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technical note

Physical Modeling of Steel Delivery during Thin Slab Continuous Casting

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Abstract

A full scale physical model of a thin slab caster with a four-hole design submerged entry nozzle (SEN) was constructed. On the basis of the dimensionless Reynolds and Froude similitude criteria, the fluid flow in a full-scale model is similar to that of the actual system and, hence, the data obtained from the water model can be applied to the actual system. In order to determine the optimum operational parameters, experiments were carried out under different casting conditions. The results showed that the four-hole nozzle design leads to a special flow pattern. It was also shown that increased casting speed and gas injection both resulted in surface turbulence. In order to avoid surface turbulence and the related casting problems, it is recommended that SEN depths of 30 and 40 cm be used for casting speeds of 3.5 and 4.5 m/min, respectively.

Keywords: Continuous casting, Thin slab, Water model, Optimization.

1- Introduction

Thin slab continuous casting (TSCC) process is nowadays inclined to minimal continuous casting plants. The continuous casting of thin slabs with only a few centimeters of thickness allows hot-direct rolling to be performed inline with a conventional finishing mill, eliminating the roughing mill. This advanced continuous-casting technology of thin slabs is growing in the steel industry owing to the associated savings in capital cost, energy, and manpower1).

In a typical TSCC machine, molten steel flows due to gravity, from a holding tundish down through the submerged entry nozzle (SEN) to a water-cooled oscillatory mold. Due to the physical properties of steel in the machine and the magnitude of the liquid velocity involved, the fluid flow in this process is essentially complex, involving 3-Dimensional turbulent liquid flow and solute transport 2,3). The flow pattern in the mold greatly influences the quality of the final product. Unsuitable fluid flow can create problems such as breakouts, meniscus freezing defects, mold slag entrapment, and entrapment of inclusion and bubbles 4). Water modeling of the process is a useful tool for understanding the complexities of the fluid flow in the mold and submold regions. Physical models are basically constructed, and in the case of water models used as cold models, to simulate the fluid mechanics behavior of the real hot and opaque system. By applying relevant similitude criteria from a fluid dynamics point of view, the water model will behave similar to the real system (prototype), allowing experiments to be performed by the cold model and visualizations and measurements to be carried out. Defining problems, recommending changes for the actual production unit, and assessing the effect of implementation on product quality are the results of water modeling 5). A physical model is highly instructive, but the data obtained are useful only if the physical similarity between the model and the prototype is duly observed. Many studies have been conducted 6-8) that strongly suggest the similarity of the fluid flows in the two systems and, thus, the applicability of the data obtained from the water model to the actual system. These similarities are, therefore, taken for granted here with no more discussion to save space except to say that they do exist. Using the evidence from F. Kemeny et al.9) , we maintain that a full scale model based on the dimensionless Reynolds and Froude similitude criteria is appropriate if the regions being modeled do not contain a two-phase (gas-liquid) flow or dispersed falling streams. It has been proven that the similitude between the full scale model and the actual steel system is maintained for 10):

1. Fluid flow behavior imparted by rising gas,
2. Pouring streams through various nozzles and under various flow conditions with corresponding surface areas indicating similar air entrainments,
3. Surface waves initiated by incoming streams, similar in shape and size,
4. Stream penetration depth for turbulent and laminar flows, and

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5. Residence time measurements.

These factors, coupled with the ability to use actual casting devices (i.e. nozzle, stopper, rods, etc), enable us to evaluate the effects of modifications to these devices on casting parameters without having to consider a scale factor.

In 2002, Saba Steel Complex started its hot charge with an EAF steelmaking process for casting thin slabs. The aim of the present work is to investigate the flow behavior in the mold region of the mentioned process. The full scale water model of the system has been calibrated and the optimum operational parameters have been determined.

2- Slab caster description

Figure 1 shows the schematic representation of the funnel-shaped mold and submold regions of the caster. The caster is an ISP type including a tundish system, a water-cooled mold, a secondary cooling system, soft reduction segments, a holding furnace, and the rolling equipment. In the soft reduction segments, the slab thickness is partially reduced while the core of the slab is still liquid. The mold of the caster has a flexible width in order to cast thin slabs with different widths. The geometric parameters of the mold and submold regions are listed in Table1.

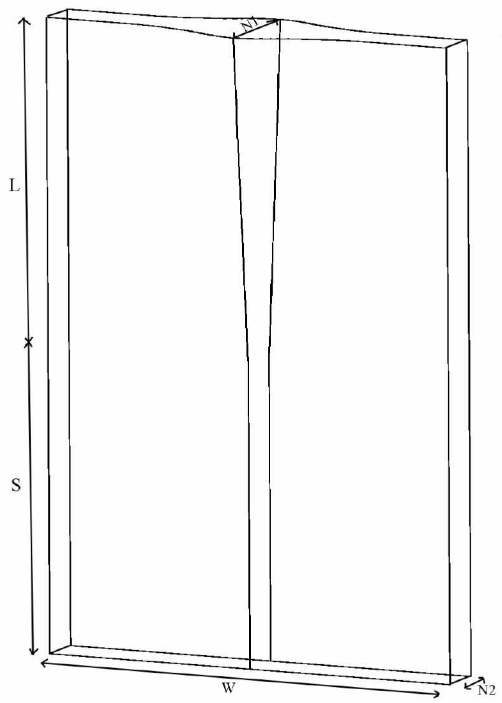

Fig. 1. Schematic representation of the upper region of the caster.

The nozzle used to transfer the molten steel from the tundish to the mold in this system is a monolithic type. The four-hole design of this nozzle (Figure 2) leads to a special flow pattern as seen in the results reported for the water model developed.

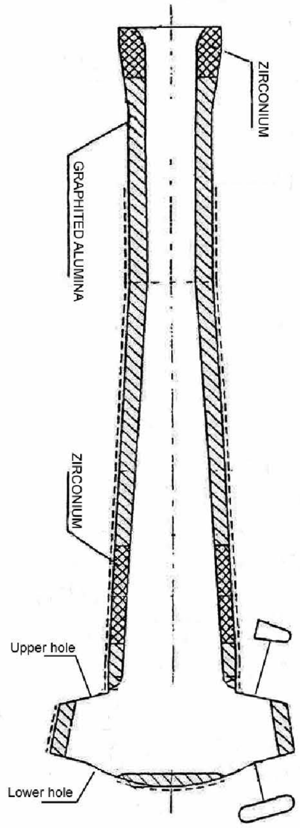

Fig. 2. Cross section of the four-hole nozzle design used in the current work and the physical model.

3- Physical model details

In order to study the flow pattern in the system, a full scale Plexiglas model of the mold and the tundish were constructed. Water was used as the flow material since its kinematic viscosity is equal to that of the molten steel [11)]. A real nozzle was also set to transfer the water from the tundish to the mold. A stopper was employed in the tundish to regulate the inlet flow rate of the water entering the mold. The casting speed was measured using a PANA METRIC PT 878 ultrasonic Debbi meter at the inlet of the nozzle. Figure 3 shows the schematic representation of the tundish, mold, and nozzle arrangement as well as their dimensions in the current work.

To investigate the flow pattern in the mold, the physical model was run under two casting speeds of 3.5 and 4.5 m/min with four SEN depths of 20, 26, 30, and 40 centimeters. The die was injected into the mold from the tundish side gate in order to observe the water flow for 20 seconds. Using a photographing system, the flow pattern of the water was extracted as photos. Surface turbulence was also determined under various casting conditions by means of the photos. The maximum wave height on the mold free surface was recorded under certain conditions and taken as the measure of surface turbulence [12)]. Argon gas was injected from the tundish side gate to the nozzle in order to study the flow behavior of the molten steel.

Table 1. Geometric parameters of the mold with respect to Figure 1.

parameter	value	parameter	Value
Mold length (L)	1.2 m	Lower mold thickness (N2)	0.062 m
Mold width (W)	1.56 m	Submold length (S)	1.00 m
Upper mold thickness (N1)	0.142 m		

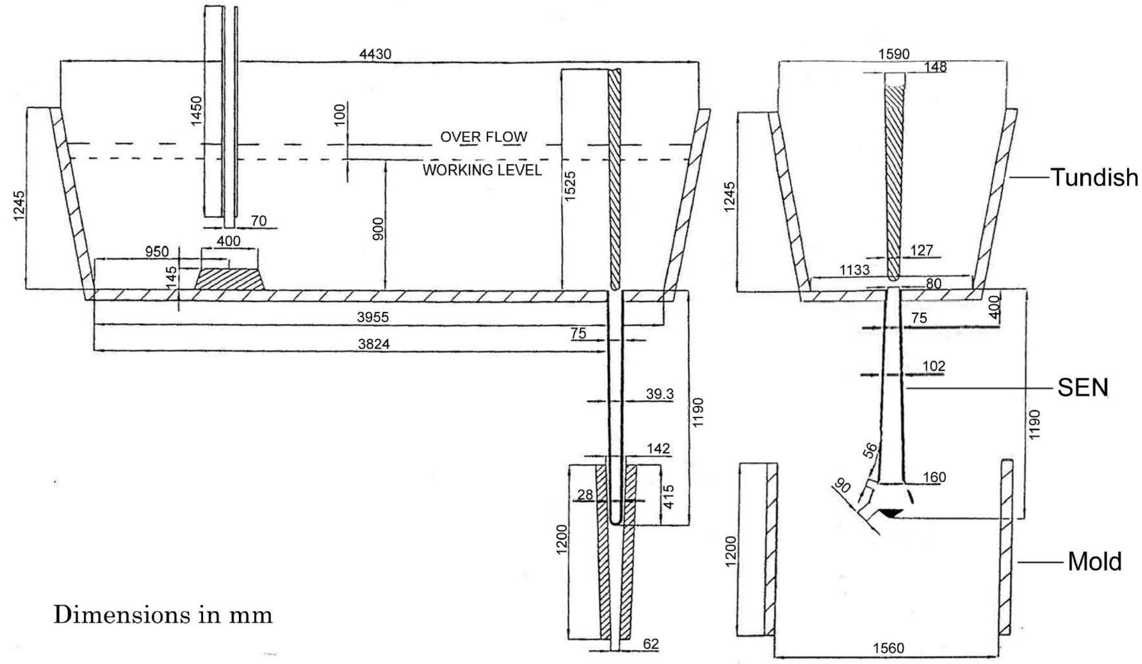

Fig. 3. Schematic representation of the tundish, mold and nozzle arrangement in the prototype.

4- Results and discussion

Figure 4 shows a photograph taken from the water model at 2 and 10 seconds after injection of the die running at a casting speed of 3.5 m/min with a nozzle submergence depth of 30 cm. The injected die shows the path of the water flow while leaving the nozzle. In order to describe the flow pattern in the mold, Figure 5 shows the schematic representation of the general flow pattern in the mentioned region of Figure 4. As seen, the special four-hole nozzle design is responsible for this flow pattern in the mold. The fluid enters the mold through the upper and lower holes. The fluid escaping from the two upper holes prevents the surface from solidifying. The outward flow from the lower holes impinges molten steel onto the narrow face while dividing it into two opposite upward and downward inhomogeneous recirculation zones. These zones lead to a uniform distribution of temperature in the mold and carries inclusions inside the surface of the mold.

Figure 6 shows the flow pattern through the gas injection into the nozzle. The fluid flow in this case consists of an upward flow for both upper and lower holes of the nozzle. This flow pattern is not suitable and may lead to flow-related problems in the casting operation. For example, it can cause high surface turbulence, which leads to the distortion of the mold powder and its absorption as inclusions.

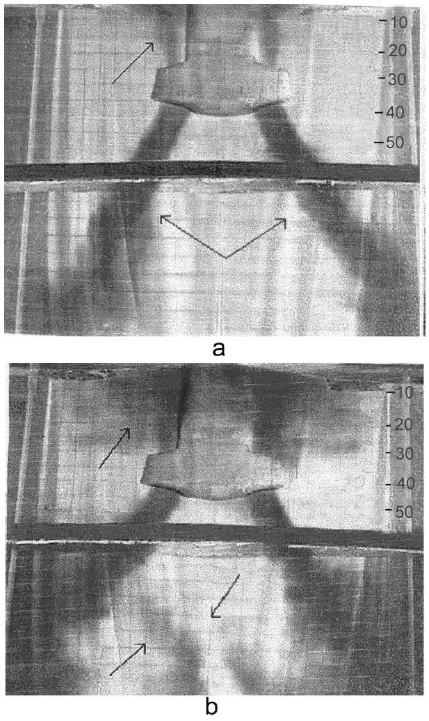

Fig. 4. Photograph of the water model running at a casting speed of 3.5 m/min with a nozzle submergence depth of 30 cm a) 4 seconds, and b) 10 seconds, after die injection.

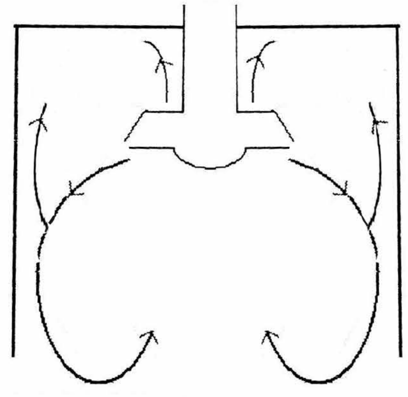

Fig. 5. Schematic representation of the general flow pattern in the upper region of the caster.

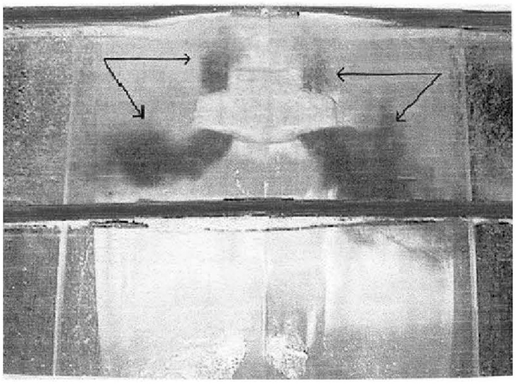

Fig. 6. Flow pattern through gas injection into the nozzle at a casting speed of 3.5 m/min with a nozzle submergence depth of 30 cm .

4-1- Effect of casting speed on surface turbulence

Generally speaking, surface turbulence increases with increasing casting speed. Figure 7 shows the effect of casting speed on maximum wave height in the free surface of the physical model at a depth of 20 cm of the SEN condition. As shown, the maximum wave height increases while the casting speed increases. These expected results are similar to those of T. Honeyands et al. [12] in their physical modeling of a thin slab caster.

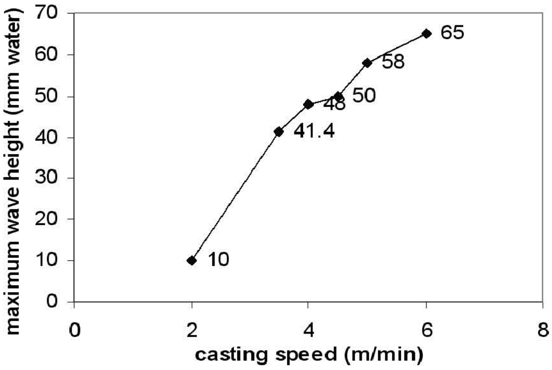

Fig. 7. The effect of casting speed on maximum wave height for a SEN submergence depth of 20 cm.

4-2- Effect of SEN depth on surface turbulence

In the thin slab continuous casting operation with similar nozzle designs, increased SEN depth leads to reduced speed of the upward flow from the upper holes of the nozzle and, thereby, to decreased surface turbulence. On the other hand, very high SEN depths result in the inclusions being carried to deeper parts of the mold and, thus, to formation of defects. Moreover, freezing of the surface melt, which is a direct result of casting at higher SEN depths, may result in shell sticking and breakout. Figure 8 shows the effect of SEN depth on the crack length in the final slab product [13]. As shown in this diagram, there is an optimum value for the SEN depth. Therefore, determining suitable SEN depths is of great importance that can be optimized by using such a water model [14,15].

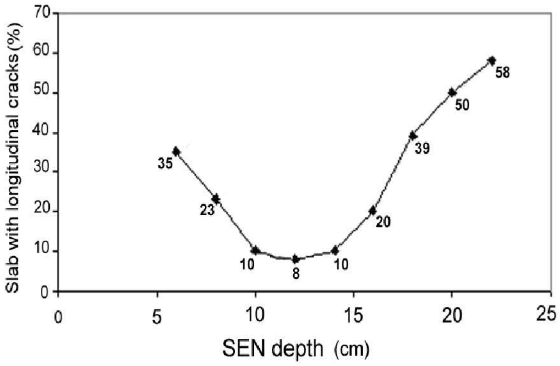

Fig. 8. The effect of SEN depth on the occurrence of longitudinal cracks in the slab product (from R.M. McDavid, B.G. Thomas, 1996).

Figure 9 shows the effect of SEN depth on maximum wave height on the surface of the mold for casting speeds of 3.5 and 4.5 m/min. With increasing casting speed, a linear decrease is clearly observed in the maximum wave height. Assuming that the allowable maximum wave height is 28 mm of water, a nozzle submergence of above 26 cm is recommended for the casting operation to reach a status where surface turbulence and powder consumption are reduced.

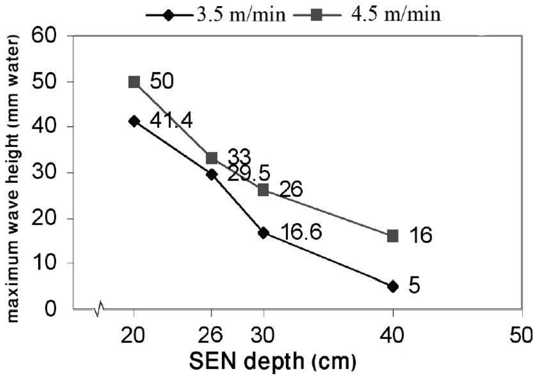

Fig. 9. The effect of SEN depth on the maximum wave height for the two casting speeds of 3.5and4.5 m/min.

4-3- Optimization of the variables

In thin slab continuous casting of steel at higher casting speeds, the issue of uniform distribution of fluid and temperature in the mold is a critical parameter. In this study, a physical model was run under different casting conditions (two casting speeds of 3.5 and 4.5 m/min and four SEN depths of 20, 26, 30, and 40 cm) to investigate the effect of SEN depth on flow pattern uniformity. For a casting speed of 3.5 m/min, SEN depths of 20 and 30 cm were found to yield a better uniformity in the flow pattern as is shown schematically in Figure 10. The same results obtained for a casting speed of 4.5m/min and SEN depths of 26 and 40 cm. However, it was found that SEN depths of 26 and 40 cm at a casting speed of 3.5 m/min and SEN depths of 20 and 30 cm at a casting speed of 4.5 m/min led to a non-uniform flow pattern in the upper region of the caster as can be seen schematically in Figure 11. These results are summarized in Table 2. On the basis of the data shown in this Table, SEN depths of 20 and 30 cm for a casting speed of 3.5 m/min and SEN depths of 26 and 40 cm for a casting speed of 4.5 m/min may be the most suitable conditions. But according to the results reported in Figure 9, which indicate the application of SEN depths above 26 cm , it is recommended that SEN depths of 30 and 40 cm should be used for casting speeds of 3.5 and 4.5 m/min, respectively, in order to avoid surface turbulence.

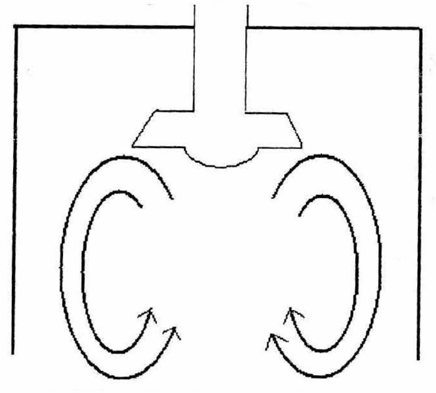

Fig. 10. Schematic representation of the uniform flow pattern in the mold, resulting from SEN depths of 20 and 30 cm at a casting speed of 3.5 m/min and SEN depths of 26 and 40 cm at a casting speed of 4.5 m/min.

Table 2. Suitable SEN depths for various casting speeds according to uniformity of fluid flow.

SEN depth / Casting speed	20 cm	26 cm	30 cm	40 cm
3.5 m/min	✓		✓	
4.5 m/min		✓		✓

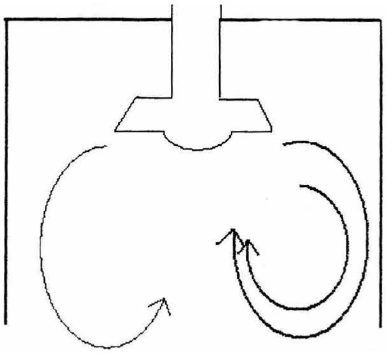

Fig. 11. Schematic representation of the non-uniform flow pattern in the mold, resulting from SEN depths of 26 and40 cm at a casting speed of 3.5 m/min and SEN depths of 20 and 30 cm at a casting speed of 4.5 m/min.

5- Conclusions

- A full scale water model of the thin slab continuous caster with a funnel-shaped mold and a four-hole nozzle design was constructed to visualize the fluid flow pattern in the upper region of the caster.
- The special four-hole nozzle design resulted in a flow pattern in which the fluid was distributed uniformly in the mold. This flow pattern prevents surface turbulence and solidification, while also leading to the uniform distribution of temperature in the mold and to carrying of inclusions inside the surface of the mold.
- Gas injection, increased casting speed, and decreased SEN depth result in surface turbulence and cause flow-related problems such as mold powder absorption and surface solidification.
- To obtain the flow pattern similarity and a safe casting operation without surface turbulence or surface freezing, it is recommended that SEN depths of 30 and 40 cm be used for casting speeds of 3.5 and 4.5 m/min, respectively.

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