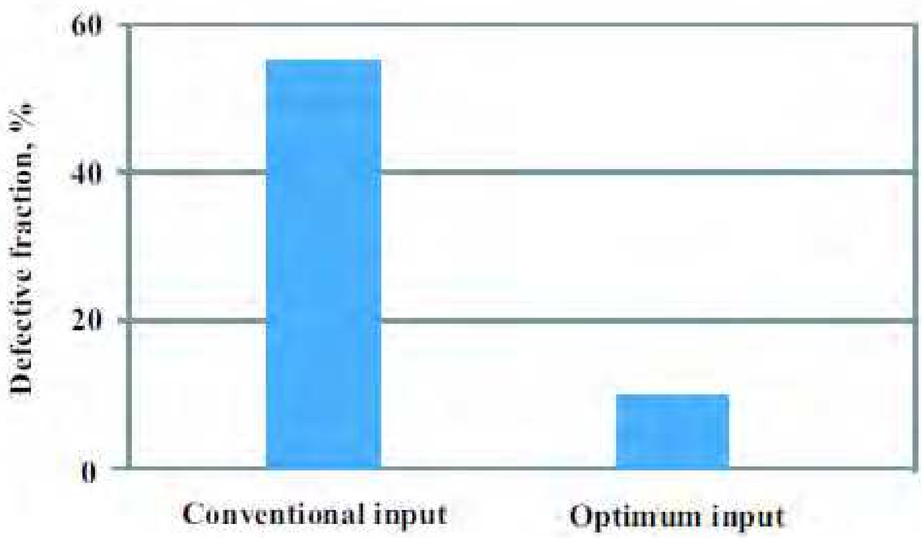

Fig. 15. Defect fraction of machining surface

8. Conclusion

In this research, an analysis technique that enables a reduction in calculation time in fluid analysis simulations was proposed and pouring control input was optimized with the purpose of reducing occurrence of defects such as blow holes and pin holes in aluminum gravity casting.
As a result of optimizing pouring control input using GA, optimum pouring control input realized liquid level control and its validity in mitigating product defects was seen through a real machine pouring experiment.

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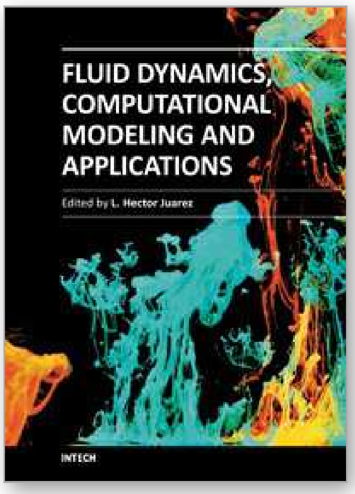

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The content of this book covers several up-to-date topics in fluid dynamics, computational modeling and its applications, and it is intended to serve as a general reference for scientists, engineers, and graduate students. The book is comprised of 30 chapters divided into 5 parts, which include: winds, building and risk prevention; multiphase flow, structures and gases; heat transfer, combustion and energy; medical and biomechanical applications; and other important themes. This book also provides a comprehensive overview of computational fluid dynamics and applications, without excluding experimental and theoretical aspects.