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New Idea of Suppressing Free Surface Vortex During Tapping Liquid Steel from Converter

Seung-Jin Lee[1,2,*], Sang-Joon Kim[1], and Hae-Geon Lee[1,3]

[1]Graduate Institute of Ferrous Technology, Pohang University of Science and Technology, Pohang, Rep. of Korea
[2]Engineering Solution Center, POSCO, Pohang, Rep. of Korea
[3]School of Engineering, Adama Science and Technology University, Adama, Ethiopia

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During tapping liquid steel from a converter to a ladle, slag may carry over due to a formation of free surface vortex. Such vortex should be suppressed in order to minimize contamination of the steel by slag. In the present study, a new idea is proposed to minimize the vortex formation by applying dual tapping hole system. The idea was tested using a rectangular shape water vessel with dual tapping holes, supplemented by a numerical simulations, in order to evaluate feasibility of the dual tapping hole system. Both the water model experiment and the numerical simulation showed similar tendencies that the dual tapping hole system is promising to prevent the vortex formation. Experimental results showed that the free surface vortex formation is highly sensitive to shape and configuration of the nozzle. From the numerical simulation, flow characteristics were obtained, and vortex canceling between two nozzles is confirmed. Effect of dual tapping hole increased with increasing distance between two holes in the present experimental condition. Finally, a 1/7.8 scale-down water vessel simulating a real converter was employed in order to confirm the validity of the above findings. The result showed almost the same tendencies with the previous findings.

Keywords: computer simulation, liquids, purification, vortex, dual tapping hole

1. INTRODUCTION

In various pyro-metallurgical processes including steelmaking, liquid metal passes a number of reactors or vessels through connecting channels. Due to the presence of rotational momentum inside vessels, a free vortex may form on the surface of the liquid metal. One of such phenomena may be referred to liquid steel tapping process. After oxygen steelmaking in a converter, a liquid steel is subject to be tapped from the converter into a ladle through a tapping nozzle. In a later stage of the tapping, the free surface vortex forms to a direction of the steel flow in the nozzle. This vortex causes entrainment of the steelmaking slag floating on top of the liquid steel. It could result in severe contamination to the steel, because impurities such as phosphorus removed in the slag may be reverted into the liquid steel. Moreover, it is known that, with the formation of vortex, flow rate of the liquid steel through the nozzle decreases rapidly, which results in considerable loss for the productivity [1,2]. This subsequently increases tapping time and decreases tapping temperature of liquid steel. Therefore, suppression of the slag entrainment has been one of the major concerns in steelmaking process for a long time.

Until now, a number of researches [3-7,13,14] have been conducted in order to figure out the mechanism of the free surface vortex formation and possible solutions to suppress it. There are some critical factors which affect the vortex formation during tapping of liquid metal: initial tangential velocity, slag or ball which covers the liquid metal, and eccentricity. And the tendency of vortex formation is interpreted by a term called "critical height", which refers to the depth of the liquid at the time of initial formation of the vortex. The higher the tangential velocity is, the higher the critical height is. Moreover, when the free surface is fluctuated, the vortex forms earlier. When other immiscible and viscous liquid covers the liquid as slag on top of liquid steel, the critical height becomes lower. Eccentricity of the nozzle from the center of the vessel is also important factor in such a way that high eccentricity lowers the critical height. Although role of such factors on the formation of vortex has been investigated, the factors are indeed uncontrollable during the process. Therefore it is necessary to find other ways to suppress the vortex formation.

In the present study, in order to suppress the vortex forma-

*Corresponding author: bloodone@postech.ac.kr

tion, a new idea is proposed. This idea is free from the above uncontrollable factors. Generally, the steelmaking converter has a single nozzle, and a free surface vortex is generated above the nozzle. The proposed idea is to intentionally induce twin vortexes by having dual nozzles in the converter. These nozzles may be located in various configurations (distance, shape, alignment with respect to tilting direction). In order to validate the idea, a water model experiment was carried out with varying these configurations, and the observation was further analyzed by a series of numerical simulations. Finally, a 1/7.8 scale-down water vessel simulating a real converter was employed in order to confirm the validity of the findings from both the water model experiment and the numerical simulations.

2. EXPERIMENTAL PROCEDURES

2.1. Apparatus for small scale water model experiment

In order to observe whether two vortexes intentionally formed above the dual nozzles cancel each other, a model study was carried out using a rectangular shape vessel with water. It has been well known that a vortex is never formed without any initial force (or velocity) in the vessel. A number of investigations proposed several methods to generate a uniform initial force [8-10]. In the present study, a natural generation method was adopted in order to generate initial force. Figure 1 shows a schematic design of this vessel. This vessel has two compartments, which are connected by a connecting hole. Water in one compartment A was allowed to move to the other compartment B. As seen in the Fig. 1, the connecting hole was located in a position in order to induce a rotating momentum when the water enters into the compartment B. This was intended to generate a vortex in the water flowing into the compartment B from the compartment A, and the water was allowed to be tapped through one or two nozzle holes made at the bottom of the compartment B.

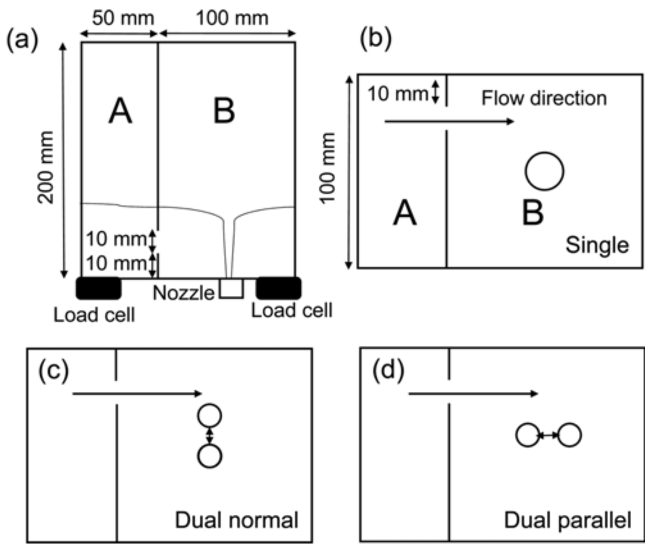

Fig. 1. Schematic figure of the rectangular water vessel: (a) side view, (b), (c), and (d) top view of single, dual normal, dual parallel, respectively.

Dimension of each compartment of the vessel is 100×100×200 mm (B) and 50×100×200 mm (A), respectively. The connecting hole has a square dimension of 10×10 mm located 10 mm above from the bottom and 10 mm away from the side wall. Distance between two nozzle holes was varied from 1 to 3 times of diameter of the nozzle hole. The diameter of the nozzle hole was varied from 10 to 11 mm, when there was only single nozzle hole (Fig. 1(b)). When dual nozzles are considered, diameter of the nozzle hole was fixed to 8 mm, but configuration of these two hole were varied as seen in Figs 1(c) and 1(d). Due to the friction increased by sudden expansion/contraction while the water passed through the nozzle, cross sectional area of the holes for single nozzle and dual nozzle should be considered. Dual nozzle had about 28% wider cross sectional area than that of single nozzle. Length of each nozzle attached beneath the bottom was 10 mm.

Flow rate was measured by 4 load cells installed at 4 corners at the bottom of the vessel in order to weigh the whole vessel assembly. Total weight of the assembly decreased as the water flowed out of the vessel, and the weight was recorded at each 1 sec. Total amount of water used was 2.1 liter. All the experiments were repeated 5 times and the obtained results were averaged, in order to get reliable data.

2.2. Numerical simulation

In order to analyze observations of the water flow in the water model experiment, fluid patterns of the water were investigated employing a numerical simulation technique. A commercial CFD package FLUENT 12.0 was used for the numerical simulations. Geometry of the system was created by GAMBIT. All the geometry was the same as the rectangular shape water model. Total number of mesh was 256,405. The numerical schemes were pressure based, transient, and 3D. Also, for the multi-phase method, VOF (volume of fluid) was selected [11]. The top of the vessel was selected as pressure inlet and the bottom of the nozzle was selected pressure outlet. Fluid pattern is governed by gravitational force(9.8m/s^2) In the VOF model, the volume fraction of water, α_w, is calculated by the following continuity Eq.:

$$\frac{\partial \alpha_w}{\partial t} + v \cdot \nabla \alpha_w = 0 \tag{1}$$

where v is the velocity vector. By its definition, the volume fraction of air, α_a, is

$$\alpha_a = 1 - \alpha_w \tag{2}$$

Density, ρ, and viscosity, μ, of the fluid are respectively calculated using the volume fraction of water:

$$\rho = \alpha_w \rho_w + (1-\alpha_w)\rho_a \quad (3)$$

$$\mu = \alpha_w \mu_w + (1-\alpha_w)\mu_a \quad (4)$$

where subscripts w and a denote water and air, respectively.

When fluid pattern in different types of nozzles are computed, mesh scheme must be similar in all cases. In order to fix the simulation condition, Grid Interface method was used [12].

2.3. Real shape water model validation

In order to confirm the validity of the findings obtained through the water model experiment (Sec. 2.1) and the numerical simulations (Sec. 2.2), a real converter shaped vessel was constructed using polymer acryl. Dimension of the vessel was reduced as 1/7.8 times as the real converter operated in a steelmaking plant of POSCO. Dual tapping nozzles were installed and flow rate of the tapping water simulating tapping liquid steel was measured by a method described in Sec. 2.1.

3. RESULTS AND DISCUSSIONS

Water flow pattern in the rectangular vessel: experiment

Experimental conditions were varied in each experiment, and the conditions are listed in Table 1. "Single" means a single nozzle with one hole at the bottom, and "Dual" means two nozzles with two holes. These two holes were either located "normal" to the incoming direction of the water, or "parallel" to the incoming direction (See Fig. 1). Distance between those two nozzles was varied as given in the Table 1.

Initially, 2.1 liter of the water was evenly filled in the vessel of two compartments. The bottom hole(s) was opened, then the water in the compartment B was drained. Subsequently, the water in the compartment A flew into the compartment B, and a vortex was created. Its formation and subsequent shape were recorded by a video camera by 30 frames per sec. Figure 2(a) shows an image taken from the recorded video for an experiment (Single11) where the vortex is clearly seen.

At the time of initial formation of the vortex, the height of the water was termed as "critical height" as mentioned earlier,

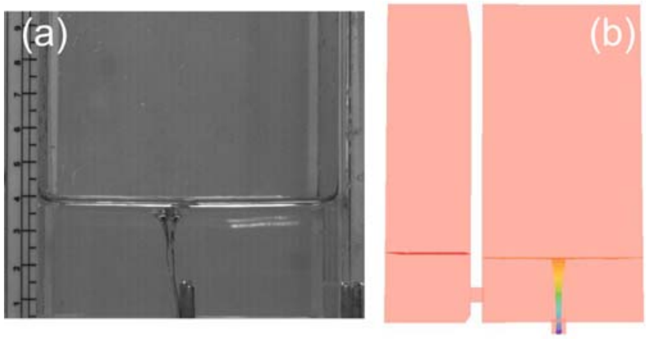

Fig. 2. Images captured for the vortex formation (a) in the water model experiment and (b) a numerical simulation for the case of Single11.

and it is listed in the Table 1 for each case. And total time taken to drain all the water from the vessel (t_{tot}) is also listed in the Table 1. The highest critical height was observed for the case of Single11. Also, total draining time for the Single 11 took more than the other cases. Decreasing size of the hole of the other single nozzle (Single10) decreased the critical height as well as the total draining time. The case of Dual-N-3 (two holes located the normal direction as far as 3 times of the hole diameter) resulted in zero critical height (vortex was not formed), and the case of Dual-P-3 (two holes located the parallel direction as far as 3 times of the hole diameter) resulted in the shortest draining time. Both observations suggest that dual nozzles are promising approach to suppress the vortex formation and to increase the productivity. In case of Dual-P-3, the vortex was initially formed at 35 mm, but it was soon disappeared and re-formed at 20 mm. Therefore, the critical height of this case was considered to be 20 mm.

Instantaneous flow rate of the water out of the vessel could be calculated from the measured data as: ((weight of the vessel at $t + \Delta t$) – (weight of the vessel at t))/Δt. It is seen by different total tapping time in each case that absolute flow rate in each case is also different, and this makes direct comparison difficult regarding flow patterns during tapping. Therefore, the flow rate of each case (Q) was normalize to its maximum flow rate (Q') in each case, and these normalized flow rate

Table 1. Various configurations employed in the water model experiment using the rectangular vessel, and results of the experiments (tapping time and critical height)

Name	Type	Hole Diameter (mm)	Center-to-Center Distance (mm)	Vortex Formation Time (sec)	Critical Height (mm)	Standard Deviation of Critical Height
Single11	Single	11	N/A	16	39	0.63
Single10		10		19	36	1.41
Dual-N-1	Dual	8	8	20	33	1.10
Dual-N-3	Normal		24	X	n.d.[a]	
Dual-P-1	Dual		8	19	36	0.63
Dual-P-3	Parallel		24	24	20[b]	

[a]Not determined because vortex was not formed.
[b]Vortex was initially formed at the height of 35 mm, but it was disappeared shortly.

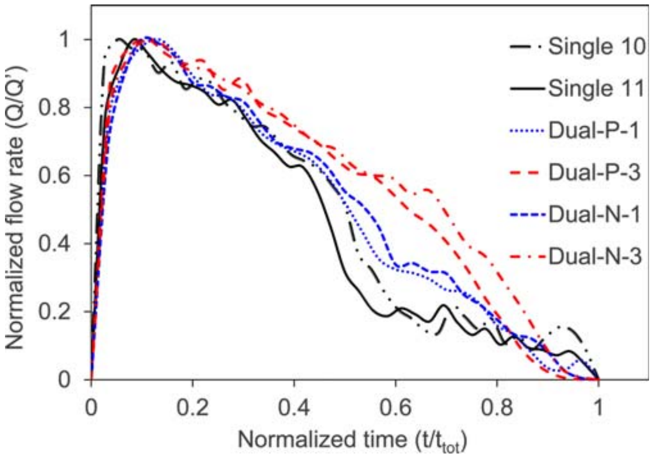

Fig. 3. Normalized flow rate measured in the rectangular water vessel, as functions of normalized draining time, for each case.

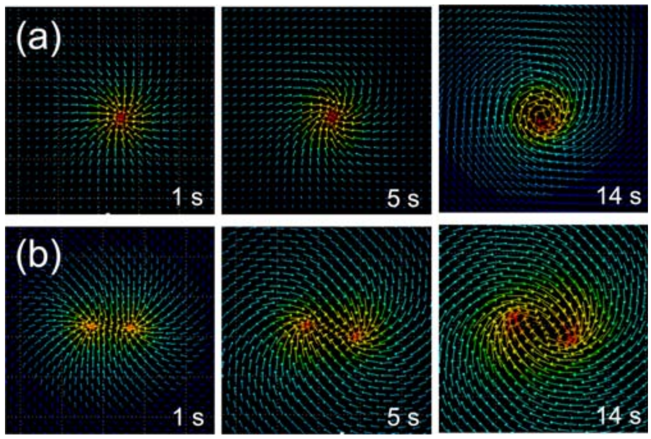

Fig. 4. Velocity vector field in (a) Single11 and (b) Dual-P-1, obtained by the numerical simulations. The results are captured at 2 mm above the bottom of the vessel. Times shown in lower-right corner represent duration time after the start of draining.

were shown at each time in Fig. 3. Decreasing (normalized) flow rate means slow draining of the water, resulting in increasing total tapping time. At a glance, two cases of single nozzle show sudden decrease of the Q/Q' around half time of the draining of the whole water. Dual nozzle cases show always higher Q/Q' than that of the single nozzle cases. It means that the sudden decrease of flow rate of dual nozzle appears later than that of single nozzle. Also the result shows that critical height of dual tapping system is always lower than single hole system. Among the dual nozzle cases, Dual-N-3 and Dual-P-3, where center-to-center distance of two nozzles were separated as far as 3 times of diameter of the hole, show higher Q/Q' than cases where the center-to-center distance was 1 time of diameter of the hole. Former two cases (3 times of diameter of the hole) did not show appreciable sudden decrease of the flow rate. This observation is consistent with the consideration of critical height that Dual-N-3 and Dual-P-3 showed 0 and 20 mm critical height, respectively. These are much lower than those of other cases. From these observations, it is concluded that dual nozzle suppresses the formation of free surface vortex, and longer distance between the two nozzle holes (3 times than 1 time) is favorable to suppress the formation of the vortex, although it is expected to exist an optimum distance for the two holes. This will be discussed in Sec. 3.4.

3.2. Water flow pattern in the rectangular vessel: numerical simulation

As described in Sec. 2.2, a series of numerical simulations were carried out in order to analyze water flow pattern in more detail. Primary purpose of the simulations was to confirm whether rotational momenta by twin vortexes cancel out each other. As seen in the Fig. 4, the velocity vector varies at each position in the vessel. Vector field at particular position, 2 mm above the bottom of the vessel, for the Single11 and the Dual-P-1 cases, respectively, are shown in Fig. 4. As time passed, the velocity around the hole increased in both cases to the tangential direction. In case of the single nozzle shown in the Fig. 4(a), the tangential velocity gradually increased. Such tangential velocity vector persists to the free surface, and it is responsible for the initiation of the free surface vortex. On the other hand, in case of the dual nozzle, the tangential velocity of the water flow near each hole increased as time passed. However, the velocity between the two holes is lower than that near the holes as seen in the Fig. 4(b). This is due to the collision between two tangential velocities of opposite directions, thus the two tangential momenta was cancelled. This cancelling effect persists to the surface of the water, and contributed to the suppression of the vortex formation.

Results of the numerical simulation were manipulated to provide flow rate of the water in the rectangular vessel, and one of the results for the case of Dual-P-1 is shown in Fig. 5. The flow rate of draining water out of the vessel is shown in the Fig. 3. The flow rate obtained from the numerical simulation shows very similar pattern to that of the water model experiment. Sudden decrease of the flow rate around 15 to 18 sec was observed in both results. Critical height obtained by the simulation was 37 mm, which is close to the value obtained by the water model experiment (39 mm). The numerical simulation thus also confirmed the decrease in the flow rate *via* the formation of free surface vortex.

3.3. Vorticity magnitude of the water flow

Vorticity magnitude (revolution per second) of the water flow may be considered as a measure to the vortex formation. Vorticity Magnitude is the magnitude of the vorticity vector. Vorticity is a measure of the rotation of a fluid element as it moves in the flow field, and is defined as the curl of the

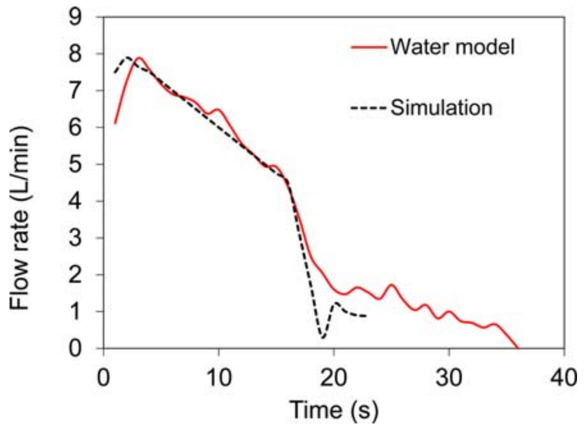

Fig. 5. Comparison of water draining obtained by the water model experiment and by the numerical simulation, for the case of Dual-P-1.

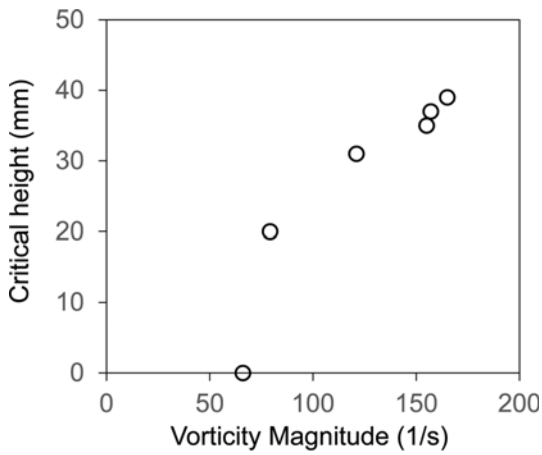

Fig. 6. Relationship between vorticity, extracted from the numerical simulation, and critical height, measured by the water model experiment, for 5(except Dual-N-3) cases considered in the present study.

velocity vector:

$$\xi = \nabla \times \vec{V} \tag{5}$$

Although it was not possible to obtain the vorticity during the water model experiment, it was extracted from the numerical simulation results. As the vorticity varies with time and location, it is necessary to discuss the vorticity unambiguously. Therefore, magnitude of the vorticity at a given location and time was chosen for each case, and it was used for finding a relationship between the vorticity and the critical height. After 20 sec, every simulation formed free surface vortex so every vorticity value is extracted at 20 sec and 2 mm above from the bottom. Figure 6 shows the relationship between the extracted vorticity magnitude and the measured critical height for the 5(except Dual-N-3) cases considered in the present study. As the vorticity above critical level may represent the initiation of real vortex, high vorticity magnitude would indicate high chance of the formation of the vortex, thereby causing high critical height. As seen in the Fig. 6, the experimentally obtained critical height shows strong correlation with the vorticity magnitude obtained from the numerical simulation. This suggests that numerical simulation for the water flow in a vessel may be utilized to the prediction of vortex formation at the free surface.

3.4. Dimensionless distance

Mazzaferro *et al*. [6] found that the critical height decreases as eccentricity increases. This implies that effect of dual tapping hole system proposed in the present study has to be attributed to two facts: canceling two vortexes as discussed in Sec. 3.2. and Sec. 3.3, and the eccentricity effect. In order to investigate these two effects independently, additional numerical simulation was carried out where the eccentricity plays an important role for the formation of vortex. A rectangular vessel was considered as shown in Fig. 1(c). Two holes (8 mm diameter) were places normal to the direction of the incoming flow. Distance between the two holes was varied from 8 mm to 40 mm at the interval of 8 (the diameter of the hole). For each case, vorticity was extracted from the numerical simulation, and was plotted as a function of a dimensionless distance (distance between the two holes divided by size of the vessel). The simulation result is shown in Fig. 7.

According to the report of Mazzaferro *et al*. [6], increasing the dimensionless distance (simply saying increasing distance between the two holes) always decreases the vorticity. If there were only one hole, increasing eccentricity would have decreased the vorticity. However, due to the additional vortex canceling effect, the suppression of the vortex formation was accelerated when there was such canceling effect. Of course, the effect could be expected when the two holes were separated within some distance. This is seen in the figure when d/D is less than approximately 0.25. This suggests that having dual nozzle is very effective to suppress the vortex formation via two independent effects. Further increas-

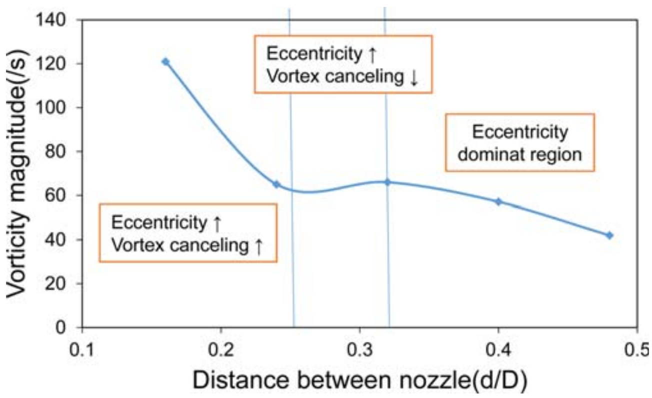

Fig. 7. Result of dimensionless analysis. Based on the vorticity analysis, effect of distance between nozzles has been checked.

ing the distance would lose the effect of the vortex canceling, while the eccentricity is still effectively working. Due to loss of the vortex canceling effect, overall vorticity does not decrease at higher d/D up to approximately 0.33 anymore. Further increase of d/D decreases again the vorticity, solely by the effect of eccentricity. The effect of two factors In short, the dual nozzle does work to suppress the vortex formation by coupling effects of vortex canceling with eccentricity effect.

3.5. Water model validation in real-shaped converter vessel

As was described in Sec. 2.3, additional validation of the above findings was carried out using a real shape converter vessel of 1/7.8 scale to the real converter. Shown in Fig. 8 are the photo of the real-shaped converter vessel, and an inclination pattern of the vessel in order to tap water inside the vessel. Titling of the vessel was controlled by motors installed in the equipment, and angle/speed for the tilting was decided by an operation condition in a steelmaking plant of POSCO. Flow rate of the water out of the vessel was monitored by a load cell. Single nozzle, dual nozzles aligned normal to the tilting direction, and dual nozzles aligned parallel to the tilting direction were tested. Distance between two nozzles were varied from 11 mm to 44 mm when dual-normal type was used, while 22 mm was used when dual-parallel type was used. Inner diameter of the single nozzle was 26 mm, and that of the dual nozzles was 22 mm. Reason why different diameter was used was already explained in Sec. 2.1. All the experiments were repeated 5 times and the obtained results were averaged, in order to get reliable data.

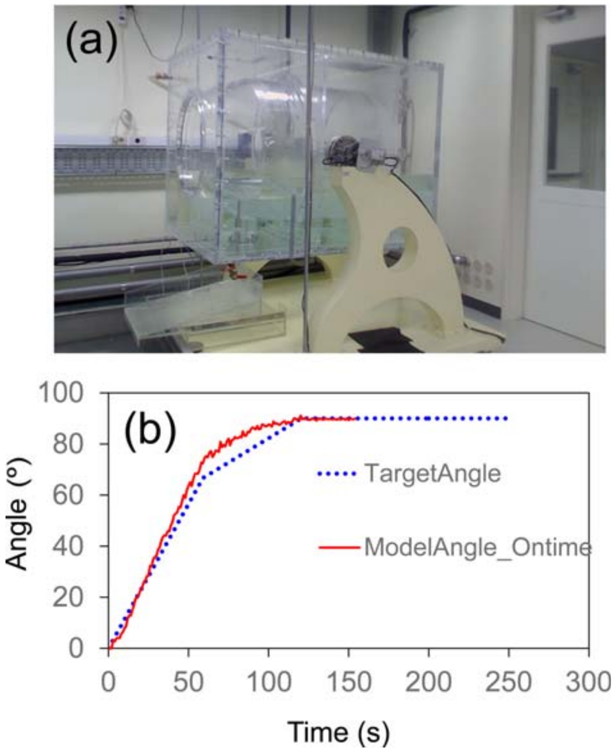

Fig. 8. (a) Real-shaped converter vessel used in the present study and (b) tilting pattern for converter vessel experiment. “TargetAngle” means setting value, and “ModelAngle_Ontime” is measured tilting pattern.

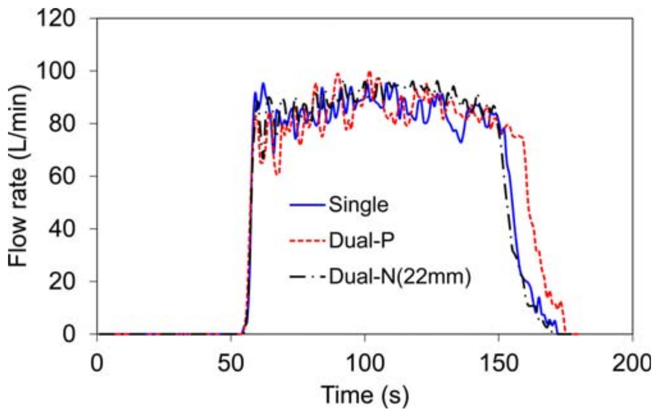

Fig. 9. Flow rate measured for real-shaped converter vessel experiment. No vortex was formed during tapping/draining of the water. Distance between dual nozzles for both cases (normal and parallel) was 22 mm.

Initiation of vortex was an important condition in the present validation test. Without any local momentum inside the water, no vortex was formed during the tapping of the water. When there was negligible local momentum in the water, flow rate was measured for each case, and it is shown in Fig. 9. During the tilting and tapping of the water, no vortex was formed. As shown in the figure, the flow rate measured for various cases (single nozzle and dual nozzles) was not noticeably different. This means that finding the present study is meaningful only when there is vortex formed during tapping/draining of liquid. However, this does not demerit the importance of the present study, because there is always intense fluid flow in the converter. This ensures the formation of vortex in the liquid steel during tapping process. Therefore, in the present study, a condition was set to intentionally induce the vortex. It was preliminarily tried to find such condition. It was found that 30 min after filling water inside the vessel, the water became too calm to induce any vortex during tapping of the water. Therefore, it was decided to wait for 10 min after filling the water, then tilting of the vessel was started.

Figure 10 shows critical height measured for the various cases (single, dual parallel, and dual normal with various distances between nozzles). Again, it is clearly seen that dual-nozzle cases resulted in lower critical height, than the single nozzle case. This subsequently resulted in less influence to the vortex formation. This figure also shows relationship between the critical height and distance between two nozzles in case of dual nozzles aligned normal to the tilting direction. Increasing the distance lowers the critical height, thereby suppressing the formation of free surface vortex. From the two water model experiments shown in Sec. 3.1 and this section, it is

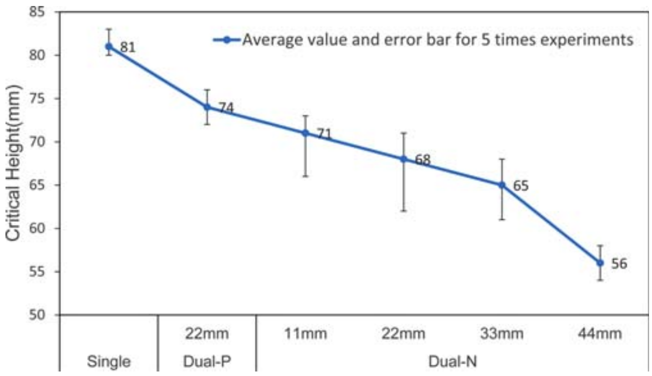

Fig. 10. Critical height measured in the real-shaped converter vessel experiment for various cases: Single, Dual-P, and Dual-N. Distance between dual nozzles are shown together.

concluded that dual nozzles are beneficial to suppress the vortex formation. Between two different configurations of dual nozzles, normal configuration is superior to parallel configuration in terms of low critical height. Moreover, increasing the distance between two nozzles decreased the critical height. From this observations, it is recommended to use dual nozzles aligned normal to the tilting direction of the converter, in order to minimize vortex formation of the liquid steel, and consequently to minimize slag carry over during tapping of the liquid steel.

4. CONCLUSION

Both water model experiments and numerical simulations were conducted in order to verify the effect of dual tapping hole system in converter. Results of both case were in good agreement with each other.

(1) Small scale water model experiment was conducted in order to figure out the effect of dual tapping hole system. In this experiment, effect of dual tapping hole system was clearly seen by checking both critical height and tapping time. Dual-N type was found to be better than Dual-P type. Also, longer distance between the two nozzle holes was favorable to suppress the free surface vortex.

(2) Vorticity magnitude was checked to figure out the effect of vortex canceling phenomena. Due to vortex canceling phenomena, vorticity magnitude was totally different according to the types of nozzles. Based on the vorticity magnitude from simulation, an optimized distance was suggested for the small vessel system. In order to suppress the vortex formation, it is desirable to control the distance between the two nozzles as far as possible. However, there's an ineffective range of distance. This corresponds to the case in the present study (Fig. 7), $0.25 < d/D < 0.33$.

(3) In the 1/7.8 scale-down converter model, the critical height difference was observed. The best case wass the Dual-N tapping system. Height difference is about 25 mm. Total tapping time decreases in case of Dual-N tapping about 9% compared with single tapping. Also critical height decreased about 30%. For the quality of steel, slag should be removed or not to entrain in the melt. Therefore, the productivity in steelmaking process may be improved by employing dual tapping hole system.

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