

REPORT

Development of Compact Submerged Entry Nozzle Shape for Thin- and Medium-Thick Slabs

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Abstract

Submerged entry nozzles for thin- and medium-thick slab continuous casting machines, which have been widely applied in recent years, consist of a cylindrical inlet section and a thinly spread, flat submerged section, which easily causes unbalanced outlet flow and poses an issue in terms of quality improvement of cast slabs. In addition, if the flat section is extremely wide, the weight increases, and handling becomes an issue. In this study, we developed a design that can eliminate mold level fluctuations and biased flow conditions while making the flat section compact. By keeping the inner bore cross-sectional area of the flattened section approximately 1.5 times that of the upper cylindrical section, the flat part can be made compact. The DiA design was applied to the outlet port, with the upper face angled downward and the lower face angled slightly upward or horizontally. This port design further reduced the meniscus velocity and the mold level fluctuations. It was also found that the introduction of a concave-step geometry in the upper cylindrical section eliminates the biased flow condition during inflow. We applied these developed geometries to actual equipment and confirmed their effectiveness in reducing the mold level fluctuation and biased flow conditions in the mold.

1. Introduction

In the process of continuous casting of steel, a general slab is poured into a thick mold of 200 mm or more, whereas a slab poured into a thin mold of 150 mm or less is called a thin- or medium-thick slab. For general slabs, the slab is first cooled, then it is reheated and rolled thinner. On the other hand, since the original thickness of thin- or medium-thick slabs is thin, it is possible to omit the rough rolling of the hot rolling process, so there is merit in greatly reducing energy consumption and manufacturing cost. Accordingly, it can be said that continuous casting of thin- and medium-thick slabs is a process attracting attention from the viewpoint of energy consumption reduction (CO₂ reduction). Therefore,

these thin- and medium-thick slab continuous casting machines are expanding not only at conventional blast furnace and electric furnace manufacturers in North America and China, but also in emerging countries such as India and Vietnam in recent years¹⁾.

Since the thickness of a thin- and medium-thick slab is approximately 50 % or less than that of a general slab, if the same throughput is attempted to be maintained, the casting speed increases by a factor of two or more, resulting in so-called high-speed casting. Therefore, the increase in molten steel surface velocity (increase in meniscus velocity) is likely to cause casting instability, such as increased mold level fluctuation. A.P. Rogler reported on recent changes in the shape of submerged entry nozzles

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(SENs) for thin- and medium-thick slabs, in which the inlet section is cylindrical, and the submerged section has a flat design with extremely wide lateral width²⁾. This is likely the result of stabilizing the flow in the mold (reduction of meniscus velocity) by increasing the inner bore cross-sectional area of the submerged part, under the constraint that the depth cannot be expanded due to the thin mold thickness (Fig. 1). However, this flat SEN is susceptible to uneven flow on either side of the mold because the wide shape of the flat SEN causes molten steel to be discharged without eliminating the biased flow that occurs in the inner bore (Fig. 2). This leads to deterioration of cast slab quality for steel grades that are sensitive to cracking. The wide shape also increases weight and makes handling difficult.

Thus, in the casting of thin- and medium-thick

slabs, it is important to ① maintain stable flow in the mold and ② improve cast slab quality. To achieve these goals, a stepped SEN with a protrusion (convex step) in the inner bore has been developed for general slabs and is achieving success in various places^{3,4)}. However, since SENs for thin- and medium-thick slabs have a large flat shape, it is difficult to introduce the convex step for suppressing the biased flow in the inner bore. Furthermore, it is difficult to reduce the cross-sectional area of the flat portion because it leads to increased meniscus flow velocity and molten metal surface fluctuations.

This paper reports the features and results of newly developed SENs for thin- and medium-thick slabs tested on-site which suppress mold level fluctuations and biased flow in the mold by making the large flat submerged part more compact.

2. Relationship Between Inner Bore Diameter and Meniscus Flow Velocity for Flat SENs

Niitsuma et al. examined the relationship between the flat inner bore cross-sectional area ratio and meniscus velocity in flat SENs⁵⁾. Fig. 3 shows an

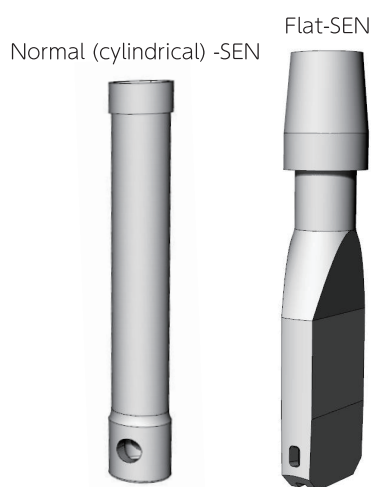


Fig. 1 Schematic design of flat SEN.

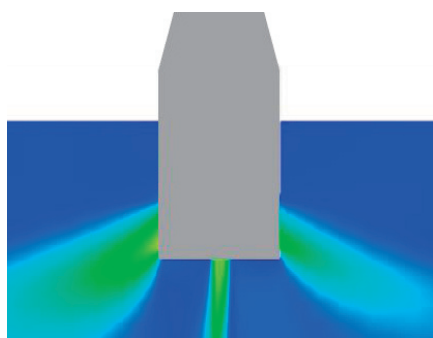


Fig. 2 Past studies of CFD. (example of biased flow)

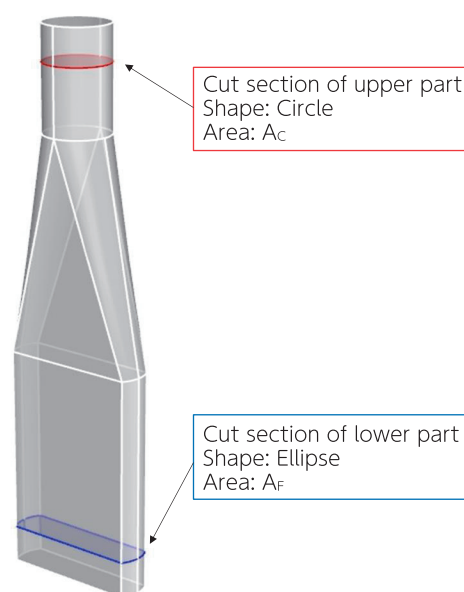


Fig. 3 Inner bore structure of flat SEN. (except outlet ports)

example of the inner bore shape of a flat SEN. Computational Fluid Dynamics (CFD) calculations were performed for four flat SEN shapes ($A_f/A_c=0.6, 0.9, 1.1,$ and 1.4), where the cross-sectional area of the lower flat part is A_f and that of the upper cylindrical part is A_c , while A_c remained fixed and A_f varied. Calculations were performed with a mold size of 100×1600 mm and a throughput of $4.0 \text{ tons} \cdot \text{min}^{-1}$, and maximum meniscus flow velocities were compared. The results are shown in Fig. 4; from Fig. 4, a negative correlation was observed between A_f/A_c and meniscus flow velocity when A_f/A_c was less than 1.0. Since the flow in the flat SEN inner bore is incompressible, the continuity equation from fluid mechanics (Eq. 1) holds true.

$$\nabla \cdot \mathbf{v} = 0 \dots\dots\dots (1)$$

Given the areas A_c and A_f of the two sections in Fig. 3 and if the respective average velocities when passing through each section, denoted as v_c and v_f , are assumed to be in steady state, then Eq. 2 holds true.

$$v_c \cdot A_c = v_f \cdot A_f \dots\dots\dots (2)$$

As shown in Eq. 2, the flow velocity in the SEN inner bore is affected by the cross-sectional area. Therefore, when A_f/A_c is smaller than 1.0, the inner bore flow velocity increases due to the decreased cross-sectional area of the flat section, resulting in an increase in the outlet flow velocity. On the other hand, when A_f/A_c is greater than or equal to 1.1, the effect on meniscus flow velocity is small. Thus, although the cross-sectional area of the flat section

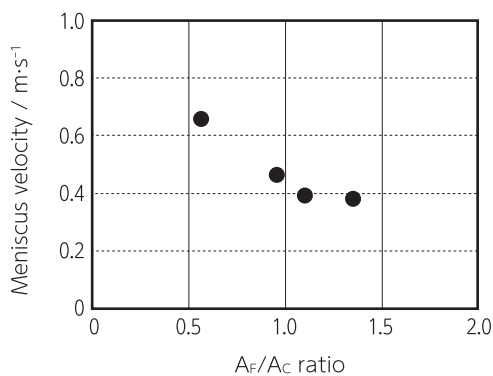


Fig. 4 The relationship between A_f/A_c ratio and meniscus velocity.

affects the flow velocity in the inner bore, if A_f/A_c is larger than 1.1, the effect on the flow in the mold is negligible, so there is no need to excessively increase the width of the submerged section. For example, if $A_f/A_c = 1.5$ for an SEN with an upper inner diameter of 80–90 mm, the flat part width would be approximately 260 mm. This value is smaller and more compact than conventional nozzles. On the other hand, the meniscus flow velocity tends to be fast at about $0.4 \text{ m} \cdot \text{s}^{-1}$, as shown in Fig. 4. Therefore, we investigated the shape of the outlet port with the goal of achieving a meniscus value of $0.3 \text{ m} \cdot \text{s}^{-1}$ or less (general slab velocity level in water model experiments, Mizukami et al.⁶⁾) with an A_f/A_c value of around 1.5, and we also adjusted the geometry of the inner bore to eliminate biased flow. The results are reported below.

3. Experiments

3. 1 Examination of outlet port design (Application of DiA port)

Fig. 5 shows the flat SEN outlet port shapes examined in this study. Both have an A_f/A_c value of 1.6. Both Shape 1 and Shape 2 have a total of four outlet ports each, one on each side, and two on the bottom. Although the lateral outlet ports of Shape 1 are angled downward, Shape 2 adopts the “DiA (Different Angle)” structure⁷⁾ in which the lower faces of the lateral outlet ports are angled upward. CFD calculations were carried out under the conditions of $4.5 \text{ m} \cdot \text{min}^{-1}$ casting speed and 130 mm mold thickness. The calculation program used was PHOENICS, a commercially available fluid calculation program, the turbulence model was the

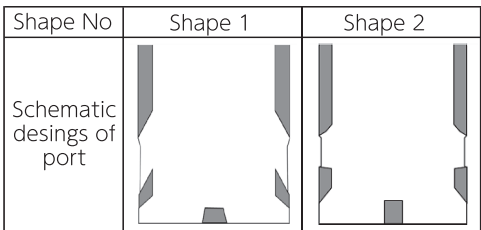


Fig. 5 Outlet port of flat SEN.

built-in $k-\varepsilon$ model, and steady-state calculations were performed under all conditions. These are the same calculation conditions as those used in the past⁸⁾.

3. 2 Investigation of elimination of biased flow

Although many results have been obtained by developing a step structure for suppressing biased flow in general slab SEN inner bores, it is difficult to create convex steps in the flat section of a flat SEN. Therefore, we focused on the cylindrical part of the upper bore and considered introducing a concave step in that part. The schematic diagram examined is shown in Fig. 6. The concave step has a length that runs from just below the mating area

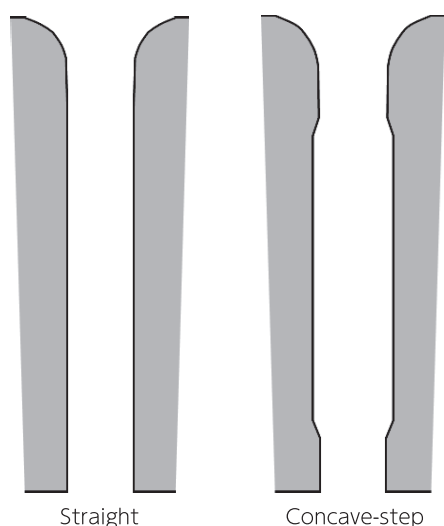


Fig. 6 Schematic diagram comparing straight and concave-step SEN.

of the internal SEN to near the underside of the TD steel shell bottom from which the SEN protrudes, and the underside of this concave step has a somewhat straight section. In this CFD calculation, the horizontal cross section of the inner bore at the top end of the SEN was used as the inlet plane, and fluid was introduced at an angle of 30 degrees to the normal of the inlet plane to generate a biased flow condition in the SEN inner bore. A comparison with normal inlet flow (flow parallel to the normal direction of the inlet face) is shown in Fig. 7. The meniscus velocities were calculated using two types of nozzles, shown in Fig. 6, and two inlet flow conditions, one parallel to and the other inclined 30 degrees to the normal direction of the inlet plane. Table 1 shows a summary of the experimental parameters.

4. Experimental Result

4. 1 Outlet port design (DiA port)

Fig. 8 shows the results of the CFD calculations. By using the DiA design for the lateral outlet ports, the meniscus velocity was reduced to less than $0.3 \text{ m}\cdot\text{s}^{-1}$. In Shape 1, where the lateral outlet ports are angled downward, the flow from the lateral outlet port merges with the flow from the bottom port, while with the DiA design of Shape 2, a divergent flow was formed after discharge. As a result, the large and strong loop flow created in Shape 1 by the merging of the strong and fast outlet flow from the lateral and bottom ports reached the surface, making

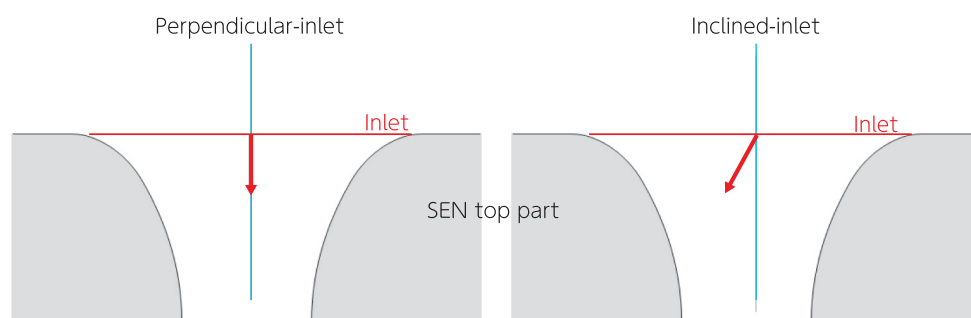


Fig. 7 Calculation setting of inclined inlet.

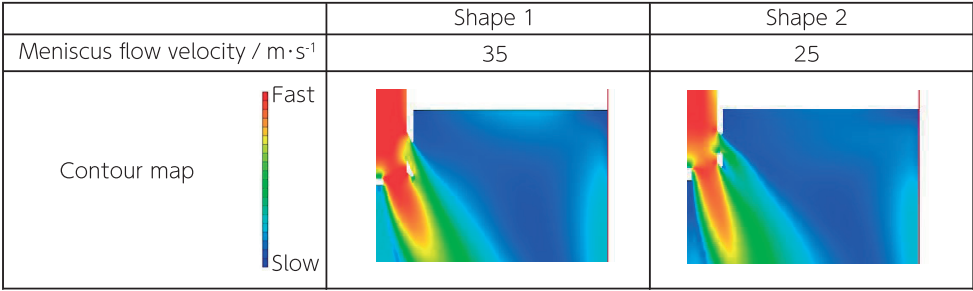


Fig. 8 Results of CFD.

Table 2 Effect of concave-step to suppress biased flow

	Calc. 3-1	Calc. 3-2	Calc. 3-3	Calc. 3-4
Bore shape	Shape 3 (straight)		Shape 4 (concave-step)	
Inlet angle	Perpendicular	30° inclined	Perpendicular	30° inclined
Velocity difference / $\text{m}\cdot\text{s}^{-1}$	0.02	0.12	0.01	0.03

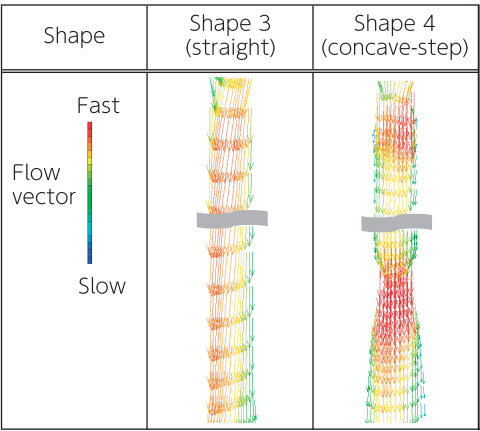


Fig. 9 Flow vector of inner bore. (Calc. 3-2, Calc. 3-4).

the meniscus velocity high; in contrast, the outlet flow in Shape 2 was dispersed and the loop flow weakened, which is considered to have reduced the meniscus velocity.

4. 2 Biased flow-eliminating geometry (concave step)

Table 2 shows the difference in meniscus velocities between the left and right sides obtained by CFD calculations of the nozzle with the biased

flow-eliminating geometry (concave step). When the inflow condition was parallel to the normal direction of inlet plane (Calc. 3-1, Calc. 3-3), no lateral differences in meniscus velocity were observed between Shape 3 with a straight inner bore and Shape 4 with an applied concave step. On the other hand, when the flow was forced into the nozzle bore at an angle of 30 degrees with respect to the normal direction to generate biased flow (Calc. 3-2, Calc. 3-4), Shape 3 showed a lateral difference in the meniscus flow velocity, while Shape 4 showed almost no difference.

The inner bore vector diagrams from Calc. 3-2 and Calc. 3-4 are shown in Fig. 9 to compare the flow conditions when passing through the concave step. In Shape 3 with the straight inner bore, the flow is directed downward along the inner bore wall. In Shape 4 with the applied concave step, the flow diffused at the upper end of the concave step (where the inner bore diameter expands), and the flow re-concentrated at the lower end (where the inner bore returns to its original diameter), thus confirming that the biased flow within the inner bore was alleviated. It is thought that this biased

flow suppression caused the resulting lack of lateral flow difference in the mold.

5. Actual Results

Fig. 10 shows an example of actual usage (Steelworks A) in which the biased flow condition in the mold was improved by an SEN with a concave step. Fig. 10 shows the maximum, average, and minimum values of the difference between the mold coolant temperatures on the right and left sides of the mold. Compared with that of the conventional product, the maximum, average and the minimum temperature differences recorded during casting using the nozzle with a concave step were close to zero. This result shows that in the mold using the conventional

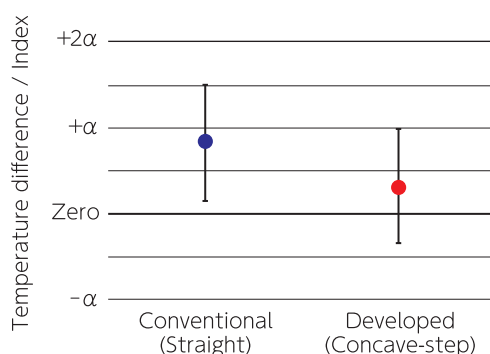


Fig. 10 Measuring results of cooling-water temperature difference.

nozzle, more heat (outlet flow) is always supplied to one side, generating a biased state. On the other hand, for an SEN with a concave step, the biased flow condition is eliminated thanks to the uniform heat supplied to the narrow sides of the mold.

At Steelworks B, a flat SEN with a concave step + DiA ports was used, resulting in a reduction of melt surface level fluctuations and stable in-mold flow was obtained.

Furthermore, as a result of using a compact flat SEN ($A_f/A_c = 1.2$) with DiA ports at Steelworks C, it obtained a track record of casting without requiring previously needed electromagnetic braking. The use of the developed compact flat SEN in thin- and medium-thick slab continuous casting machines at various locations has resulted in stabilization of the molten surface level inside the mold and suppression of biased flow.

6. Summary

Regarding SENs for thin- and medium-thick slabs, which are expected to be increasingly adopted overseas in the future, by creating a concave step at the top and optimizing the shape of the outlet ports, we have developed an SEN with a more compact flat section that was proven in both simulation and on-site usage to suppress molten surface level fluctuations and biased flow inside the mold.

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