

Development of Pouring Work Training Simulator with Indicating Operation Score for Efficient Skill Acquisition

Takumi Miura¹ and Yoshiyuki Noda¹

Abstract— This paper is concerned with an advanced training simulator of pouring work in the casting industry. The pouring work is a process of pouring high temperature molten metal into a mold. It is a dangerous environment for the worker. On the other hand, since it affects the quality of casting products, the skilled workers are required. In this study, the training simulator with indicating the operation score of the pouring work in the monitor is developed for acquiring safely and efficiently the pouring skill for the novice worker. The trainee can perform the pouring work while aiming to improve his skill by referring the operation score in the simulator.

I. INTRODUCTION

The pouring work in the casting industry is a dangerous work for the workers because they are pouring the high temperature molten into the mold with dust exposure[1][2]. In recent years, the automatic pouring machines have been developed and applied in the casting production lines with mass production. However, it is difficult to apply the pouring machines in the casting factories with high-mix low-volume production. In these factories with high-mix low-volume production, the molten metal is poured by the manual operation of skilled workers. Therefore, the knowledge and skill succession in the pouring work is the key to continuing performance of the casting factories. In a traditional fashion, on the job training has been applied to the practical pouring work for acquiring the skill. However, the pouring work by a novice worker increases risk of the accident. Moreover, it is difficult to acquire the skill in the on the job training without a quantitative assessment to the pouring work.

In conventional studies about the training of casting work, the training system for the mold matching work has been developed using the front view monitor and the force display device[3]. The training support system for the pouring work has also been developed using the stereoscopic video see-through display[4]. In the previous study[5], the training simulator for the pouring work has been developed using visual representation and the force display rotational joystick. These conventional training simulators have incorporated the virtual reality technologies for training safely with enhancing a sense of reality. However, the quantitative assessment of operational status in the pouring work was not included in the conventional training simulators. Therefore, the trainee spends a lot of time to acquire the skill by the training simulators. To solve this problem, the training simulator with displaying the graphs of the operational status in the

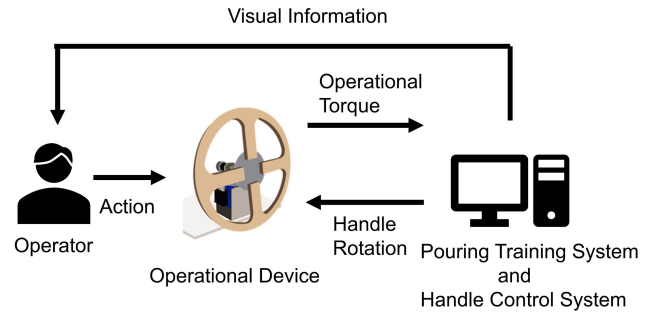


Fig. 1. System configuration of training simulator for pouring work

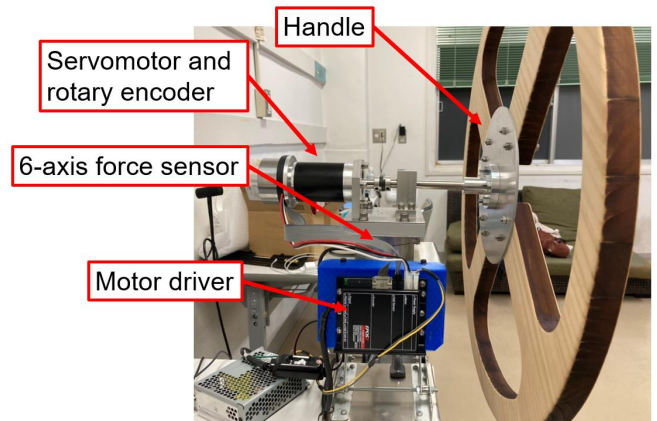


Fig. 2. Handle-type operational device (side view)

pouring work has been developed by the present authors[6]. In this simulator, the flow rate and the falling position of the outflow liquid from the ladle and the liquid level in the sprue cup have been displayed for improving efficiently the pouring skill. Moreover, the handle type operational device as the input interface in the simulator has been developed for improving the realistic sensation. However, it was difficult to grasp that the trainee improves his/her skill of the pouring skill while training. And, it is required to assess and indicate the level of the trainee's skill for motivating the trainee. In this study, we develop the training simulator of pouring work with indicating the operation score for grasping quantitatively the trainee's skill while training. It is easy to improve the skill of pouring work by referring the operation score. Moreover, the trainee's ranking based on the operation score can be indicated after the pouring work in the training for increasing the motivation of the training. We propose the operation score which can be derived by the error of the target level

¹T. Miura, and Y. Noda are with Department of Mechanical Engineering, University of Yamanashi, 4-3-11, Takeda, Kofu, Yamanashi, 400-8511, Japan g23tm024, noday@yamanashi.ac.jp

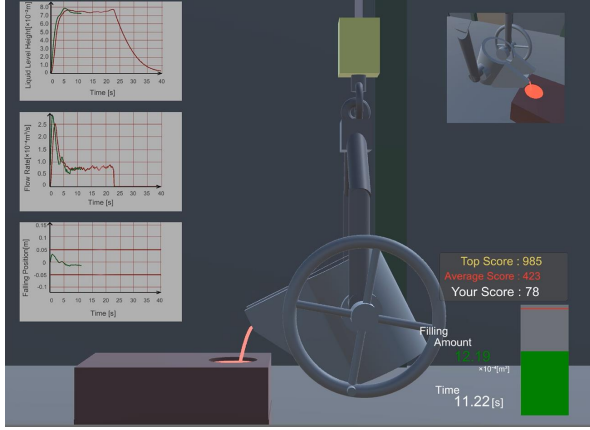


Fig. 3. Visual display of training mode in training simulator

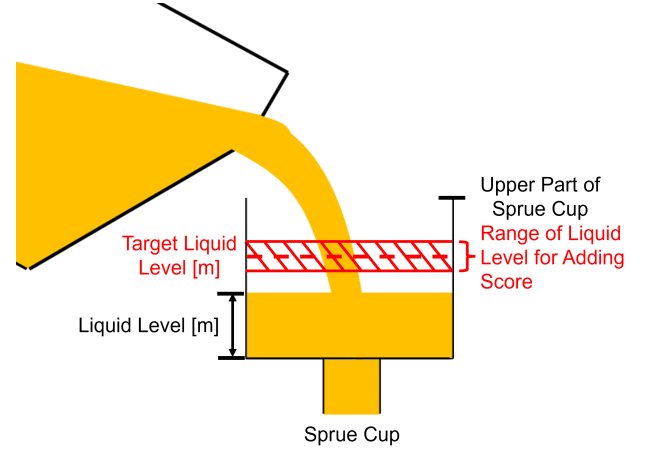


Fig. 5. Scoring area in sprue cup

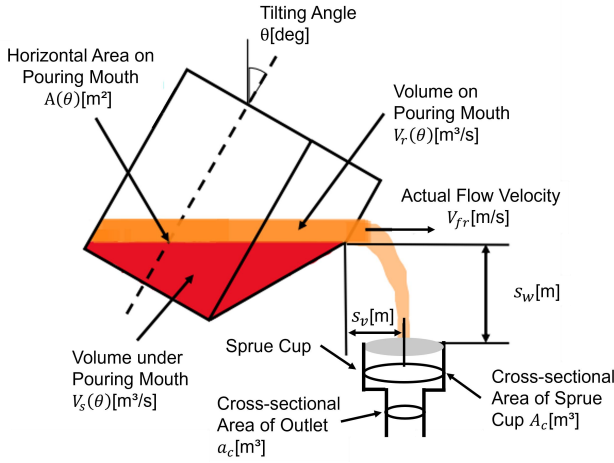


Fig. 4. Pouring condition at tilting angle θ of ladle

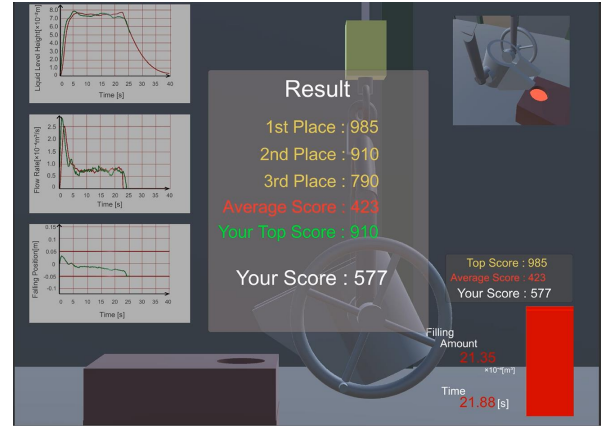


Fig. 6. Display of operation score and ranking after pouring work

and the liquid level in the sprue cup in the pouring work and the variation in the liquid level. The efficacy of the developed training simulator is verified by the training experiments.

II. TRAINING SIMULATOR OF POURING WORK

The system configuration of the training simulator of pouring work is shown in Fig. 1. The operator can rotate the handle in the operational device. The handle attached to the ladle in the simulator is also rotated synchronously, and the molten metal is poured into the mold by tilting the ladle. The operator can watch the virtual environment of the pouring work visualized in the display device such as a display monitor and a head mount display. The virtual environment is designed using Unity, one of the game programming. However, the physics engine preliminary installed into Unity is not used in this study. We design the virtual environment of pouring work based on the mathematical model of the pouring process proposed in [7].

III. HANDLE-TYPE OPERATIONAL DEVICE

Figure 2 shows the configuration of the handle-type operational device. The operational torque added to the handle

can be detected by the six-axis force sensor mounted on the operational device. The handle can be rotated by the servomotor connected the center shaft of the handle. The rotating angle and its angular velocity can be detected by the rotary encoder attached to the servomotor. The handle rotation is controlled by the admittance control approach with the virtual model of handle rotation. The virtual model of rotating handle is represented as

$$J\ddot{\phi} + c_h\dot{\phi} = T, \quad (1)$$

$$\theta = g_r\phi, \quad (2)$$

where J and c_h are the inertia moment and the viscous damping coefficient of the virtual handle, respectively. ϕ and T are the rotating angle of the handle and the operational torque added to the handle, respectively. θ is the tilting angle of the virtual ladle. g_r is the gear ratio between the handle rotation and the ladle tilting. In this study, J , c_h and g_r are provided as $0.005[\text{kgm}^2]$, $0.01[\text{Nms/rad}]$ and 0.1 , respectively.

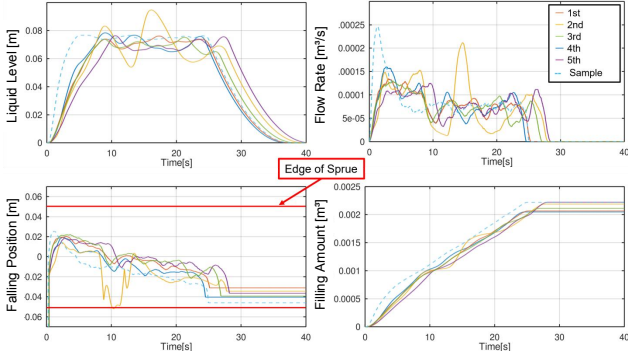


Fig. 7. Experimental results of skill assessment before training without indicating score of pouring work (Trainee A2)

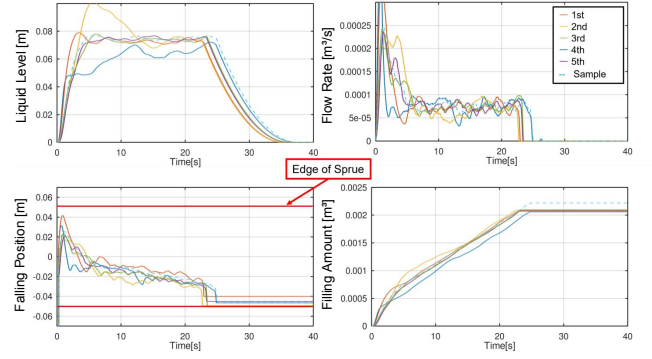


Fig. 9. Experimental results of skill assessment before training with indicating score and ranking of pouring work (Trainee B2)

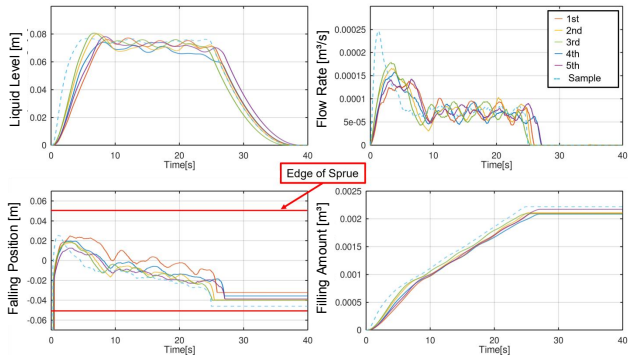


Fig. 8. Experimental results of skill assessment after training without indicating score of pouring work (Trainee A2)

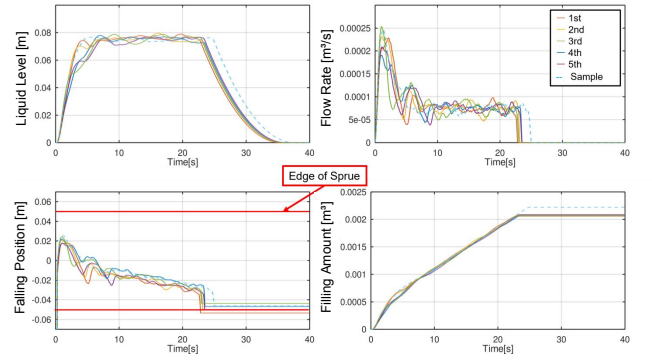


Fig. 10. Experimental results of skill assessment after training with indicating score and ranking of pouring work (Trainee B2)

IV. VISUAL DISPLAY IN TRAINING SIMULATOR

The virtual environment of the pouring work is displayed in the training simulator as shown in Fig. 3. In the case of monitor display, the side view of pouring work is displayed for easily recognizing the status of pouring work. And, the operator can grasp the liquid filling condition in the sprue cup by the diagrammatic perspective view of pouring work which appears at the upper right of the screen. The filling volume of the liquid flowing into the mold can be indicated by the bar graph at the lower right of the screen. When the volume of the liquid filled into the mold is achieved to the target volume, the bar is turned to red color. The operator can finish the pouring work in this situation.

A. Mathematical Model for Pouring Process

The virtual environment of the pouring process in the training simulator can be designed based on the mathematical model of the pouring process proposed in [7]. The illustration of the pouring process is shown in Fig. 4. From Fig. 4, the pouring flow rate can be derived as

$$\frac{dh(t)}{dt} = -\frac{1}{A(\theta(t))} \left\{ q(h(t)) + \left(\frac{\partial V_s(\theta(t))}{\partial \theta(t)} + \frac{\partial A(\theta(t))}{\partial \theta(t)} \right) \omega(t) \right\}, \quad (3)$$

$$q(t) = c \int_0^{h(t)} L_f(h) \sqrt{2gh} dh, \quad (4)$$

where θ and ω are the tilting angle of ladle and its angular velocity, respectively. h is the height of the liquid over the pouring mouth, q is the pouring flow rate, A is the horizontal area on the pouring mouth, and V_s is volume under pouring mouth. The average velocity of the outflow liquid on the end of the pouring mouth is shown as

$$V_f(h) = \frac{q(h)}{A_p(h)}, \quad (5)$$

where A_p is the cross-sectional area of liquid on the end of pouring mouth, and c is the flow rate coefficient, g is the acceleration of gravity. In this study, the flow rate coefficient is provided as 0.75. Here, the cross-sectional area of the flowing liquid on pouring mouth can be contracted under the influence of gravity force. Therefore, the average velocity of the outflow liquid is increased in response to the contraction of the cross-sectional area. The average velocity is compensated as

$$V_{fr} = \beta_1 V_f + \beta_0, \quad (6)$$

where β_0 and β_1 are correction factors, which are obtained from calibration experiment [8]. In this study, $\beta_0 = -0.210$, $\beta_1 = 2.542$ are provided. The falling trajectory of the outflow

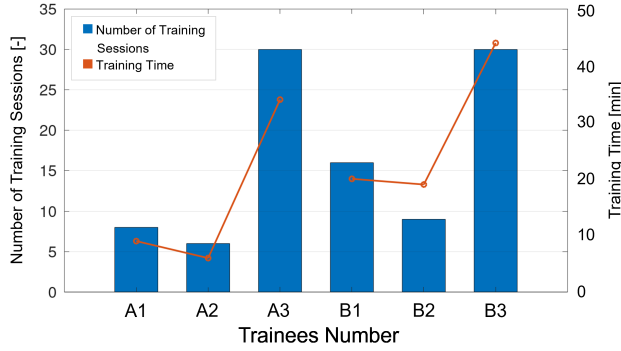


Fig. 11. Experimental results of number of training sessions and training time in six trainees

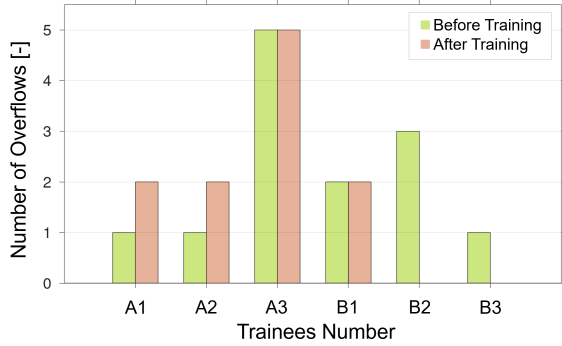


Fig. 12. Experimental results of number of overflows in six trainees

liquid from the ladle can be represented by the parabolic motion as

$$S_v(t) = V_{fr}(t) \sqrt{\frac{2S_w(t)}{g}}, \quad (7)$$

where S_w is the vertical falling position from the tip of the pouring mouth. S_v is the horizontal falling position from the tip of pouring mouth.

The outflow liquid from the ladle is flowed into the sprue cup placed on the mold. The liquid level in the sprue cup can be represented as

$$\frac{dh_L(t)}{dt} = \frac{1}{A_c} (q(t) - c_o a_c \sqrt{2gh_L(t)}), \quad (8)$$

where h_L is the liquid level in the sprue cup and A_c and a_c are the cross-sectional areas of sprue cup and its outlet, respectively. c_o is the outlet flow coefficient. In this study, A_c , a_c and c_o are provided as 0.0079[m²], 0.0013[m²], and 0.78, respectively.

B. Operational Status Graph of Pouring Work

The graphs located on upper to middle right show the time series data of the liquid level in the sprue cup, the pouring flow rate and the falling position of the outflow liquid on upper surface of sprue cup as shown in Fig. 3. In the graphs of the liquid level in the sprue cup and the pouring flow

rate, the red lines indicate the operational status of reference pouring work which is obtained in the pouring work by the skilled worker. The trainee can train the pouring work in the simulator as tracking the reference operational status. In the graph of the falling position of the outflow liquid, the red lines show the edges of sprue cup. The trainee is required to perform the pouring work as maintaining the falling position between the red lines for avoiding to spill the liquid from the sprue cup. The trainee can acquire efficiently the skill of pouring work by checking the graphs of operational status in the simulator.

C. Operation Score of Pouring Work

The operation score by which the trainee's pouring work is evaluated quantitatively is indicated on middle right of the screen as shown in Fig. 3. The highest and average operation scores in all of the trainees are also indicated on the screen. The scoring method of the pouring work in the training is represented as

$$J = \sum_{i=0}^n d(h(i)) + P, \quad (9)$$

$$d(h(i)) = \begin{cases} 2, & (|h_t - h(i)| \leq \epsilon_h \\ & \text{and } |h(i) - h(i-1)| \leq \epsilon_t), \\ 1, & (|h_t - h(i)| \leq \epsilon_h) \\ 0, & (\text{else}) \end{cases} \quad (10)$$

$$P = \begin{cases} -450, & (h(i) > h_{uc} \text{ or } |P_f(i)| > r_{sc}), \\ 0, & (\text{else}) \end{cases} \quad (11)$$

$$, (i = 0, 1, \dots, n)$$

where J is the operation score and d is the additional score. $d = 2$ is given when the absolute error of the target level h_t and the liquid level h in the sprue cup is within the scoring area which has the boundary condition ϵ_h as shown in Fig.4 and the variation of the liquid level h is suppressed within the boundary condition ϵ_t . $d = 1$ is given when the absolute error of the target level and the liquid level is only within the scoring area. P is the penalty. If the liquid in the sprue cup with the height h_{uc} is overflowing or the falling position $|P_f|$ of the outflow liquid from the ladle is spilled from the sprue cup with the radius r_{sc} , the operation score is decreased as $P = -450$. In this study, the target liquid level is $h_t = 0.075$ [m], the boundary of the error from the target liquid level is $\epsilon_h = 1 \times 10^{-3}$ [m], and the boundary of the variation of the liquid level is $\epsilon_t = 2 \times 10^{-5}$ [m].

After finishing the pouring work in the training, the ranking based on the operation score is displayed as shown in Fig. 6. The indication of the score ranking as shown in Fig. 6 has the top three scores and the average score in all of the trainees. And, the top and latest scores of the present trainee are also appeared in the ranking indication. The trainees can motivate the training of the pouring work by checking the score ranking.

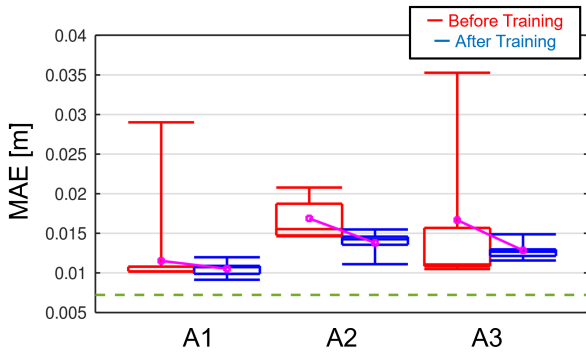


Fig. 13. Experimental results of root mean squared error of liquid level from target liquid level in spruce cup (Group A)

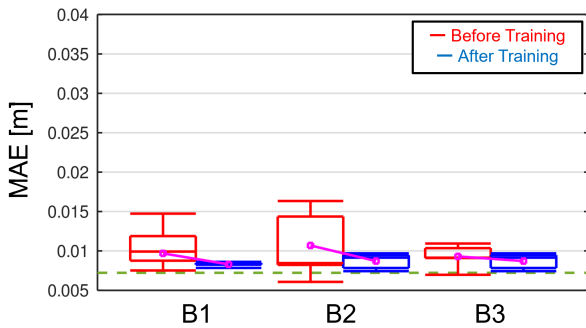


Fig. 14. Experimental results of root mean squared error of liquid level from target liquid level in spruce cup (Group B)

V. EXPERIMENTAL VERIFICATION

The efficacy of the developed training simulator is verified by the training experiments. In the experiments, the target liquid level in the spruce cup is set to 0.075[m]. Because it is required to maintain the high liquid level for achieving the liquid filled into the mold to the target volume in a short time and avoid the liquid in the spruce cup overshooting the height 0.08[m]. The target volume of the liquid filled in the mold is provided as $20 \times 10^{-4}[\text{m}^3]$ in this study.

A. Experimental Procedure

The training experiments are performed with six trainees. In order to verify the efficacy of the developed training simulator, the trainees are equally divided into two groups: group A, which is trained without the indication of operation score and ranking while viewing the operational status graph introduced in the conventional training simulator, and group B, which is trained with the indication of operation score and ranking while viewing the operational status graph. The experimental procedure is shown as follows;

- 1) All of the trainees are briefed on the purpose of the experiment, the experimental procedure and the operational method of the training simulator.
- 2) Skill assessment before training; Trainees perform test of pouring work five times.
- 3) Training; Trainees in group A (the group without the indication of operation score and ranking) and group

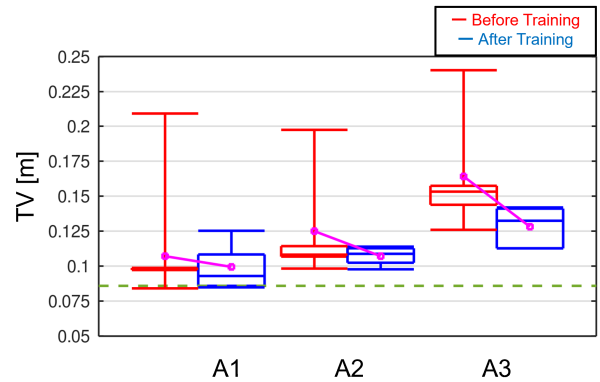


Fig. 15. Experimental results of total variation for evaluating fluctuation in liquid level data (Group A)

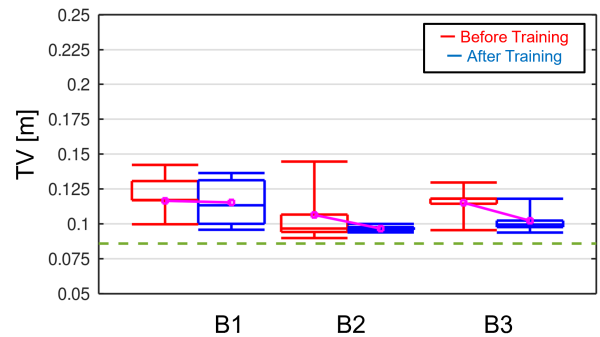


Fig. 16. Experimental results of total variation for evaluating fluctuation in liquid level data (Group B)

B (the group with the indication of operation score and ranking) can each use the simulator to continue pouring work at least five times until the trainee is satisfied. They can stop when they feel that they have acquired the pouring skill sufficiently or when they are bored.

- 4) Skill assessment after training; Trainees perform test of pouring work five times.

B. Experimental Results

The experimental results of one trainee in group A are shown in Figs. 7 and 8. Figure 7 shows the results in the skill assessment before training. The graphs (a), (b), (c), and (d) in the Fig. 7 are the results of the liquid level in the spruce cup, the pouring flow rate, the falling position of outflow liquid and the volume of liquid filled in mold, respectively. The results obtained in the five operations in pouring work are appeared in the graphs. Figure 8 shows the results in the skill assessment after training. The layout of graphs in the Fig. 8 is same as the Fig. 7.

The experimental results of one trainee in group B are shown in Figs. 9 and 10. Figures 9 and 10 show the results in the skill assessment before and after training, respectively. The layout of graphs in the Figs. 9 and 10 is same as the Fig. 7. In the results of the skill assessment before the training shown in Fig. 9, the large fluctuations have been

appeared in the operational data. The fluctuating operation is not desired in the pouring work. The fluctuating operation was suppressed by the training with the indication of the operation score and ranking as shown in Fig. 10. Comparing the results of skill assessment in groups A and B, it is shown that the trainee in group B operates the simulator with less fluctuation in skill assessment after training. The trainee was able to pour stably the liquid into the mold by training the pouring work using the simulator with the indication of the operation score and ranking.

Figure 11 shows the results of the number of operations in pouring work during the training and the whole time taken for the training. The bar graph shows the number of operations in pouring work and the line graph shows the whole time taken for the training. It is shown that group B tends to train more often than group A and take more time for the training. Figure 12 shows the results of the number of times which the liquid is overflowed from the sprue cup in the skill assessment before and after the training. It is shown that the trainees in group A could not improve the skill which suppresses the overflow from sprue cup. On the other hand, the trainees in group B could improve the operational skill for suppressing the overflow from the sprue cup.

C. Evaluation by Error of Target Level and Liquid Level in Sprue Cup

The pouring works by the trainees can be evaluated quantitatively using the data of the liquid level in the sprue cup. It is important to control appropriately the liquid level in the sprue cup for keeping highly the quality of casting product. In the evaluation, the mean absolute error (MAE) between the target liquid level and the liquid level in the sprue cup by the pouring work of the trainee is used as

$$MAE = \frac{1}{n} \sum_{i=1}^n |h_t - h(i)|, (i = \frac{t}{\Delta t}, n = \frac{t_{ff}}{\Delta t}) \quad (12)$$

where t and Δt are the time from starting the pouring operation and the sampling period, respectively. t_{ff} is the time at accomplishing the liquid filled into the mold to the target volume. The box-and-whisker diagrams in Figs. 13 and 14 show the evaluation results of MAE to the five operations in pouring work by the trainees of the groups A and B, respectively. In Figs. 13 and 14, the red and blue colored boxes are the results of the operations before and after the training, respectively. And, the green lines are the result of the operation by the skilled worker. In Fig. 14, it is shown that the pouring works after the training by the trainees in the group B can be approached to the target liquid level. The variation of each operation in pouring work after the training by the trainees in the group B is also small.

Moreover, we evaluate the fluctuation in the liquid level data using the total variation (TV) as

$$TV = \sum_{i=1}^n |h(i) - h(i-1)| \quad (13)$$

The box-and-whisker diagrams in Figs. 15 and 16 show the evaluation results of TV to the five operations in pouring work by the trainees of the groups A and B, respectively. The color and the layout in Figs. 15 and 16 are same as Figs. 13 and 14. In Fig. 16, it is shown that the pouring works after the training by the trainees in the group B can operate the simulator with less fluctuation in the liquid level. It is shown that the skill of pouring work can be improved efficiently by the developed training simulator with indicating the operation score and ranking.

VI. CONCLUSIONS

In order to acquire safely and efficiently the pouring skill in the casting industry, we developed the training simulator for pouring work using the indication of operation score and ranking in the gamification technology. In particular, the trainee can grasp his own skills quantitatively and efficiently improve the pouring skill by training while watching the operation score and ranking. In the experimental results, it is shown that the pouring skill of the trainee can be improved efficiently by using the developed training simulator.

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