Development of Swirling-flow Submerged Entry Nozzles for Slab Casting

Yuichi TSUKAGUCHI,[1] Hiroshi HAYASHI,[2] Hidenori KURIMOTO,[3] Shinichiro YOKOYA,[4] Katsukiyo MARUKAWA[5] and Toshihiro TANAKA[6]

1) Corporate R&D Labs., Sumitomo Metal Industries, Ltd., 16-1 Sunayama, Kamisu, Ibaraki 314-0255 Japan.
2) Sumikin Iron & Steel Corp., 1850 Minato, Wakayama 640-8555 Japan. 3) Steel Making Department, Kashima Works, Steel Sheet, Plate, Titanium & Structure Steel Company, Sumitomo Metal Industries, Ltd., 3 Hikari, Kashima, Ibaraki 314-0014 Japan. 4) Division of Applied Process Metallurgy, KTH, SE-100 44 Stockholm, Sweden.
5) Sumitomo Metal Industries, Ltd., 5-33-4 Katahama, Chuo-ku, Osaka 541-0041 Japan.
6) Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871 Japan.

(*Received on December 24, 2009; accepted on March 5, 2010; originally published in Tetsu-to-Hagané, Vol. 95, 2009, No. 1, pp. 33–42*)

We began development of swirling-flow submerged entry nozzles in 1997 as a fundamental and effective measure for controlling the flow pattern in continuous casting molds. As a first step, we developed a swirling-flow submerged entry nozzle for round billet casting at the Wakayama works. We then began developing swirling-flow submerged entry nozzles for slab casting. The main purpose of the present work was to demonstrate that the formation of swirling flow in submerged entry nozzle improves productivity and the quality of products in continuous casting. We examined swirling-flow submerged entry nozzles with a swirl blade in these main bodies because such an arrangement is the easiest way to apply swirling flow to submerged entry nozzles in continuous casters without investment by facilities. We had only to change the submerged entry nozzle in the experiment. Swirling-flow submerged entry nozzles for slab casting were developed and their operation examined at the Wakayama and Kashima works. It was found that the proposed submerged entry nozzles increased the casting speed and improved the surface quality of slabs and steel sheets.

KEY WORDS: continuous casting; submerged entry nozzle; swirling flow; surface quality; casting speed.

1. Introduction

The generation of swirling flow in a submerged entry nozzle is a fundamental way to stabilize flow in a continuous casting mold. The swirling-flow submerged entry nozzle can improve the surface quality of slabs and steel coils and increase the casting speed by increasing flow stability in the mold. We have researched the technology of swirling flow in a submerged entry nozzle to prove its effectiveness in continuous casting.[1–8] The final goal of our research has been to prove the effect of swirling flow in a submerged entry nozzle for slab casting by applying submerged entry nozzles with a swirl blade equipped inside the nozzle to existing continuous casting machines. This is the easiest way to apply swirling flow to a submerged entry nozzle for continuous casting without additional investment by facilities. An additional aim of our research has been to match the effect of electromagnetic devices. Since the flow swirling in a submerged entry nozzle uses only the energy of the head difference between a tundish and mold, this swirling flow technology is an energy-saving means to improve flow in the continuous casting mold without the use of electromagnetic devices, which generally cost several hundred million yen.

The development of submerged entry nozzles with swirling flow for continuous casters in steelmaking works started with investigation of the durability of the swirl blade and intensity of swirling flow in the multi-strand round billet caster since the risk to casting operation and the quality of products for round billets was considered relatively small.[9,10] The development of this technology for slab casters then began. Before the technology was applied to slab casters, we carried out water model experiments and CFD simulations to design the swirl blade and the internal geometry of the submerged entry nozzle and obtain information on the suitable consumption of head energy between the tundish and mold; the shape of the outlet ports could then be designed to produce stable and appropriate flow in the mold.[11–13]

In this paper, swirling-flow submerged entry nozzles were designed, then evaluated in a water model experiment and applied to industrial slab casters. The application involves casting ultra-low carbon steel for galvanized automotive panels, which allows for evaluation of the swirling flow in the case of one of the most stringent grades of steel sheet in terms of surface quality.

2. Problems with the Conventional Nozzle and Advantages of the Swirling-flow Nozzle

First, problems with conventional submerged entry nozzle are summarized to clarify the purpose of developing the submerged entry nozzle with swirling flow. Generally, conventional submerged entry is problematic in terms of flow in the nozzle for slab casters as stated below.

In a conventional submerged entry nozzle, a downward flow in the nozzle changes direction by colliding with the bottom of the nozzle. The flow then spouts out mainly from the lower region of the outlet ports, which causes a strong flow in the lower region and a suction flow in the upper region of the outlet ports. The strong flow in the lower region of the ports causes fluctuations in the molten steel surface in the mold. In addition, the downward flow colliding with the bottom of the nozzle turns upward and produces vertical fluctuations in the angle of the outlet flow from the ports.

On the other hand, wobbly downward flow in the nozzle affects the balance of the flow rates of two flows spouting from two outlet ports at the bottom of the nozzle. The fluctuation of the outlet flow angle and the imbalance of the outlet flow rates result in self-excited flow oscillation in the mold. The flow oscillation in the mold causes a Karman vortex on the weak-flow side as shown in **Fig. 1**(a). The Karman vortex and the suction flow in the upper region of the outlet ports draw down mold powder into the molten steel and thus form mold powder defects in products. Furthermore, the fluctuation of the molten steel surface in the mold is promoted on the strong-flow side, and the molten steel flow rate decreases on the weak-flow side. A decrease in the casting speed is required to suppress the molten steel surface fluctuation on the strong-flow side, which induces flow stagnation on the weak-flow side. The flow stagnation decreases the Saffman effect[14–16)] as the flow velocity decreases at the front of the solidified shell and reduces the surface temperature of molten steel in the mold; these phenomena give rise to entrapment of inclusions or bubbles in the solidified shell. The problems mentioned above are schematically shown in Fig. 1.

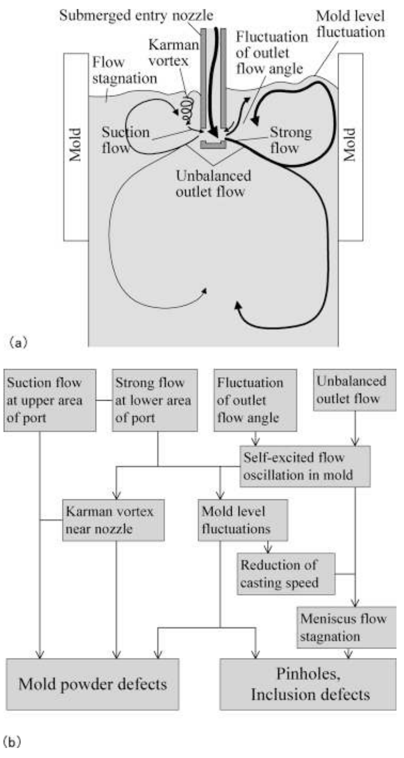

Fig. 1. Bad influences of conventional nozzle.

The purpose of developing the submerged entry nozzle with swirling flow is to effectively address the problems stated above for the conventional submerged entry nozzle. Specifically, in the case of the submerged entry nozzle with swirling flow, the centrifugal force acting on molten steel inside the main body of the nozzle promotes outlet flow from the upper region of the outlet ports, and the distribution of the outlet flow velocity becomes homogeneous, which prevents suction flow in the upper region of the ports, as shown in **Fig. 2**. Furthermore, the centrifugal force acting in the nozzle promotes a balanced distribution of the outlet flows from the two ports at the bottom of the nozzle. As stated above, the submerged entry nozzle with swirling flow restrains the self-excited flow oscillation in the mold and thus prevents molten steel surface fluctuation and flow stagnation.

3. Water Model Experiment

3.1. Experiment Conditions and Specification of a Submerged Entry Nozzle

Before commencing an industrial-scale experiment for steel casting by slab casters, we confirmed the fundamental operation of the submerged entry nozzles with swirling flow for the conventional nozzles in full-scale water model experiments.

Table 1 gives the experimental conditions of the full-scale water model experiments and **Figs. 3** and **4** are schematic diagrams of the full-scale water models. These are models of casters in the works at Wakayama and Kashima respectively. The flow velocity was measured by a laser Doppler velocimeter in the case of the Wakayama model and by a small propeller velocimeter, 3 mm in diam-

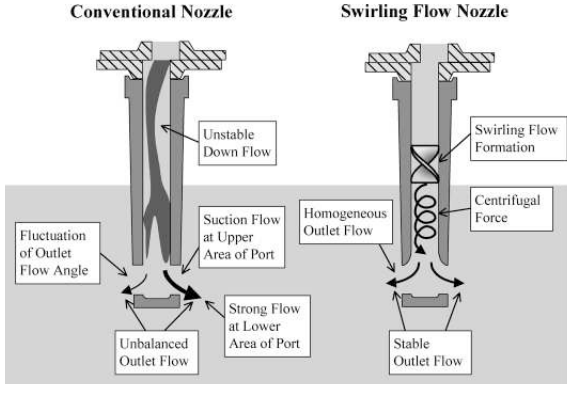

Fig. 2. Schematic view of flow formation in nozzle.

Table 1. Water model specification and condition.

	Wakayama caster	Kashima caster
Scale	1/1	1/1
Mold size	210 × 1850 (mm)	270 × 1650 (mm)
Bath depth	1850 (mm)	2315 (mm)
Corresponding casting speed	1.6 – 2.0 (m/min)	1.5 (m/min)

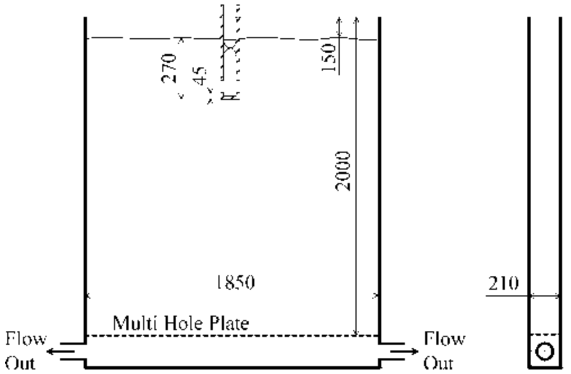

Fig. 3. Schematic geometry of water model set-up (Wakayama).

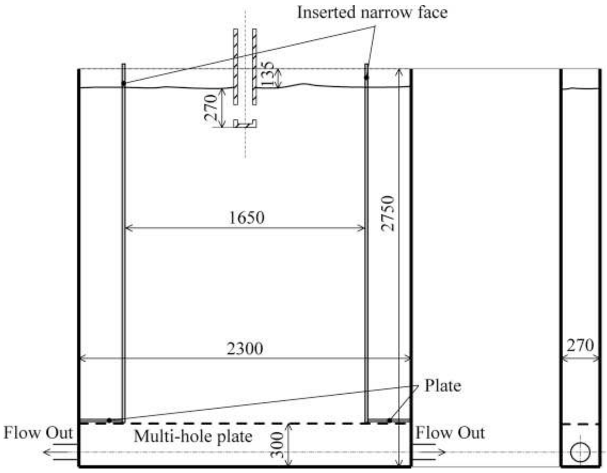

Fig. 4. Schematic geometry of water model set-up (Kashima).

Table 2. Specification of swirling flow nozzles.

	Wakayama caster	Kashima caster
Internal diameter D_1 (Diameter of swirl blade)	100 (mm)	123 (mm)
Internal diameter D_2	80 (mm)	98 (mm)
Length of swirl blade L	100 (mm)	163 (mm)
Twist angle of swirl blade θ	120 (°)	175 (°)
Cross-section of outlet port	55w×90h (mm)	55w×90h (mm)
Upper wall shape of outlet port	R60 (mm)	R90 (mm)
Lower wall angle of outlet port	Upward 10 (°)	Upward 10 (°)

eter in the case of the Kashima model. The sampling pitch of the measured velocity data was 2.6 ms for the laser Doppler velocimeter and 0.5 s for the small propeller velocimeter.

Table 2 and **Figs. 5** and **6** present specifications of the submerged entry nozzles with swirling flow. The nozzles around the outlet ports have an outer diameter of 140 mm for the Wakayama caster and 161 mm for the Kashima caster.

Table 3 gives the specifications of the conventional submerged entry nozzles. The nozzles have a uniform internal diameter. The outlet ports are rectangular, and the upper wall and lower wall of the outlet ports are sloped at the same constant angle. The nozzles around the outlet ports have an outer diameter of 140 mm for the Wakayama caster and 150 mm for the Kashima caster.

Figure 7 is a schematic diagram of the conventional submerged entry nozzle for the Wakayama caster as an example. The nozzles for the Wakayama and Kashima casters have basin-shaped internal bases as shown in Fig. 7. The basin depth is between 10 and 15 mm, which is designated as the vertical distance between the line of intersection of the internal surface of the main nozzle body with the lower wall of the outlet ports and the internal base.

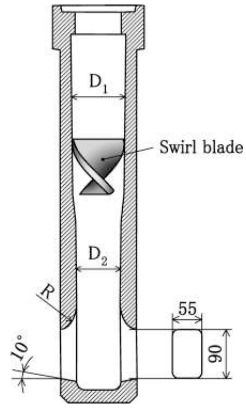

Fig. 5. Dimension of swirling flow nozzle.

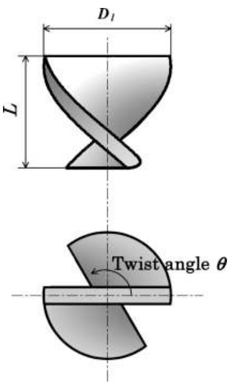

Fig. 6. Dimension of swirl blade.

Table 3. Specification of conventional nozzles.

	Wakayama caster	Kashima caster
Internal diameter	80 (mm)	83 (mm)
Cross-section of outlet port	55w×90h (mm)	90w×92h (mm)
Upper wall angle of outlet port	Upward 10 (°)	Downward 30 (°)
Lower wall angle of outlet port	Upward 10 (°)	Downward 30 (°)

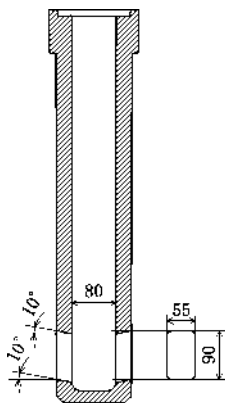

Fig. 7. Dimension of conventional nozzle (Wakayama).

3.2. Experiment Results

3.2.1. Flow Velocity at the Outlet Port

Figure 8 shows the horizontal flow velocity at the outlet port of the conventional submerged entry nozzle for the Wakayama caster. The flow velocity at the outlet port was measured in a vertical plane 5 mm from the outlet port. The nine measurement points in Fig. 8 are the intersections of three vertical and three horizontal positions of the outlet port. The three vertical positions are at non-dimensional widths of −0.3, 0 and 0.3 and the three horizontal positions are at non-dimensional heights of 0.2, 0.5 and 0.8. The bar height in Fig. 8 shows the average value of the measured flow rate for 3 min at each point.

As seen in the upper region of Fig. 8, there is a vortex in the outlet ports. In addition, the vortex visibly changes direction owing to unstable downward flow in the main nozzle body. Figure 8 shows the flow velocity at the outlet port in each case of the rotational direction of the vortex. The same vortex in the outlet ports was reported by Bai *et al.*,[17] Ramos-Banderas *et al.*[18] and Yoshida *et al.*[19]

Figure 8 shows that the flow velocity distribution at the outlet port is influenced by the rotational direction of the vortex. For example, in the case that the rotational direction of the vortex is clockwise (left side of Fig. 8), the outlet flow velocity in the lower-right region is relatively high where the downward flow collides with the internal base of the nozzle. On the other hand, the outlet flow velocities in the lower-left and upper-right regions are relatively low. Considering the fluctuation of the outlet flow velocity, suction flow may well occur in the region in which the outlet flow velocity is relatively low. In the case that the rotational direction of the vortex is counter-clockwise, the outlet flow distribution has a left–right reversed pattern.

The vortex changes its rotating direction owing to the unstable downward flow in the main nozzle body. Accordingly, the real outlet flow is estimated to fluctuate between the two outlet flow distribution patterns shown in Fig. 8. Meanwhile, in the case of the conventional submerged entry nozzle for the Kashima caster, no vortex in the outlet ports is observed; thus, the vortex in the outlet ports is thought to be due to the narrow width of the outlet ports. In other words, the downward flow in the nozzle colliding with the internal base generates the vortex prior to flowing out from the outlet ports in the case that the width of outlet port is narrower than the internal diameter of the nozzle.

Figure 9 shows the horizontal flow velocity at the outlet port of the submerged entry nozzle with swirling flow for the Wakayama caster. As shown in Fig. 9, the outlet flow velocity for the submerged entry nozzle with swirling flow is homogeneous over the entire area of the outlet port. As a result of the homogeneous outlet flow, the measured maximal outlet flow velocity is approximately half that of the conventional submerged entry nozzle.

Figure 10 shows the horizontal outlet flow velocity distribution of the conventional submerged entry nozzle for the Kashima caster. The bar height length in Fig. 10 shows the average value of the measured flow rate for 3 min at each point.

In the case of the conventional submerged entry nozzle for the Kashima caster, for which the width of the outlet ports is larger than the internal diameter, no vortex in the outlet ports is observed. Accordingly, the vortex does not affect the outlet flow distribution. On the other hand, the outlet flow is concentrated to the lower region of the ports; therefore, there is suction flow at the centers and in the upper regions of the ports.

Figure 11 shows the horizontal flow velocity at the outlet

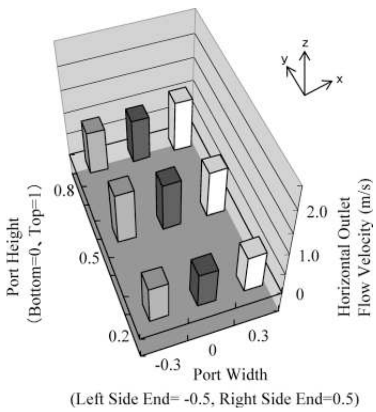

Fig. 9. Outlet flow velocity distributions of swirling flow nozzle (Wakayama, corresponding casting speed = 1.6 m/min).

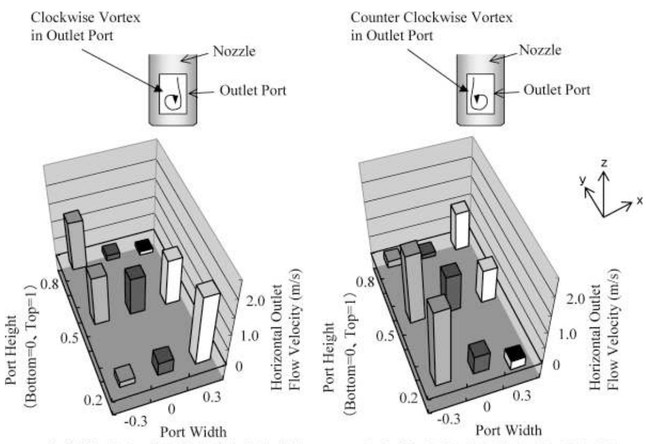

Fig. 8. Outlet flow velocity distributions of conventional nozzle under two directions of vortex in port (Wakayama, corresponding casting speed = 1.6 m/min).

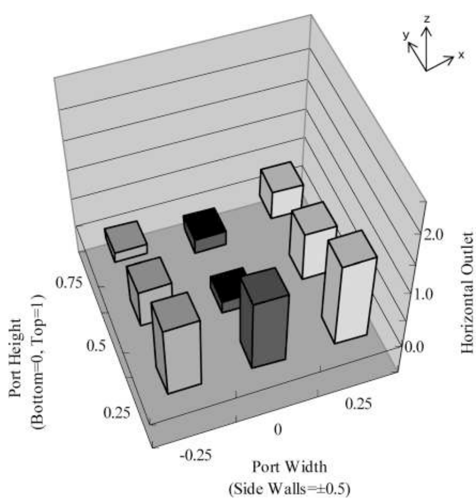

Fig. 10. Outlet flow velocity distributions of conventional nozzle (Kashima, corresponding casting speed = 1.5 m/min).

port of the submerged entry nozzle with swirling flow for the Kashima caster. As seen in Fig. 11, the outlet flow velocity of the submerged entry nozzle with swirling flow is more homogeneous over the entire area of the outlet port than that of the conventional submerged entry nozzle. The outlet flow velocity in the upper region of the port is higher than that in the lower region of the port in Fig. 11 because the centrifugal force generates a dominant extended flow along the R-shaped upper wall of the port.

Figure 12 shows the average standard deviations of the flow velocity data obtained at each point in Figs. 8, 9, 10 and 11 as an index of the outlet flow stability. Data in the case of the clock-wise vortex in the outlet port are adopted from Fig. 8. As clear seen in Fig. 12, the outlet flows of the submerged entry nozzles with swirling flow are more stable than those of the conventional submerged entry nozzles. Specifically, the submerged entry nozzles with swirling flow are effective in terms of both a homogeneous outlet flow distribution and stable outlet flow velocity.

3.2.2. Flow in the Mold

The horizontal surface flow velocity along the wide face of the mold was measured at 1/2 thickness, 1/4 or 3/4 width, and 50 mm below the fluid surface in the mold. **Figures 13** and **14** show the transitions of the surface flow velocity for the conventional nozzles and submerged entry nozzles with swirling flow for the Wakayama and Kashima casters respectively. The surface flow velocity is measured at 1/4 width of the mold with the laser Doppler velocimeter for the Wakayama caster and at both 1/4 and 3/4 width with the small propeller velocimeter for the Kashima caster. Data presented in Figs. 13, 14 and **Fig. 15** are averages for 5 s and thus exclude instantaneous fluctuations of the velocity caused by small vortexes. In these figures, positive values on the vertical axis indicate surface flow in the direction from the narrow face of the mold to the submerged entry nozzle.

Figure 13 shows that fluctuation of the surface flow velocity decreases approximately by half with application of

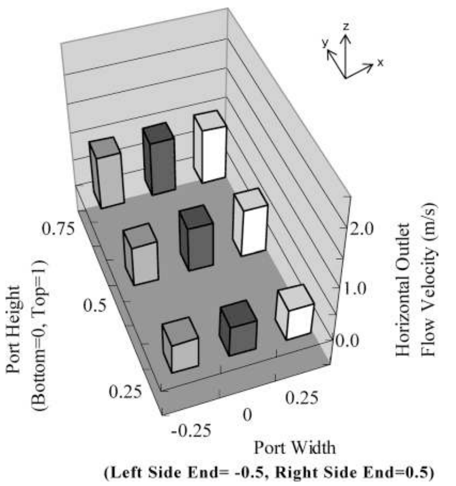

Fig. 11. Outlet flow velocity distributions of swirling flow nozzle (Kashima, corresponding casting speed=1.5 m/min).

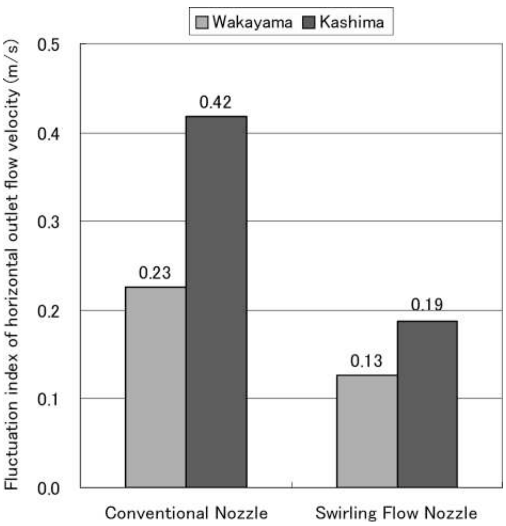

Fig. 12. Effect of swirling flow nozzle on stability of outlet flow velocity.

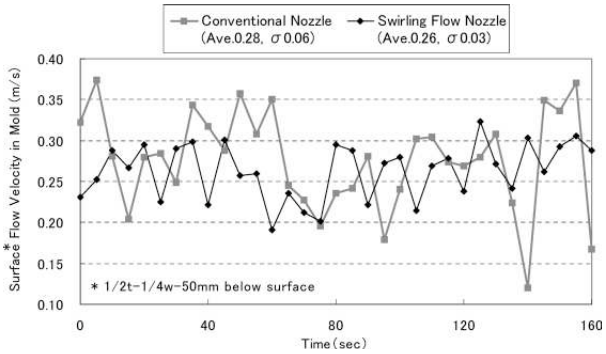

Fig. 13. Effect of swirling flow nozzle on surface flow stability in mold (Wakayama, corresponding casting speed=1.6 m/min).

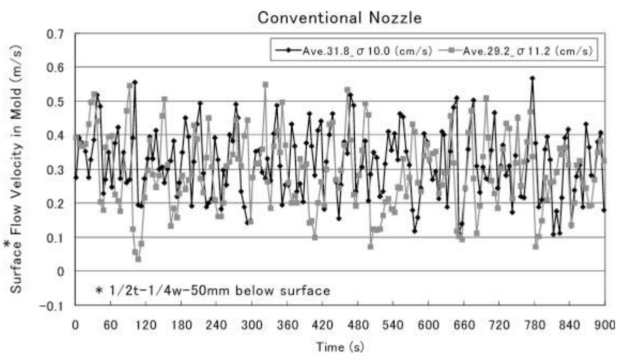

Fig. 14. Transition of surface flow velocity with conventional nozzle (Kashima, corresponding casting speed=1.5 m/min).

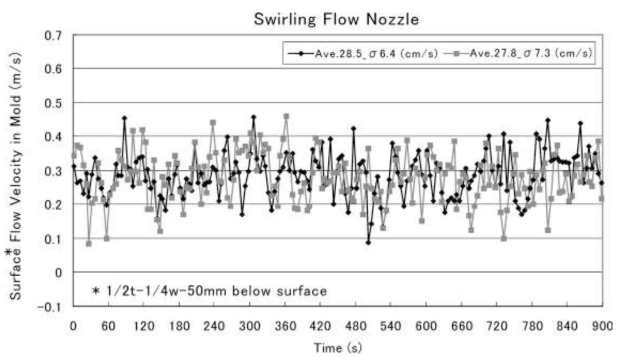

Fig. 15. Transition of surface flow velocity with swirling flow nozzle (Kashima, corresponding casting speed=1.5 m/min).

the submerged entry nozzle with swirling flow for the Wakayama caster. In this case, the conventional submerged entry nozzle has an upward outlet port angle; however, the actual outlet flow has a downward angle, and thus, there is a double-roll flow pattern[13] in the mold in which the surface flow is directed from the narrow face of the mold to the submerged entry nozzle.

As seen in Figs. 14 and 15, the submerged entry nozzle with swirling flow for the Kashima caster also made 30% decrease in fluctuation of the surface flow velocity.

As mentioned above, the submerged entry nozzles with swirling flow for both the Wakayama and Kashima casters reduce the fluctuation of the surface flow velocity since the swirling flow in the submerged entry nozzles has the effect of stabilizing the molten steel flow in the mold as we had expected.

The surface flow velocities for the Wakayama caster are measured for a short duration because of the limited data storage of the laser Doppler velocimeter. On the other hand, the surface flow velocities for the Kashima caster are measured for a relatively long duration; accordingly, the effect of the submerged entry nozzle with swirling flow in stabilizing the flow formation in the mold is thought to be well evaluated for the casting condition of the Kashima caster.

Figure 16 shows the ratio of time in which all surface flow velocity data in Figs. 13, 14 and 15 are in the proper range of 0.2–0.3 m/s. In addition, the ratio of time in which the surface flow velocity is in the range of 0.1–0.4 m/s is also shown in Fig. 16. The time ratio of the proper surface flow velocity is greater for the swirling-flow submerged entry nozzle as shown in Fig. 16.

Considering that the actual rate of surface defects detected on steel sheets is several percent at most, the time ratio of the proper range of the surface flow velocity—56% in the case of the conventional submerged entry nozzle—is relatively small. This means that 44% of the slab surface is cast under a poor condition of the surface flow velocity. This value of 44% seems too large when compared with the small surface defect rate of several percent. If the proper range of the surface flow velocity is wider than the above mentioned range (for example, if 0.1–0.4 m/s is the real proper range), the time ratio of the proper range of the surface flow velocity increases to 89% in the case of the conventional submerged entry nozzle. In this case, the ratio of casting time under the poor condition of the surface flow velocity is 11%. This is not much larger than the actual surface defect rate. From this viewpoint, the proper range of the surface flow velocity of 0.2–0.3 m/s is considered to be too small. The reason may be that the conventionally reported range of 0.2–0.3 m/s is an average value for a long duration, whereas all data in Figs. 13, 14 and 15 are averaged over the relatively short duration of 5 s; that is, the proper range of the surface flow velocity must be wider than the conventionally reported range when we focus on data averaged over a short duration. However, it is difficult to define the proper range of the surface flow velocity by strictly comparing only the time ratio of the proper surface flow velocity with the surface defect rate of the steel sheets since surface defects are caused by many factors in a complicated manner.

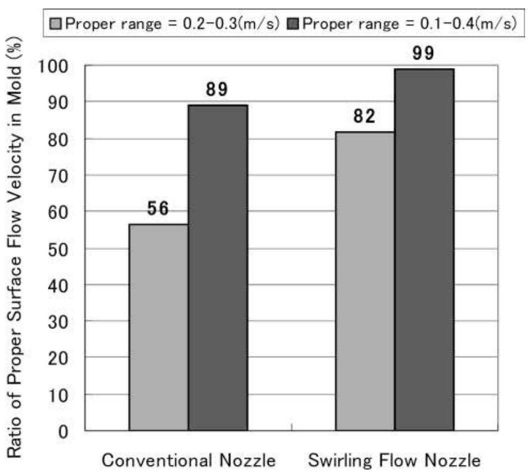

Fig. 16. Effect of swirling flow nozzle on flow velocity control in mold.

4. Examination of the Slab Caster

4.1. Casting Conditions and Specifications of the Submerged Entry Nozzle

As the next step of development of the submerged entry nozzles with swirling flow, the nozzles were applied to industrial slab continuous casting in steel works to investigate the effects of stabilizing flow in a mold and improvements of the surface quality of slabs and steel sheets.

Casting conditions in the Wakayama and Kashima works are given in **Tables 4** and **5**. Ultra-low carbon steel for galvanized steel panels of automobiles, one of the most severe steel grades in terms of surface quality, was selected for the examination. In the case of casting with the submerged entry nozzles with swirling flow, the effect of stabilizing flow was estimated in the mold. Accordingly, we could cast at higher speed with the submerged entry nozzles with swirling flow.

The submerged entry nozzles have the same dimensions as those in the water model experiment. The material of the main body and swirl blade is alumina–graphite.

4.2. Results of Casting Examination

4.2.1. Flow in the Mold

Figures 17 and **18** show the mold level fluctuations

Table 4. Casting condition (Wakayama).

Items	Specifications	
Mold Size (mm)	210t × 1780–1880w	
Steel Grade	Ultra Low Carbon Steel for Automobile Panels	
Casting Speed	Swirling Flow Nozzle	Max. 1.5–1.8 m/min.
	Conventional Nozzle	Max. 1.3 m/min.

Table 5. Casting condition (Kashima).

Items	Specifications	
Mold Size (mm)	270t × 1500–1625w	
Steel Grade	Ultra Low Carbon Steel for Automobile Panels	
Casting Speed	Swirling Flow Nozzle	Max. 1.4–1.6 m/min.
	Conventional Nozzle	Max. 1.4 m/min.

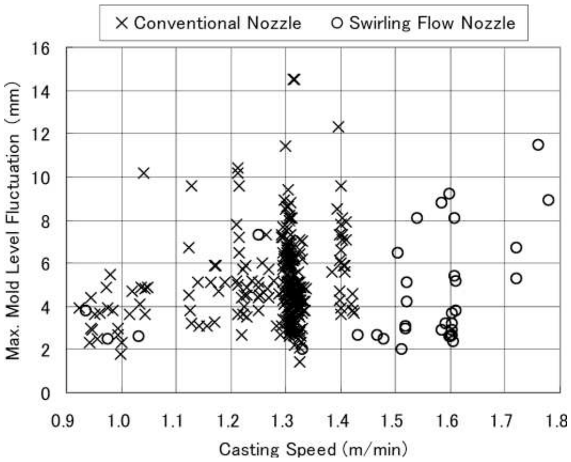

Fig. 17. Effect of swirling flow nozzle on mold level fluctuation (Wakayama).

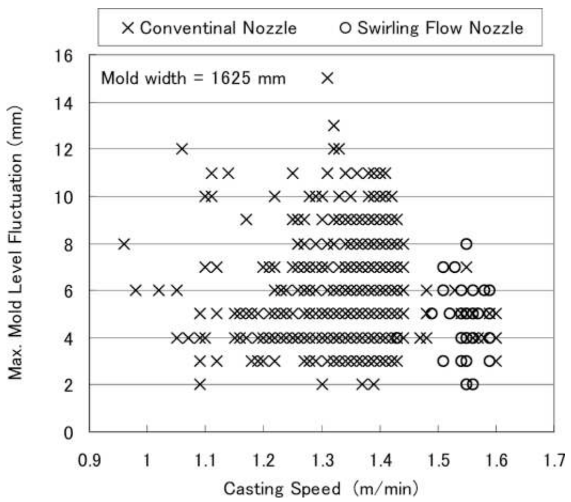

Fig. 18. Effect of swirling flow nozzle on mold level fluctuation (Kashima).

against casting speeds at the Wakayama and Kashima works to estimate the effects of stabilizing the flow in the mold that the submerged entry nozzles with swirling flow would have. The mold level fluctuation in these figures is the difference between the lowest and highest mold levels during one slab casting. The cycle time of a mold level fluctuation is 10–30 s in general. This cycle time is significantly less than the casting time for one slab, which is between 4 and 7 min.

Both Figs. 17 and 18 show that mold level fluctuations are well controlled to lower fluctuations with the submerged entry nozzles with swirling flow despite the higher casting speeds. The mold level is measured by an eddy current sensor and controlled by PID controller so that it can be kept at a target level. The results in Figs. 17 and 18 show that mold level fluctuations were especially high at higher casting speed in the case of conventional submerged entry nozzles. The origin of mold level fluctuations are the self-excited flow oscillation or the wavy molten steel surface produced by the strong outlet flow from the ports as shown in Fig. 1. The submerged entry nozzles with swirling flow restrain these origins of the mold level fluctuation as we had expected.

The effect of the submerged entry nozzle with swirling flow on the flow balance fluctuation in the mold is shown in **Fig. 19**. The flow balance fluctuation index σ_H is a standard deviation of the flow balance index H, which is calculated from the cooling intensity of each narrow face of the mold. The flow balance index is a parameter of the self-excited flow oscillation in the mold. As seen in Fig. 19, the submerged entry nozzle with swirling flow effectively restrain the self-excited flow oscillation, which is one of the origins of the mold level fluctuation.

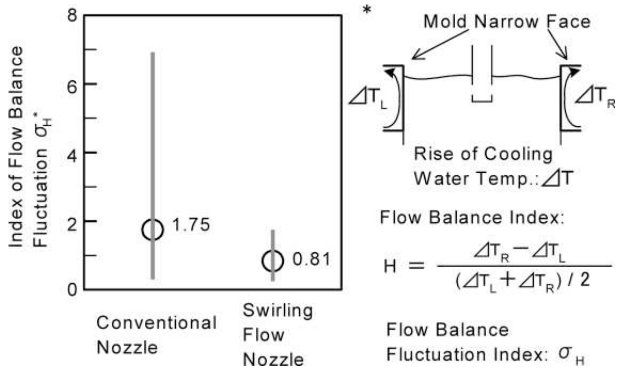

Fig. 19. Effect of swirling flow on stable flow formation in mold (Wakayama).

4.2.2. Surface Quality of Slabs and Steel Sheets

(1) Pinholes in Slabs

Figure 20 shows the rejection rate for slabs produced at Wakayama due to pinhole formation on the slab subsurface, which is observed after 1.5 mm surface scarfing. **Figure 21** shows the effect of the submerged entry nozzle with swirling flow in reducing the number of pinholes on slabs produced at Kashima. The entire surfaces of slabs were scarfed by a machine to a depth of 2.5 mm and then areas 60 mm in width were scarfed to a maximum depth of 1 mm with a hand torch along each of 1/2 width line, 1/4 width line and 3/4 width line. Subsequently, the pinholes were counted on slabs. Accordingly, the number of pinholes in a slab at 2.5–3.5 mm depth was estimated.

As shown in Figs. 20 and 21, pinholes in the slab subsurface are remarkably reduced by applying the submerged entry nozzles with swirling flow. This is thought to be due to the nozzles achieving a proper surface flow velocity in the mold and thus preventing the entrapment of bubbles on the solidified shell.

(2) Surface Defects on a Steel Sheet

Figure 22 compares the rates of sliver defects on coils of galvanized steel sheets produced at Wakayama between the cases of submerged entry nozzle with swirling flow and conventional nozzle. Galvanized steel sheets were produced from slabs through hot strip, cold strip and galvanizing processes and then inspected so that defect areas of the coils could be cut off. The surface defect rate index in Fig. 22 shows the weight ratio of the cut-off area of coils due to slab defects such as pinholes and inclusions. As seen in the figure, the application of the submerged entry nozzle with swirling flow reduced the rate of surface defects to 1/5 of the rate in the case of using conventional nozzle.

In the same manner, **Fig. 23** shows the rate of surface defect on coils of galvanized steel sheet at Kashima. The

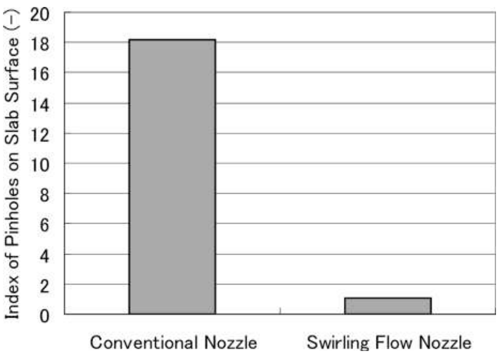

Fig. 20. Effect of swirling flow nozzle on pinholes on slab surface (Wakayama).

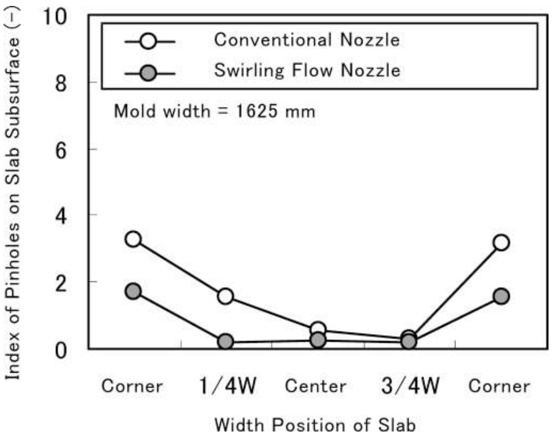

Fig. 21. Effect of swirling flow nozzle on pinholes on slab surface (Kashima).

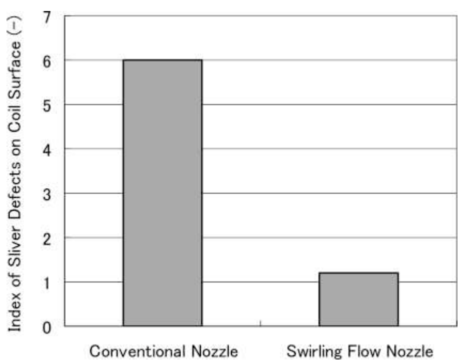

Fig. 22. Effect of swirling flow on surface quality of coils (Wakayama).

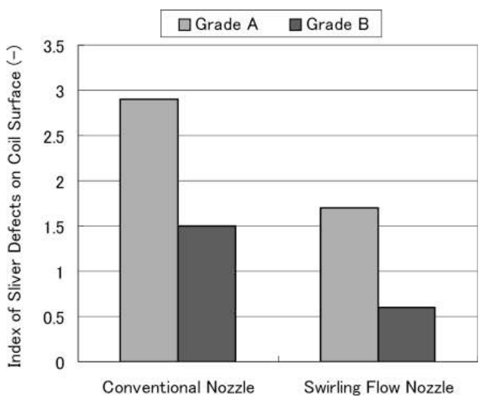

Fig. 23. Effect of swirling flow on surface quality of coils (Kashima).

counted number of surface defects induced by pinholes or inclusions of slabs is indicated in the figure.

As seen in Fig. 23, the defects on the galvanized steel sheet decreased by half with the application of the submerged entry nozzle with swirling flow.

(3) Conclusion on Surface Quality

The effect of the submerged entry nozzles with swirling flow in stabilizing the flow in the mold was illustrated by the above-mentioned improvements in the surface quality of slabs and steel sheets, which matches the effects of electromagnetic flow-control devices in molds.[22–24)]

4.2.3. Outlet Port Clogging of the Submerged Entry Nozzle

The areas of the outlet ports after approximately 450 t of steel casting are shown in **Fig. 24** for the submerged entry nozzle and conventional nozzle, and **Fig. 25** shows the internal views of the outlet ports. Originally, the outlet ports of the two kinds of nozzles were of the same size. As is clear from Figs. 24 and 25, clogging of the outlet port is effectively prevented by the swirling flow in the submerged entry nozzle. This is because the outlet flow is homogenous and stable in the case of the submerged entry nozzle with swirling flow as shown in Figs. 8 and 9, and this prevents vortex formation and flow stagnation at the outlet ports that are responsible for the adhesion of non-metallic inclusions.

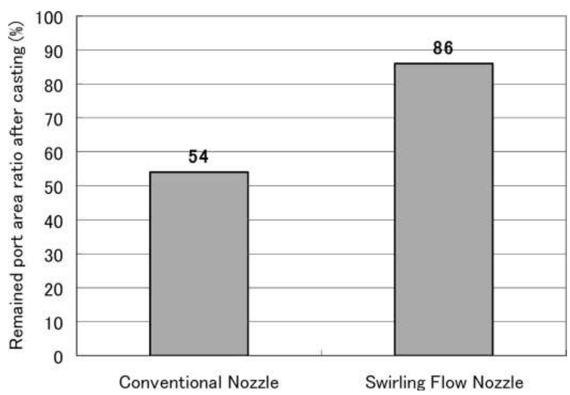

Fig. 24. Effect of swirling flow on prevention of outlet port clogging.

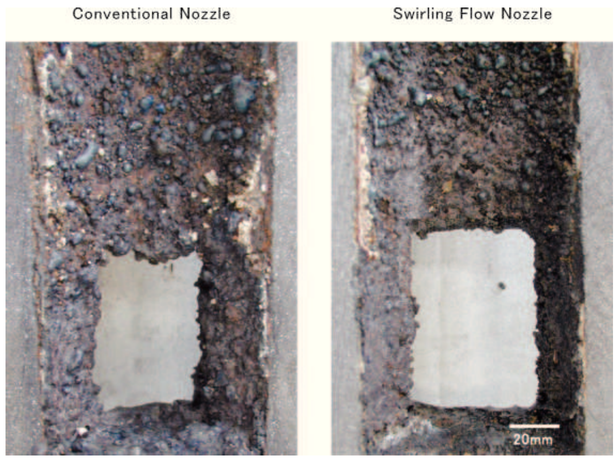

Fig. 25. Comparison of internal view of port after casting (Wakayama).

Prevention of outlet port clogging makes the outlet flow stable during the entire casting period, which is effective in stabilizing the surface quality of slabs and steel sheets.

5. Conclusion

The submerged entry nozzles with swirling flow for slab casting were designed and evaluated in full-scale water model experiments and industrial casting examinations at the Wakayama and Kashima works. These experiments clearly showed that the combination of the swirling flow generation with proper intensity in the submerged entry nozzle and adequate design of the outlet ports improves the stability of flow in the mold remarkably, and reduces surface defects on slabs and steel sheets of ultra low-carbon steel destined to be galvanized automobile panels, which are one of the most severe grades of steel. The submerged entry nozzles with swirling flow were designed on the basis of previous research.[11–13] The effect using the submerged entry nozzles with swirling flow was comparable to that of using electromagnetic flow control devices in a mold.[22–24]

This work has been the first development of submerged entry nozzles with swirling flow that employs a twisted blade. We achieved our initial goal of the nozzle development in verifying the effectiveness of the swirling flow generation in submerged entry nozzle as a fundamental measurement to stabilize the molten steel flow in the mold. The results of this research clearly indicate the importance of flow control in the submerged entry nozzle, which has notable influence on flow stability in the mold.

The twisted blade as a swirling-flow generator has been the most suitable way to evaluate the effect of swirling flow in that only the submerged entry nozzle needs to be replaced in an industrial continuous caster. However, this is not a fully-satisfied device to generate swirling flow because it has low energy efficiency of 20% which results in the limited swirling flow intensity[11] and its long-term use brings on the clogging of nonmetallic inclusions.

With the development of a new technology to generate swirling flow without drawbacks, the benefits of the swirling-flow generation in a submerged entry nozzle may be applied widely in continuous casting.

REFERENCES

1) S. Yokoya, S. Takagi, Y. Tsukaguchi, M. Iguchi, S. Hara and K. Marukawa: *CAMP-ISIJ*, **15** (2002), 160.
2) S. Furuhashi, M. Kawamoto, T. Kato, S. Hiraki and Y. Tsukaguchi: *CAMP-ISIJ*, **15** (2002), 161.
3) H. Hayashi, Y. Tsukaguchi, K. Iwata, K. Nonobe and S. Yokoya: *CAMP-ISIJ*, **15** (2002), 162.
4) S. Ohtani, S. Yokoya, S. Takagi, Y. Tsukaguchi, S. Hara and K. Marukawa: *CAMP-ISIJ*, **15** (2002), 163.
5) T. Harada, Y. Tsukaguchi, S. Yokoya, S. Takagi, S. Hara and K. Marukawa: *CAMP-ISIJ*, **15** (2002), 164.
6) Y. Tsukaguchi, K. Nonobe, S. Yokoya, S. Takagi, S. Hara and K. Marukawa: *CAMP-ISIJ*, **15** (2002), 165.
7) Y. Tsukaguchi, T. Watanabe, S. Yokoya, S. Hara, K. Marukawa and K. Nonobe: *CAMP-ISIJ*, **15** (2002), 839.
8) S. Kosaka, M. Yoshiwara, H. Hayashi, K. Iwata, Y. Tsukaguchi and S. Yokoya: *CAMP-ISIJ*, **16** (2003), 949.
9) Y. Tsukaguchi, M. Kawamoto and S. Furuhashi: *ISIJ Int.*, **44** (2004), 350.
10) Y. Tsukaguchi, H. Hayashi, S. Yokoya, T. Tanaka and S. Hara: *Tetsu-to-Hagané*, **93** (2007), 575.
11) Y. Tsukaguchi, O. Nakamura, P. Jönsson, S. Yokoya, T. Tanaka and S. Hara: *ISIJ Int.*, **47** (2007), 1436.
12) Y. Tsukaguchi, O. Nakamura, S. Yokoya and S. Takagi: *Tetsu-to-Hagané*, **91** (2005), 245.
13) Y. Tsukaguchi, O. Nakamura, S. Yokoya and S. Takagi: *Tetsu-to-Hagané*, **91** (2005), 581.
14) Y. Ohtani, J. Fukuda, A. Kiyose, T. Kawase, J. Nakashima and K. Nakamura: Proc. of 1st. Int. Cong. on Science and Tech. of Steelmaking (ICS'96), ISIJ, Japan, (1996), 97.
15) W. Yamada, A. Kiyose, J. Nakashima, J. Fukuda, K. Okazawa and K. Miyazawa: *CAMP-ISIJ*, **12** (1999), 682.
16) T. Tou, T. Imoto, Y. Konno, H. Kondo, H. Yamamura, M. Wakoh, E. Takeuchi and A. Itou: *CAMP-ISIJ*, **14** (2001), 13.
17) H. Bai and B. G. Thomas: Material Processing in the Computer Age III, (2000), 86.
18) A. Ramos-Banderas, R. D. Morales, R. Sanchez-Perez, L. Garcia-Demedices and G. Solorio-Diaz: *Int. J. Multiphase Flow*, **31** (2005), 643.
19) J. Yoshida, M. Morishita and T. Mimura: *CAMP-ISIJ*, **21** (2008), 87.
20) K. U. Koehler, P. Andrzejewski, E. Julius and H. Haubrich: Proc. of 78th ISS Steelmaking Conf., (1995), 397.
21) T. Tokonami, Y. Onoe, K. Matsuo, H. Tai, M. Morishita, H. Yasunaka and K. Ayata: *CAMP-ISIJ*, **9** (1996), 606.
22) M. Morishita, H. Mori, R. Suzuki, K. Miyake, T. Nakaoka and Y. Hosokawa: *CAMP-ISIJ*, **14** (2001), 6.
23) A. Idogawa, Y. Kitano and H. Tozawa: *Kawasaki Steel Giho*, **28** (1996), No. 1, 46.
24) J. Kubota, N. Kubo, M. Suzuki, T. Ishii, R. Nishimachi and N. Aramaki: *Tetsu-to-Hagané*, **86** (2000), 271.