IMPROVEMENT OF MOLD CONDITIONS
FOR
THIN SLAB CASTING OF STEEL

A Thesis
Presented in Partial Fulfillment of the Requirements for
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ABSTRACT

The nature of molten steel flow in continuous casting mold influences the operation of the caster and the quality of the steel slab produced. The molten steel flow depends on the Submerged Entry Nozzle (SEN) design, casting speed and the mold design. In the case of a thin slab caster, metal delivery is particularly challenging due to the high casting speed and the large aspect ratio of the mold. This can lead to added problems like shell growth non-uniformity, surface turbulence and mold flux entrapment, inclusion floatation and meniscus freezing at the broad face. In the present work, computer models were developed for analyzing the fluid flow conditions in a given thin slab caster. The computer models were also developed to analyze heat transfer and mixing in the caster. The analysis of computer model results for different SEN configurations has led to a new innovative SEN design for reducing the defects in the thin slab produced. Water modeling was used as a tool to verify the results of the mathematical model and to make small changes in the SEN design and analyze the fluid flow in the thin slab caster. The combination of both mathematical modeling and water modeling techniques have led to a new innovative SEN design which provides better stability, intermixing and solidification characteristics than that of the SEN designs currently being used.
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To my parents
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<tr>
<td>C</td>
<td>Concentration</td>
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<tr>
<td>$C_1$, $C_2$ and $C_\mu$</td>
<td>Constants appearing in turbulence model</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat</td>
</tr>
<tr>
<td>$D_{\text{eff}}$</td>
<td>Effective diffusivity of tracer in molten steel</td>
</tr>
<tr>
<td>$D_o$</td>
<td>Molecular diffusivity of tracer in molten steel</td>
</tr>
<tr>
<td>$D_t$</td>
<td>Turbulent diffusivity of tracer in molten steel</td>
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<tr>
<td>$f_x$</td>
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<td>Convective heat transfer coefficient for cooling at mold walls</td>
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<tr>
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<td>Pressure</td>
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<td>$Pr$</td>
<td>Prandtl number</td>
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<tr>
<td>Re</td>
<td>Reynolds number</td>
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<tr>
<td>T</td>
<td>Temperature</td>
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<tr>
<td>U</td>
<td>x-direction velocity component</td>
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<tr>
<td>U'</td>
<td>Fluctuating component of the instantaneous velocity</td>
</tr>
<tr>
<td>V</td>
<td>y-direction velocity component</td>
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<tr>
<td>T_0</td>
<td>Liquidus temperature of steel</td>
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<tr>
<td>w_{cast}</td>
<td>Casting speed</td>
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<tr>
<td>Δl</td>
<td>Thickness of solidified layer</td>
</tr>
<tr>
<td>Δz</td>
<td>Distance from the meniscus towards negative y direction</td>
</tr>
<tr>
<td>ε</td>
<td>Dissipation rate of kinetic energy</td>
</tr>
<tr>
<td>θ</td>
<td>Dimensionless time</td>
</tr>
<tr>
<td>ρ</td>
<td>Density of molten steel</td>
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<tr>
<td>σ_k and σ_c</td>
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CHAPTER 1

INTRODUCTION

Since its inception in 1960’s continuous casting of steel has rapidly replaced ingot casting and has become the preferred method for the casting of steel. In a few years every steel plant in the world is expected to produce steel through continuous casting process. The increase in popularity of the continuous casting process has occurred concurrently with tremendous advances in the development of new materials with comparable or superior mechanical properties than steel. For steel to remain a competitive material, it is necessary to further improve the quality of the steel produced in the steel mills. Improvement in the quality results not only in greater acceptance by the customer but also in reducing costs associated with the production of steel. The reduction in costs via quality improvements can be achieved by reducing wastage of material, energy and manpower. To achieve the goal of making steel at the lower cost but of the same or better quality a new process, ‘Thin Slab Casting’, is getting popular for the past decade. Thin slab casting is the process in which thinner, about 2-inch thick slabs are cast instead of the traditional 10-inch thick slab, with a minimal change to the existing continuous casting process.
In the continuous casting of steel, the quality of slab produced depends on the Submerged Entry Nozzle (SEN) design, casting rate and mold design. This is because these parameters have a great influence on the fluid flow pattern in the continuous casting mold (Fig. 1.1). The quality of the steel depends on the fluid flow pattern because the nature of fluid flow affects the surface turbulence, flux distribution, meniscus freezing, flux entrapment, argon entrapment, inclusion entrapment and nozzle clogging in the continuous casting mold. All these problems have been studied in general [e.g. 1,2] or for particular cases [e.g. 3, 4,5], in the recent past. Unfortunately, most of the work has been done for thick slab casting process and little is known about thin slab casting process.

Since the thickness in a thin slab caster is about one quarter to one fifth that of a thick slab continuous caster, the casting speeds are much higher in a thin slab caster. Therefore, in the case of thin slab casting the quality of steel slabs produced is difficult to control because metal delivery is particularly challenging due to high casting speed and large aspect ratio (width to thickness ratio) in the mold. For a given mold shape and casting rate, the SEN design is the most important parameter which influences cast metal quality. High surface velocity and turbulence, and oscillation of the flow pattern may cause mold flux slag shearing and vortexing, which will result in mold slag ingress. The conditions leading to such slag entrainment have not been studied for thin slab casting conditions.
Figure 1.1: Representation of fluid flow in the mold.
The steel industry has considerable demand to cast different grades of steel in successive heats. The recirculatory nature of the fluid flow in the mold and the strand coupled with the continuous nature of its operation is likely to result in considerable amount of mixing between the successive grades. This intermixed grade of steel between two heats is undesirable. The intermixing not only occurs in the mold but also in the tundish. It is possible to eliminate mixing in the tundish by “flying tundish change” i.e. by changing tundishes containing the different grades of steel. There has been some work on intermixing in thick slab continuous casting mold and strand by Huang and Thomas [6] and by Damle [7]. Huang and Thomas [6] did their work on flying tundish change whereas Damle [7] concentrated his work on coupled intermixing in both tundish and mold. No studies have been done on intermixing for the case of thin slab casting.

Mathematical models can increase the understanding of flow in thin slab caster, and help to determine how to avoid and minimize problems and defects in the thin slab casting process. The objective of this work is to develop a new SEN design for improving the quality of thin slab by observing the fluid flow patterns. This was achieved by understanding the casting conditions in the thin slab caster. The effect of casting condition parameters was studied by:

- Developing a computational model of turbulent flow conditions in the thin slab caster.
- Developing the heat transfer computational model and studying its effect on the molten steel flow in the thin slab caster.
- Developing a mathematical model for studying the extent of intermixing in thin slab casting conditions. Also, to study the effects of parameters like casting speed, casting angle and submergence depth on the intermixing. The mixing studies have been done for both flying tundish change and for coupled mixing in both tundish and mold. For the latter part, intermixing data in tundish was obtained from water modeling results from FOSECO Inc.

Simulation of molten steel flow in the thin slab caster is also done using water modeling techniques. For this, a half scale water model of plexiglass was built. One of the reasons for conducting water modeling experiments was to validate the mathematical modeling results. Another reason was to make minor changes in the new SEN design and find out the effects due to these changes. The water modeling was necessitated by the fact that the mathematical model is a two dimensional model which predicts the casting conditions in the centerline plane of the caster. Also mathematical model has the limitation of being the time-averaged model of a turbulent system. So it is expected that the fluid flow profiles predicted through mathematical modeling may not be exactly the same observed in the real caster. So water modeling, being more reliable, is conducted after mathematical modeling in order to get the correct results. The mathematical modeling is used before water modeling because it is more economical than water modeling and easier to make small changes in the mathematical model and analyze its effects.

This work is a step in determining what can be done to minimize defects in thin slab casting conditions. By understanding how fluid flow relates to the thin slab quality an
optimum flow pattern that minimizes the defects can be found. To obtain this optimum flow pattern in the mold a new SEN design can be developed using the mathematical and water modeling techniques.
CHAPTER 2

LITERATURE REVIEW

2.1 The Continuous Casting Process

The continuous casting process involves three metallurgical vessels – ladle, tundish, and mold, and their interconnecting nozzles. A schematic diagram of continuous casting process is shown in Fig. 2.1. In a typical steelmaking operation, molten steel from the Basic Oxygen Furnace (BOF) or an Electric Arc Furnace (EAF) is poured into the ladle. Ladle capacities generally range from 60 to 250 metric tons. In a ladle, the molten steel is subjected to several metallurgical operations, which have a significant bearing on the quality of the final cast product. These operations include alloy additions, vacuum degassing, and inert gas purging.

The ladle containing the molten steel is then transferred to the casting bay. Fig. 2.1 shows the schematic of the continuous casting setup. The steel from the ladle is then poured into the tundish. The tundish acts as a buffer vessel between the ladle and the mold with the
Figure 2.1: Schematic diagram of the continuous casting setup [7].
dual purposes of distributing the molten steel to different strands and maintaining the throughput of steel during ladle change over periods.

From the tundish, molten steel is fed into the continuous casting mold where solidification of the molten steel begins. The continuous casting mold is typically made of copper and is water cooled. In the mold, a thin shell of solidified steel is formed. Below the mold, lies the spray region where further solidification occurs. In this region cooling occurs by a combination of convective and boiling heat transfer due to the impingement of water sprays on to the surface of the strand. After the spray region, cooling of the strand takes place by radiation of heat from the strand to the surroundings. The region beyond spray cooling zone is called the radiation cooling zone. In this zone complete solidification takes place. A schematic representation of the various cooling zones for a continuously cast steel strand is shown in Fig. 2.2. The process is rendered continuous by the steady withdrawal of the partially solidified strand from the mold by the withdrawal rolls shown in Fig. 2.1. After the strand is completely solidified, it is cut by means of mechanical shears or gas torches to the required length.

The quality of the final cast product is determined by its conformance to the customer specified composition and properties. The properties of the solid steel product depends on its microstructure, extent of macrosegregation, cleanliness, the extent and distribution of surface and subsurface cracks. These characteristics are influenced by the metallurgical transport phenomena occurring at various stages of the continuous casting process. In particular the fluid flow and heat transfer processes that take place in different continuous
Figure 2.2: Schematic diagram showing the different cooling zones in the continuous casting machine [7].
casting reactors (ladle, tundish and mold) control the cleanliness, microstructure, and extent and distribution of surface and subsurface cracks. Macroseggregation depends on the fluid flow and the mass transport of various species during the solidification process. Since mass transport is strongly dependent on the diffusion coefficient of the species in the question, and, the diffusion coefficient is a strong function of temperature for most substances, heat transfer during solidification also plays an important, though indirect role in determining the extent of macroseggregation. Thus, it is seen that the transport processes, in particular fluid flow (momentum transport) and heat transfer strongly influence the quality of cast product.

The slab produced by a traditional continuous casting process has a thickness of the order of 15 to 23 cm (6 to 10 inches). Typically, sheet thickness demanded by the customers are of the order of 1 to 2 mm. Thus, the cast slab has to be further reduced in thickness by hot rolling. Defects, especially surface and subsurface ones can be exacerbated during the rolling process. In the continuous casters, the cast slab is held for a period of time on a slab holding area before transferring to a rolling mill where the slab has to be reheated. There is sufficient time available for the examination of the slab for surface defects, and their removal (at least partially) by processes such as scarfing, for example, before the slab is rolled. It may therefore be argued that production of slabs which are free of surface defects is not a very critical task. However, sub-surface and internal defects cannot be removed by surface cleaning processes such as scarfing. Moreover, removal of surface defects is an added cost, the elimination of which can only go on to increase the competitiveness of the steel company. Also, several companies are adopting direct rolling
processes to save energy costs. In such situations the cast slab is directly charged into the reheating furnace before being rolled to its final size. Hot charging of slab saves considerable energy that is required for slab reheating, but it also puts a greater onus on the caster to produce defect free slabs. Hence, there is considerable incentive for the production of defect free clean steel slabs of a consistent and high quality right at the caster.

In addition to producing defect free slabs, it is necessary to produce slabs that adhere to customer specified compositions. A slab out of composition is at least as likely to be rejected by the customer as a slab with surface and internal defects. Off composition slabs are frequently produced when different grades of steel are cast in a sequence. During this process, mixing between grades takes place and results in the casting of slabs that are out of the specification of either grade. These slabs have to generally be down graded. To reduce the amount of down graded slabs, it is essential to reduce the flowrate between the two grades of steel being cast in a sequence. Mixing is also controlled by the fluid flow profiles in the reactors.

To reduce and eventually eliminate defects in the cast slab, it is necessary to understand the root causes. For this, a fundamental understanding of the fluid flow and heat transfer taking place at various stages of the continuous casting process is essential. Such an understanding should help in predicting the quality of the product as a function of various operating parameters such as casting rate, casting width, grade of steel being cast, degree
of superheat of the molten steel, design of the submerged entry nozzle, design of tundish etc.

2.2 Thick slab casting

Thin slab casting process is becoming popular because of its unique advantages of lower capital investment and operating cost. But in the case of thin slab casting the quality of steel slabs produced is difficult to control because metal delivery is particularly challenging due to high casting speed and large aspect ratio (width to thickness ratio) in the mold. Due to these challenges or technical barriers the thin slab casting was regarded as a revolution by Brimacombe and Samarasekera [2]. A good amount of research work on the fluid flow in the mold of continuous caster is done using mathematical modeling and water modeling techniques or both. Most of the work has been done for thick slab casting and little work is available on thin slab casting. Therefore, in this section, thick slab casting conditions are discussed in the context of thin slab casting technique and the defects observed in the thin slabs.

2.2.1 Modeling Background

In 1986, Robertson et al [8] stated that the computational flow model (even with accepted limitations like two dimensionality) could be applied confidently to real situations. According to their model, if the flow field under investigation had planes of symmetry in
which most of the practically observed features could be observed, the qualitative
predictions of the flow pattern can be treated with confidence. They also stated that the
quantitative predictions of velocity (and pressure) could also be treated with confidence
except for recirculating and stagnant regions.

One of the first systematic studies of fluid flow in a slab caster was carried out by
Thomas et al [9]. They also confirmed that if sufficient care is taken, the mathematical
models are capable of reproducing the flow phenomenon observed in a turbulent,
metallurgical system, such as continuous slab casting mold. Furthermore, they stated that
a 2-D model can produce adequate results if the essential flow characteristics of the
physical system are found in the simulated plane.

Flow modeling with full-scale water models allows both Reynolds number and Froude
number similarity. It also permits the use of industrial flow controls and nozzles, which
can help in reproducing the real flow conditions. Therefore water modeling is an
excellent technique to throw light on the basic flow phenomena and for visualization of
complex phenomena that are difficult to model mathematically. But mathematical models
of fluid flow can also incorporate the process of heat transfer and solidification,
electromagnetic stirring and braking, inclusion or bubble tracking, which are difficult to
simulate with water models. This was proved by the results obtained by Flint [10] in
1990. Therefore Herbertson et al [1] suggested that both approaches should be employed
to predict results, which match well with the prototype.
Kovscek et al [11] satisfied the Froude number, Reynolds number and Euler number relationships in their water model. Froude number relates the inertial forces to the gravitational forces, the Reynolds number relates the inertial forces to the viscous forces, and the Euler number relates inertial to pressure forces. Euler number similitude is used for correct pressure head relationships. Weber number is used to relate inertial forces to surface tension forces. This similitude is used to model bubble formation and interfacial surface breakdown. This similitude was not possible to model in the water model used by Kovscek et al at a scale factor of unity.

However it was found by Kovscek et al that it is easier to entrain oil into water than slag into the steel. Therefore, oil will be entrained in the model before it could be entrained in steel in the real system. This is because the surface tension of oil-water system is significantly less than the slag-steel system, and also because the differential density of oil/water is about 0.1 g/cc whereas that of the slag/steel system is about 4.5 g/cc [12]. The model is therefore conservative and the philosophy of the model operation was to define the conditions that oil entrainment could be avoided in the water model and apply those conditions with appropriate scaling. This water/oil technique was also used by Emling et al [12] to study mold slag entrainment using different casting parameters.

2.2.2 Fluid flow in the mold

Fluid flow in the mold is a highly complex multi phase phenomenon with solidification. Figure 1.1 shows the schematic flow patterns in the liquid pool in the continuous casting
mold. Molten steel from the tundish is delivered to the mold using bifurcated SEN. The molten metal stream exits the SEN ports and strikes the solid steel shell along the narrow face of the mold. Upon impact with the narrow face, the metal stream splits into two portions. The upper portion of this stream flows along the narrow face towards the meniscus. It then flows horizontally along the metal-mold slag interface until it meets the corresponding molten metal stream from the other side of the SEN and flow downwards to form the upper recirculation zone. Similarly a portion of the fluid stream from the SEN flows downwards along the narrow face and then recirculates upwards near the center of the slab. This is the lower recirculation zone as shown in Fig. 1.1. The solidified steel shell is withdrawn continuously at a constant speed. Therefore, the shell profile as seen at different intervals of time remains constant. The flow in the liquid pool in the continuous casting mold is therefore is a steady state phenomena. However the fluid flow pattern may change with time depending upon the incoming liquid metal flow pattern and its temperature.

Fluid flow in the mold has a strong influence on the quality of cast product. Metal flow in the mold influences inclusion flotation, mold slag entrapment, shell growth uniformity and nozzle clogging. Molten metal delivery from the SEN to meniscus also influences the early stages of solidification, which has a profound impact on the surface quality of the cast product. The point at which the molten steel stream impinges the narrow face of the mold is an important parameter. Most of the incoming superheat in the molten metal stream is transferred at the point of impingement. So the local reheating and thinning of the steel shell takes place. If casting conditions are such that the impingement point is
below the mold, then this could lead to rapid thinning of shell and eventually a breakout. On the other hand, if the impingement point is too high then it leads to high velocities of fluid at the surface, which might cause slag entrapment. The position of impingement point is determined by the submergence depth, port angle and the mold width. The impingement point is lower for wider molds. Therefore the width of the mold should have an optimum value. An appropriate submergence depth is needed because a shallow SEN would result in single loop flow, with very high metal/slag interfacial velocities. This can cause mold slag entrapment and hence surface defects.

In 1988 Teshima et al [3] used water modeling experiments and found that the level fluctuation of the molten steel in a continuous cast mold, which caused surface defects in slab, could be controlled by the submerged entry nozzle design and other casting parameters. The major factors that affect the fluctuation are the casting rate, outlet angle of the nozzle, mold width and the gas injection rate to the nozzle. Teshima et al explained the fluctuation by the momentum of the pouring stream given to the free surface in the mold,

\[ F = \rho Q_L V (1 - \sin \theta) / 4D \] \hspace{1cm} (2.1)
where the variables are explained Fig. 2.3.

Figure 2.3: Schematic diagram of flow in one half of the mold [3].

$$V = Ax^{-e}Q^{-f}d^{-g}(1 / \cos \alpha)^{-h} \exp(BQg)$$

(2.2)

where, \(d\) is the diameter of the nozzle and A, B, e, f, g, h are the constants determined by the nozzle design. The collision speed of the pouring stream, V can be obtained by simply substituting half of the mold width, \(W/2\), for \(x\) in equation 2.2.
It was suggested that the optimum range of $F$ is $3 < F < 5$, to obtain sound products. This agreed well with the operational know-how that there is an optimum condition of the free surface in a mold i.e. too stable or too much fluctuated free surface should be avoided to obtain slabs of good surface quality. They confirmed their results and successfully applied the casting practice to Fukuyama no.5 caster to produce slabs of superior surface properties even at casting speeds upto 3m/min.

Kubota et al [4] estimated that a powder slag particle is caught from the molten steel stream as shown in Fig. 2.4. This powder slag particle is transported into the strand by the molten steel stream and then adheres to the solidified shell. Usually this surface stream is turbulent consisting of various sizes of vortices. These vortices are responsible for the entrapment of mold slag particles. At high casting speeds there is a threshold velocity of the surface stream for entrapping powder slag. Also at low casting speeds, the slab produced had powder slag particles as inclusions. These were entrapped by the ‘extended surface’ of the solidified shell on the molten steel meniscus as shown in Fig. 2.5.
Figure 2.4: Surface stream as mold powder catcher [4].

Figure 2.5: Inclusion in slab cast at low speed [4].
Nakamura et al [13] followed their work to decrease the surface defect due to slag entrainment on Ultra Low Carbon steel. They applied mold Electromagnetic stirring (EMS) automatically to keep the F value within the optimum range to minimize the total defect on ULC.

It is reported in many cases that a vortex is present on the surface of the mold. Gebhard et al [14] found that the vortices oscillate with a period of 15 to 30 seconds, decreasing with increasing flow rate of molten steel. As the velocity reached a peak value on the right side of the SEN, the vortex formed on the left side and vice versa. Flux entrapment by the shearing action of surface waves is reported to have a limit of 0.25 to 0.3 m/s. Above this limit, flux entrapment by this phenomenon is likely. The effect of the meniscus oscillation on this phenomenon was clearly apparent. Although time-averaged surface velocity may be 0.2 m/s, the surface velocity may reach 0.4 m/s, at the peak of oscillation, which is above the critical limit of flux entrapment.

Argon gas is employed at several stages in the continuous casting process (ladle, tundish, and mold) to encourage mixing, to help prevent nozzle clogging and to promote the flotation of solid inclusion particles from the liquid steel. It enters the continuous casting mold after injection into the SEN, and eventually escapes from the liquid steel surface through the mold flux powder layer. The injected argon gas bubbles influence the flow pattern, which has corresponding effects on the quality of steel produced. The extent of this effect is intensified by the volume expansion of the gas bubbles in the high temperature steel, which could increase its ambient temperature volume up to 5 times,
under typical casting conditions. Therefore, even a small rate of argon gas injection, 3% volume flow ratio of gas to liquid steel at the SEN inlet, could result in up to 15% gas volume fraction in the mold, with significant effects on the flow pattern. Thomas and Huang [6] found that argon gas bubble injection changes the liquid flow pattern most in the upper portion of the mold. The impingement point and the recirculation centers shift upward while the lower portion of the mold is less affected as shown in Fig. 2.6. Larger bubbles float more easily and leave the mold faster, so have less effect on the flow pattern, but possibly more effect on surface turbulence. Argon gas injection causes superheat to be removed higher in the caster, moves hot spot upwards, lowers the peak heat flux, and delivers more heat to the wide face and meniscus regions. David Creech [15] also studied the effect of Argon bubbles on the fluid flow of the molten steel using mathematical modeling techniques.
Figure 2.6: Effect of argon gas bubbles size and injection rate on flow pattern in steel caster [6].

The argon gas injection has also some disadvantages. In 1997 Thomas et al [16] also found that the argon gas is very effective in removing inclusions from the molten steel. They also concluded that the argon bubbles may be entrapped on the inside radius of the solidifying shell. Although argon bubble entrapment should be similar for all grades cast under the same flow conditions, it leads to severe surface defects in low strength steel, such as ultra low carbon steel. When the slab is rolled into thin product, the subsurface
bubbles elongate. Later during annealing, they can expand to raise the surface of the sheet locally, creating defects such as blisters or in the shape of pencil pipe. An innovative water/oil technique was used to model the steel/slag system in the mold by Emling et al [12] to study the potential causes of subsurface defects caused by the entrapment of inclusions or gas bubbles in the advancing inner radius solidification front. Gas injection into the mold caused the buildup of foamed oil around the submerged entry nozzle. It was found that the foamed oil was easily entrained in the water during modeling.

Superheat dissipation in the continuous caster was studied using mathematical modeling techniques. The mathematical models were developed to compute fluid flow velocities, temperature distribution with in the liquid pool and heat transfer to the inside of the solidifying shell by Huang, Thomas and Najjar [17]. They found that the three dimensional (3-D) velocity and heat transfer predictions compared reasonably well with the experimental and two dimensional (2-D) results. The results indicated that the maximum heat transfer to the shell occurs at the point of impingement on the narrow face, as shown in Fig. 2.7. It was also found that most of the superheat is dissipated within the mold and that the casting speed and superheat temperature influence the heat flux the most. It was also found that the mold width, jet angle and the submergence depth effect the superheat dissipation.
Figure 2.7: Superheat dissipation in the strand [17].

2.2.3 SEN design

The nature of the fluid flow leaving the Submerged Entry Nozzle (SEN) has a significant effect on the fluid flow in the mold and heat transfer in the growing shell, which in turn affects the quality of slab produced. The fluid flow in the SEN is shown in Fig. 2.8. The profile shows that most of the molten steel comes out of the lower part of the port and the top of the port is the area of relatively stagnant flow, where the fluid actually recirculates
back to the SEN. Such stagnant regions form preferential sites for the deposition of nonmetallic inclusions such as alumina. These inclusions result in the clogging of SEN port. The changes in the fluid flow behaviour while the nozzle clogging is developing were investigated by Kohler et al [18]. They found that the flow patterns on the either side of the SEN in the mold became unsymmetrical due to the clogging of the nozzle. This unsymmetrical flow means that the stream velocities on the left and right side of the SEN are different. Unsymmetrical flow is disadvantageous because the velocities on one side of the mold are higher. Consequently, the jet penetrates deeper into the strand and the vortexing becomes prominent and there is shearing of slag into the molten metal surface. This leads to decreased cleanliness in the final product. Therefore availability of a system that generates a warning to the operator that the flow pattern is becoming unsymmetrical in mold can improve the quality of the steel produced.
Figure 2.8: Unbiased fluid low in SEN [7].
The fluid flow rate to the mold from the tundish is controlled by a slide gate, but this causes biased fluid flow in the SEN as shown in Fig. 2.9. This uneven flow in the nozzle sometimes results in the formation of a vortex near the nozzle and entrapment of mold powder on the meniscus. Yokoya et al [19] were successful in designing a SEN to suppress this kind of uneven flow inside a nozzle using a contraction nozzle. This contraction nozzle is shown in Fig. 2.10. The uneven flow is mitigated through two flow patterns; (I) The stream which has high velocity flowing along the wall is diverted by the step and flow into the low velocity region; (II) The stream confluencing near the opposite side is turning around the step, forming a double spiral movement; and then velocity distribution becomes more uniform with flowing through the contraction, as shown in Fig. 2.11.

The angle of the SEN port with reference to the horizontal is a very important parameter which governs the nature of fluid flow in the continuous casting mold. Figures 2.12 and 2.13 respectively show the calculated flow profiles within the SEN and the mold for different port angles. It is observed that the actual outlet angle of the molten steel is less than the nominal port angle. Hintikka et al [20] found that the effective port angle can be directed 10 to 40 degrees deeper downward than the nominal SEN port angle. They found that in a wide mold upwardly inclined SEN port angle is beneficial with respect to inclusion floatation whereas in a narrow mold the effect is opposite.

Vaterlaus [21] developed a new Whirl SEN which induces the whirl in the SEN to reduce the mold fluid velocity, penetration depth and mold level fluctuation. Due to the
centripetal forces, the inclusions cannot stick to the SEN wall and therefore, prevent nozzle clogging. This also prevents air aspiration. The Whirl SEN is as shown in Fig. 2.14.

Figure 2.9: Biased flow in SEN due to the slide gate [1].
Figure 2.10: Contraction nozzle used for correcting the biased flow [19].

Figure 2.11: Flow pattern for contraction nozzle [19].
Figure 2.12: Nozzle model results for five different nominal outlet angles of the ports [9].
Figure 2.13: Flow profiles for different SEN port angles [9].
Figure 2.14: Flow control in tundish and mold by PVC/Whirl SEN [21].
2.3 Thin Slab Casting

In the case of a thin slab caster, metal delivery is particularly challenging due to high casting speed and large aspect ratio of the mold [2, 5, 24 .. 34]. This may lead to added problems like shell growth uniformity, surface turbulence, mold powder entrapment, inclusion floatation, and meniscus freezing. Casting rate is the most important parameter which affects the problems in the mold but since the volume of molten steel being cast cannot be changed, change in the SEN design and mold geometry is required to get high quality thin slabs at high casting rates.

The basic flow pattern in a thin slab casting mold of four large recirculation loops is expected from the previous studies of the conventional/thick slab casters. However due to higher velocities the surface turbulence became more intense leading to vortex formation and slag entrapment. Honeyands and Herbertson [5], and Honeyands et al [24] found that the fluid flow in the mold was strongly oscillatory, despite the centerline geometric symmetry and steady inlet flow. The period of oscillation was a function of casting speed, SEN design and submergence depth. They stated that understanding the driving force of the oscillation and developing means to suppress it would lead to an increase in productivity and cleaner steel.

Wunnenberg et al [25] have compared the Nucor/SMS Compact Strip Production (CSP) process and the Arvedi Inline Strip Production (ISP) process. The layouts of these processes are shown in Fig. 2.15 (a) and (b). Brimacombe and Samarasekera [2] have
discussed five different processes for thin slab casting. These processes are tabulated in Table 2.1. The various types of molds used for the different processes for casting thin slab are as shown in Fig. 2.16. The CSP process uses a funnel shaped mold [27,28] whereas in the ISP process parallel mold is used [29,30]. The funnel shape of the CSP mold allows SEN to fit into the mold and also to cast very thin slabs of about 50 to 55mm. Every process has a different type of mold as well as different type of nozzle design. The SEN design used in the ISP process by Mannesmandemag for thin slab casting of steel is as shown in Fig. 2.17. In CSP process a bifurcated nozzle is used, as shown in Fig. 2.18. The nozzle is tapered at the bottom to fit into the CSP funnel shaped mold. Nucor Crawfordsville, Indiana (CSP process) [27] have developed the SEN to primarily optimize the outflux velocities, outflux pulse from the SEN and the flow pattern in the mold. Achieving higher service life was also an important goal. The CSP process has to rely on the use of EMBr and Liquid Core Reduction techniques to produce good quality of steel slabs. It has been reported that in the CONROLL process at ARMCO (now AK steel) Mansfield a three port SEN is used. The fluid flow in the mold resulting from this three port nozzle is as shown in Fig. 2.19. The authors [31, 32] claimed that the mold has calm, stable and hot meniscus, no oscillating side waves, and increased SEN lifetime. Also, the thin slab produced had no longitudinal, surface and corner cracks, no slag entrapments, and no oscillation marks are present on the surface of the slab. Another nozzle as shown in Fig.2.20 has been patented by Vesuvius Crucible Company [33] in order to produce better quality of steel slabs. The aim is to improve upon the standing wave and other problems by making the velocities at the exit of the SEN more uniform. This helps in stabilizing the fluid flow inside the mold and also, reducing the standing
wave and the oscillation inside the strand. This leads to better quality of slabs produced. Robinson et al [34] have detailed in Fig. 2.21, how the change in the SEN design can reduce the biased flow in the mold. The evolution of the better and new SEN designs have consistently reduced the oscillation and bias in the mold flow.

Figure 2.15: Layouts of the (a) Nucor CSP and (b) Arvedi ISP processes [25].
<table>
<thead>
<tr>
<th>Process and Company</th>
<th>Installation, Start Date, (Steelmaking)</th>
<th>Primary Heat Extraction Device</th>
<th>Reheating or Holding Furnace</th>
<th>Section Size (mm)</th>
<th>Casting Speed and Oscillation</th>
<th>Grades Cast</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSP Nucor, Crawfordsville, IN, U.S.A. 1989 (EAF)</td>
<td>Funnel-shaped mold</td>
<td>Soaking furnace equalizing at 1,100°C ±10°C</td>
<td>50 × 900-1,550</td>
<td>4.5–6 m/min stroke 6 mm</td>
<td>Commercial production of plain carbon steels outside peritectic range (No 0.065–0.15% C grades)</td>
<td></td>
</tr>
<tr>
<td>SMS Nucor, Hickman, AR, U.S.A. 1992 (EAF)</td>
<td>Funnel-shaped mold</td>
<td>Soaking furnace</td>
<td>50 × 1,220-1,560</td>
<td>60 × speed (m/min)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concast</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ILVA, Terel, Italy, 1993 (ACD)</td>
<td>Funnel-shaped mold</td>
<td>Soaking furnace</td>
<td>Not available</td>
<td></td>
<td>High alloyed and stainless steels</td>
<td></td>
</tr>
<tr>
<td>ISP Mannesmann Demag</td>
<td>Arvedi ISP Works, Cremona, Italy 1992 (EAF)</td>
<td>Straight mold with sub-mold roller segment that reduces slab to 40 mm during solidification followed by three shaping stands that reduce slab to 15-30 mm</td>
<td>Inductive reheating to temperature of 1,100–1,150°C</td>
<td>60-80 × 650-1,350</td>
<td>2.8 m/min ↓ 4.5 m/min ↓ 11.13 m/min stroke 1 a 1 to 10 mm frequency 400 cpm</td>
<td>Commercial production of plain carbon – stainless steels</td>
</tr>
<tr>
<td>CONTROLL Voest-Alpine</td>
<td>Avesta, Sweden 1988 (Stainless shop)</td>
<td>Parallel mold with in-line rolling</td>
<td>Pusher-type reheating furnace</td>
<td>80 × 2,100</td>
<td>2.4 m/min</td>
<td>Commercial production of stainless steels</td>
</tr>
<tr>
<td></td>
<td>Voest Alpine Stahl, Linz, Austria Trials 1990 (LD furnace)</td>
<td>Parallel mold with in-line rolling</td>
<td></td>
<td>80 × 1,285 (or 1,030)</td>
<td>3.7 m/min Not reported</td>
<td></td>
</tr>
<tr>
<td>Thin Slab</td>
<td>Saldarine, Italy Trials 1990</td>
<td>Lens-shaped mold</td>
<td>Induction reheating – equalizing furnace</td>
<td>30–70 × 900–1,500</td>
<td>1.5–6 m/min stroke 3.5 mm frequency 180–500 cpm</td>
<td>Trials with low carbon steels – fine grained Al-killed steels – NbV microalloyed steels – quality steels for welded pipe – low &lt;0.08% C – medium carbon steels</td>
</tr>
<tr>
<td>Caster Twin Belt</td>
<td>Kawasaki Steel Chiba Works, Japan</td>
<td>Twin belts</td>
<td>Direct rolling without reheating</td>
<td>30 × 800–1,000</td>
<td>8–13 m/min no oscillation moving belt</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Commercial thin slab casting operations [2].
Figure 2.16: Cross-sections of different thin slab casters [26].
Figure 2.17: SEN for ISP process [29].
Figure 2.18: SEN for CSP process [27].
Figure 2.19: Fluid flow resulting from the use of three port SEN [31,32].
Figure 2.20: SEN design patented by Vesuvius Crucible company [33].
Figure 2.21: SEN design and the resultant fluid flow evolution [34].
2.4 Mixing during grade change operation

Due to increasing demands from customers for greater number of grades and tighter composition control, steel companies are being required to cast an increasing number of grades. A grade of steel refers to a particular specification of various alloying elements (composition). The different grades of steel have to be cast on sequence, preferably without stopping the caster. In a continuous casting process this can be done in two ways. The first method is known as flying tundish operation. In this case, the tundish containing the old steel grade is removed from the casting area. This tundish is then replaced by a tundish containing the new grade of the steel to be cast. This movement of the tundishes is called a “tundish fly”. During the tundish fly operation it is necessary to lower the casting rate or even to stop the caster. This can have a detrimental effect on the quality of the slab produced. A tundish fly would be especially unfeasible if several grades are to be cast in a relatively short period of time. This would necessitate frequent tundish changes and possible stoppages in the caster that is highly undesirable.

To avoid problems associated with a tundish fly, another technique called the low tundish operation is frequently employed. In this, the tundish containing the old grade of steel being cast is first emptied to a certain depth, before pouring of the new grade from the ladle commences. The new grade is usually poured at a rate that is much greater than the steady state casting rate. This is done to fill the tundish to its normal operating level as quickly as possible. Once the normal operating level is reached, the teeming rate from the ladle to the tundish is reduced to its normal steady state rate. During this operation, the
casting rate is generally kept constant. However there may be situations where the casting rate may be reduced while the tundish is being emptied. The changes from the ladle to the tundish may be carried out in a step fashion or continuously in a ramp function.

In a continuous casting system, the tundish and the mold are continuous reactors, whereas the ladle is a batch vessel/reactor. Therefore, mixing between two grades takes place in the mold and the tundish. In the low tundish operation, mixing between the two grades of steel takes place in the tundish as well as the mold. This results in the casting of some amount of the mixed grade. Since this mixed grade does not meet the specification of the customer, it usually has to be downgraded or scrapped. The problem of the production of mixed chemistry during a grade change operation is quite serious.

To reduce the amount of mixed grade, it is necessary to understand the effect of various operating parameters on the quantity of mixed grade produced. These operating parameters include the depth to which the tundish with the old grade is emptied, the rate at which the tundish is filled with the new grade, the presence or absence of flow control devices, the casting rate, the slab width, slab thickness, and the SEN design. Mixing between the grades is strongly influenced by the flow profiles in the system.

The literature on the effects of operating parameters on the amount of mixed grade produced is relatively scarce. Studies of the grade change process are important not only from the point of view of optimizing the operating parameters to minimize the amount of mixed grade produced, but also to develop the ability to predict the limits of the transition.
region to implement automatic slab/billet shearing processes in order to cut the appropriate length of the slab corresponding to the transition grade.

Diener et al [35] have reported that on emptying the tundish with the old grade to a depth below the normal operating depth before commencing the filling of the tundish with the new grade resulted in a lower quantity of transition metal as compared to the case where the pouring from the ladle with the new grade commenced almost immediately after pouring from the last ladle with the old grade. In the work of Damle [7], the reference of Burns et al has been cited to refer to their water modeling experiments, which establish the fact that mixed grade produced is lower when the tundish is emptied to a lower depth. It is also reported that on increasing the width of the slab being cast the intermixed length of slab decreases.

Little effort has been devoted to understanding the mixing that occurs in the mold during a grade change process. Huang and Thomas [36] studied the effect of some casting parameters on the mixing in the mold by means of mathematical modeling. In this work, a grade change with a flying tundish operation was simulated. Therefore, coupling between the mixing in the tundish and in the mold was not taken into account in this work. The authors assumed flow field to be isothermal and steady state. The inlet concentration was fixed to that corresponding to the new grade. The concentration throughout the mold was then calculated as a function of time. The top six meters of the steel shell was simulated using a three dimensional mathematical model. The remaining portion of the strand was simulated using a one dimensional model. The latter was done
to economize on the computing time. Solidification was not included. They found that the intermixed length in a slab depends primarily on its thickness and not on its width. This is shown in Fig. 2.22. In this work, it was also found that the casting at higher speeds increased the length of the intermixed slab produced. Higher speeds decreased the time needed to reach a given concentration. This is partially compensated by the simultaneous increase in the metallurgical length, as shown in Fig. 2.23. It was also found that the angle of the SEN port did not have a significant effect on the intermixed length except near the slab surface. This is due to the fact that changing the SEN port angles only affects the flow in the upper portion of the mold, the intermixed length along the slab surface is affected by changing the SEN angles whereas there is no effect on the intermixed length on the slab centerline. This is shown in Fig. 2.24.

Damle [7] studied the coupled intermixing in tundish and mold. He found that the mixing in the mold is unavoidable because of the recirculatory flow in the mold. Therefore, the mixing in the tundish must be minimized in to reduced the off grade length of intermixed steel produced. He also concluded that the intermixed length of the steel increased with casting rate.
Figure 2.22: Effect of slab dimensions on the length of the mixed slab produced in a flying tundish grade change operation [36].

Figure 2.23: Effect of casting speed on the length of the mixed slab produced in a flying tundish grade change operation [36].
Figure 2.24: Effect of SEN jet angle on the length of mixed slab produced in a flying tundish grade change operation [36].
2.4 Summary

Metal delivery in a slab caster significantly influences the product quality and productivity. Mathematical and water modeling techniques can be successfully employed to understand the various metal delivery related phenomena and determine the effects of SEN design and casting practices. It is suggested in the literature that coupled mathematical and water modeling techniques should be used to determine the nature of slab casting process.

Important phenomena that influence the slab quality are shell thinning, flux and inclusion entrapment, meniscus freezing and vortex formation. These phenomena have to be optimized simultaneously. This is done by changing the mold design, SEN design, submergence depth and argon injection rate accordingly. The major emphasis is on production of cleaner steel by having optimum surface velocity of the molten metal stream with respect to the slag as represented in Fig. 2.25.

Most of the work has been done for thick slab casting and not for thin slab casting. Some additional problems are encountered in thin slab casting. The most significant problem in thin slab casting is that the molten steel enters mold at high velocities. This means more turbulence in the mold, more slag/liquid shearing and therefore resulting in more flux entrapment. Molten metal with greater force coming at higher velocity will impinge with
greater force on solidified shell and so there is greater chance of melting of the steel shell. Also, nozzle clogging is very important phenomena because it makes the flow unsymmetrical in mold and hence leads to defects in the steel slabs produced. It has also been found that there is oscillation and vortex formation in the mold. Understanding the driving force for oscillation and vortex formation and developing means to suppress it would lead to increase in productivity and cleaner steel.

Intermixing of different steel grades being continuously casted is a major problem in slab casting. There has been some work done on the intermixing in thick slab casting but no work has been done for thin slab casting of steel.

Figure 2.25: Schematic representation of the connections between product quality and the intensity of surface flows [1].
CHAPTER 3

MATHEMATICAL MODELING

To understand the fluid flow, temperature distribution, and solute diffusion in thin slab casting mold, a finite element model was developed to calculate the above phenomenon within the molten steel pool inside the shell in the mold and strand region of a thin slab casting machine. The fluid flow in the mold is symmetrical and so only one half of the mold is simulated.

3.1 Assumptions

The mathematical model involves the following assumptions:

1. The process is at steady state except in the case of the study of intermixing of two grades of steel. Process parameters except tracer concentration do not change with time. The fluid flow in the case of intermixing is assumed to be at a steady state but the concentration of tracer is time dependent.
2. By taking into account the fact that width/thickness ratio is very large and ignoring the end effects, the geometry of the process can be approximated as two-dimensional.

3. Symmetry was assumed so only one half of the two dimensional mold was modeled.

4. The modeled portion can actually accurately describe the phenomenon taking place at the centerline of the thin slab caster.

5. Liquid steel is incompressible and is a Newtonian fluid.

6. The physical properties of molten steel are assumed to be isotropic in nature.

7. Diffusivity was not considered to be temperature dependent.

8. The tracer was considered to be non-buoyant.

9. The heat flux across the top layer i.e. the meniscus was considered negligible as compared to the heat flux through the mold walls. This is assumed because of the presence of mold flux at the meniscus is non-conducting.

### 3.2 Equations solved

Various equations were solved using the finite element techniques using the FIDAP software [37]. These equations are as following:

**Continuity equation**

The continuity equation, which represents conservation of mass, can be expressed, for a steady state and incompressible fluid flow,

\[
\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{3.1}
\]

where \( U \) and \( V \) are the velocity components in the \( x \) and \( y \) directions, respectively.
Turbulent Navier–Stokes equation

The Navier–Stokes equation, which is a momentum balance equation, can be expressed, for a steady state, turbulent, and incompressible fluid flow, in the following form,

\[
\left( U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} \right) \rho = -\frac{\partial P}{\partial x} + \rho f_x + 2 \frac{\partial}{\partial x} \left( \mu_{\text{eff}} \frac{\partial U}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_{\text{eff}} \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right)
\]

(3.2)

\[
\left( U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} \right) \rho = -\frac{\partial P}{\partial y} + \rho f_y + 2 \frac{\partial}{\partial y} \left( \mu_{\text{eff}} \frac{\partial V}{\partial y} \right) + \frac{\partial}{\partial x} \left( \mu_{\text{eff}} \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right)
\]

(3.3)

where \( \mu_{\text{eff}} \) is the effective viscosity and is the sum of molecular viscosity, \( \mu_0 \) and turbulent viscosity, \( \mu_t \).

Equation for conservation of thermal energy

Conservation of thermal energy can be written as,

\[
\left( U \frac{\partial T}{\partial x} + V \frac{\partial T}{\partial y} \right) \rho C_p = \frac{\partial}{\partial x} \left( K_{\text{eff}} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{\text{eff}} \frac{\partial T}{\partial y} \right) + H
\]

(3.4)

where \( K_{\text{eff}} \) is the sum of molecular conductivity, \( K_0 \) and turbulent conductivity, \( K_t \) and \( H \) is the heat generation term.
Equation for conservation of mass

\[
\frac{\partial C}{\partial t} + \left( U \frac{\partial C}{\partial x} + V \frac{\partial C}{\partial y} \right) = \frac{\partial}{\partial x} \left( D_{\text{eff}} \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y} \left( D_{\text{eff}} \frac{\partial C}{\partial y} \right) + R
\]  

(3.5)

where \( D_{\text{eff}} \) is the sum of molecular diffusivity, \( D_o \) and turbulent diffusivity, \( D_t \) and \( R \) is the mass generation term.

### 3.3 Turbulence model

The two equation \( k-\varepsilon \) model of turbulence of Launder and Spalding was used for the turbulence considerations. Governing transport equations for turbulent kinetic energy, \( k \), and its dissipation rate, \( \varepsilon \), can be written as,

For turbulent kinetic energy,

\[
\left( U \frac{\partial k}{\partial x} + V \frac{\partial k}{\partial y} \right) \rho = -p\varepsilon + \mu_t \phi + \frac{\partial}{\partial x} \left( \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial y} \right)
\]  

(3.6)

For dissipation rate of turbulence,

\[
\left( U \frac{\partial \varepsilon}{\partial x} + V \frac{\partial \varepsilon}{\partial y} \right) \rho = -C_2 \frac{\rho}{k} \varepsilon^2 + C_1 \mu_t \phi \frac{\varepsilon}{k} + \frac{\partial}{\partial x} \left( \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial y} \right)
\]  

(3.7)

where,

\[
k = (U' U')/2
\]  

(3.8)

\[
U = U_o + U'
\]  

(3.9)

\[
\mu_{\text{eff}} = \mu_o + \mu_t
\]  

(3.10)
\[ \mu_t = C_{\mu} \rho k^2 / \varepsilon \]  \hspace{1cm} (3.11)

\[ K_{\text{eff}} = K_o + K_t \]  \hspace{1cm} (3.12)

\[ K_t = C_{p} \mu_t / Pr \]  \hspace{1cm} (3.13)

\[ D_{\text{eff}} = D_o + D_t \]  \hspace{1cm} (3.14)

\[ D_t = \mu_t / \rho \text{Sc}_t \]  \hspace{1cm} (3.15)

where,

Pr is the turbulent Prandtl number. In the present simulation, a value of 1 is taken for Pr.

Sc_t is the turbulent Schmidt number. In the present simulation, Sc_t is taken to be 1.

\( C_p \) is isobaric specific heat of molten steel.

\( \varphi \) in equations (6) and (7) is given by,

\[ \varphi = 2 \left( \frac{\partial U}{\partial x} \right)^2 + 2 \left( \frac{\partial V}{\partial y} \right)^2 + \left( \frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right)^2 \]  \hspace{1cm} (3.16)

According to Launder and Spalding [38], the five constants appearing in equations (3.6) and (3.7) take the following values,

\[ C_1 = 1.44, \; C_2 = 1.92, \; C_\mu = 0.09, \; \sigma_k = 1.0, \; \sigma_\varepsilon = 1.3 \]
3.4 Boundary Conditions

The governing equations were subject to boundary conditions on every surface of the computational domain. The computational domain for modeling thin slab caster is as shown in Fig. 3.1. The gravitational force is applied in the negative y direction.

3.4.1 Inlet

The mold cavity is fed by a bifurcated, submerged entry nozzle, which has an important influence on the flow pattern. To account for this, the velocity is fixed to have a normal component in the downward direction at the inlet. The velocity component in the x-direction at the inlet is taken to be zero. The normal component is dependant on the casting speed and has a constant value. The turbulence parameters, k and ε are fixed at the inlet, at the values of 0.00913 and 0.089 respectively. These values were calculated by assuming the deviating component of the velocity to be about 10% of the inlet velocity.

In the case of the temperature distribution calculations, the temperature across the inlet plane is fixed to the casting temperature, T₀ (1823 K). This temperature corresponds to 25K of superheat as the liquidus temperature of the steel is taken to be 1798 K.

In the case of study of intermixing due to grade change operation the concentration value of the tracer was changed from 0 to 1 at time, t=0. This was done in the case of flying
Figure 3.1: Computational domain for thin slab casting process.
tundish change. In the case of the study of coupled intermixing in tundish and mold, the
concentration of tracer at inlet was time dependent. These time dependant concentration
values of the tracer at the inlet of the mold were supplied by Don Zackrais of FOSECO
Inc. [39]. These concentration values were generated by conducting water modeling
experiments on the tundish and recording the tracer concentrations at the outlet with
respect to time.

3.4.2 Submerged Entry Nozzle

The Submerged Entry Nozzle (SEN) dimensions were calculated according to the design
supplied by FOSECO Inc.. Similar calculations were carried out on the new designs,
which were tested using mathematical modeling. The variation in the thickness of SEN
was taken into account by keeping the cross-sectional area in 2-d and 3-d cases the same.
Therefore, the dimensions in the 2-d math model were decided by dividing the cross-
sectional area with the thickness of the mold. The SEN walls were simulated by assuming
a no slip boundary condition i.e. the velocities, k, and ε are taken to be zero at the nodes
corresponding to the wall.
3.4.3 Symmetry Boundary

At the symmetric boundary, the velocity component in x-direction normal to symmetry boundary is taken to be zero. The heat flux and the diffusive flux across the boundaries are also taken to be zero.

3.4.4 Top Surface

The top surface or the meniscus is treated in the same way as the symmetry boundary i.e. the velocity component normal to the meniscus (y-direction) is constrained as zero and there is no heat and diffusive flux across the meniscus.

3.4.5 Mold Wall

The mold wall was modeled as a no-slip boundary condition. The velocity, turbulent kinetic energy, and dissipation were taken to be zero at the mold wall. The solidified shell was not modeled because its thickness was negligible as compared to the width of the mold. This can be seen from the following equation [7].

$$\Delta l = k_s \sqrt{\frac{\Delta z}{w_{cast}}}$$  \hspace{1cm} (3.17)

In the above equation, $\Delta l$ is the thickness of the solidified layer, $\Delta z$ is the distance from the meniscus and $w_{cast}$ is the casting speed. The value of the solidification constant $k_s$ was
taken to be $0.00327 \text{ m s}^{-0.5}$. The shell thickness at the 4 m below meniscus is 2.26 cm. Therefore ratio of shell thickness to width of the mold is 0.00122, which is negligible. A fixed temperature, nominally equal to the liquidus temperature is imposed on the narrow and wide face mold walls, which should behave like a solid wall.

In the mathematical modeling of intermixing studies the diffusive flux across the mold wall boundary was taken to be zero.

3.4.6 Outlet

As suggested by Patankar [40] no boundary condition on the velocity was imposed on the outlet of the mold. This is because the flow at the outlet was fully developed. The gradients of the turbulent kinetic energy, $k$ and turbulent dissipation, $\varepsilon$ were taken to be zero at the outlet so as to obtain a faster convergence [37].

3.4.7 Internal boundaries

All the above stated boundaries may be termed as external boundaries. However there are some instances where the values of the variables have to be fixed at certain points within the calculation domain. Such a situation may arise while modeling the flow inside the SEN with different kinds of ports. The velocities, turbulent kinetic energy and dissipation were set to zero at the walls of the SEN. Calculations were not carried out inside the domain of the walls.
3.5 Mesh

The finite element software FIDAP generates the mesh for the computational domain. The mesh is as shown in Fig. 3.2. Approximately 60 x 100 elements, and about 6500 nodes were used for the simulation. The size of elements near the boundary was smaller than the elements in the inner part and lower portion of the mold. The elements used were two noded linear elements at the boundaries and four noded quadrilateral elements in the rest of the mesh.

3.6 Solution procedure

The following steps were taken in the present work to calculate the flow conditions in a thin slab casting mold:

1. Calculations were carried out to predict only fluid flow conditions in the calculation domain. No heat transfer was considered in these calculations. The Eqs. 3.1 .. 3.3, and 3.6 .. 3.16 were solved simultaneously.

2. Calculations were then performed to get coupled fluid flow profiles with temperature variation in the mold. The conservation of thermal energy equation 3.4 was solved simultaneously with fluid flow equations stated above.

3. The time dependant concentration contours were then predicted by modeling the grade change operation in caster. The time dependant Eq. 3.5 was solved after
solving the fluid flow in the caster. The velocity values generated by fluid flow solution were substituted in Eq. 3.5 to solve for the tracer concentration contours.

Figure 3.2: Mesh generated by FIDAP for mathematical modeling.
CHAPTER 4

WATER MODELING

The opacity and the high temperature of molten steel renders it difficult to make direct observations and measurements of various flow parameters within the mold. Therefore, researchers have used water modeling to simulate the flow of molten steel in the tundish and the mold. It is a relatively inexpensive, convenient, and highly instructive way to observe the flow of water in scaled down models of metallurgical reactors. Water modeling also offers a convenient means of validation of mathematical models.

Before embarking on a review of the fluid flow for Thin Slab Casting of steel, some terms used are explained as following:

1. **Pulse Input**: At a certain time a pulse of tracer is instantaneously introduced into the system. Mathematically, a pulse input is represented by the Dirac-delta function. In practice, it is impossible to instantaneously input a tracer into the system. However, an adequate approximation to a pulse input can be made as long as the input time is much less than the mean residence time of fluid in the system. Figure 4.1(a) shows the inlet concentration profiles for a pulse input of tracer.
2. **Step input:** When at a certain time the concentration at the inlet is suddenly changed and maintained at that level, the input concentration profile represents a step as shown in Fig. 4.1(b).

3. **Mean residence time:** The theoretical mean residence time, \( \bar{t} \), is defined as the ratio of the volume of fluid in the mold to the volumetric flow rate. The real mean residence time, \( t_m \), of a fluid is obtained from the actual residence time distribution plot.

4. **Residence time distribution (RTD):** The residence time distribution of a fluid for a system indicates the amount of time spent within the system by different fluid particles input to the system. The plot of the outlet concentration of the tracer with time is called the residence time distribution of the system. Typical RTD plots for the pulse and tracer inputs are as shown in Figs. 4.2(a) and 4.2(b). The RTD for a pulse input is called a C-curve and for a step input is called a F-curve.

### 4.1 Selection of an appropriate tracer

For visualizing the flow of fluid in the mold, a tracer is introduced at the inlet and the profiles of the tracer is recorded using a video camera. The concentration of tracer is also monitored at the outlet to get the RTD plots.
Figure 4.1: Schematic diagram of (a) pulse input and (b) step input.
Figure 4.2: Schematic residence time distribution curves for (a) pulse input (C-curve) and (b) step input (F-curves).
Essentially a perfect tracer should merely tag a volume of fluid as it flows and should not influence the system and its properties at all. The tracer should be non buoyant and should not effect the fluid flow. Salt solutions have been used earlier as tracer in the water modeling studies [7]. In general salt solutions have slightly greater density than that of water. Also in actual systems copper has been as a tracer in the molten steel. But copper is denser than the steel and so is not a very appropriate tracer.

In the water modeling setup for studying thin slab casting of steel the red colored water soluble dye of Warner-Jenkinson Co. was used as the tracer. Since it is a water soluble dye and also in a very small proportion in water, therefore the difference in the density of tracer solution and water is considered to be negligible. Therefore, it is a nearly perfect tracer. The dye is detected at the outlet by the colorimeter which detects the amount of light transmitted through the water at the outlet and relates it to the concentration of the dye in the water.

4.2 Similarity criteria for the water modeling of molten metal flows

In water modeling the flow of molten steel is simulated by that of water. For the results of the water model to be translated to describe the flow of molten steel in the thin slab casting mold, it is necessary that certain criteria be satisfied. These criteria are known as “similarity criteria”. Satisfaction of these criteria ensures that the flow of water in the
water model is similar to the flow of molten metal in the reactor. The criteria ensure that the following similarity conditions are satisfied between model and prototype:

1. **Geometric similarity:** Satisfaction of this condition requires that all the dimensions of the model be in the same proportion to each other as the corresponding dimensions of the prototype, in other words geometric similarity requires that the model and the prototype be of the same shape.

2. **Mechanical similarity:** This is applied to systems which are subject to forces.
   a) **Dynamic similarity:** Forces acting at a given time or at a given location in a model and a prototype should bear a fixed ratio.
   b) **Kinematic similarity:** This condition is satisfied if all the velocities in the model system are in the same proportion to the velocities at the corresponding points in the prototype system. Attainment of geometric and dynamic similarity necessarily results in the satisfaction of kinematic similarity.

3. **Thermal similarity:** This is achieved if the proportion of heat transfer by each mode of conduction, convection and radiation should be the same in the model and the prototype.

Geometric similarity in the water model can be achieved by making sure that all the dimensions of the model are in the same ratio to the corresponding dimensions of the prototype. This ratio is called the scaling factor. In our case the scaling factor of half \((L_m/L_p)\) was used.
Dynamic similarity is probably the most important of all the similarity criteria, because the nature of the forces acting in the system determine the fluid flow profile in the system. Some of the forces that are important in the systems with flowing fluids are inertial forces, viscous forces, surface tension forces and buoyancy forces. Dynamic similarity between the model and the prototype is usually attained by ensuring that certain dimensionless numbers, or, groups between the two remain constant. These dimensionless groups represent ratios of the relevant forces acting on the fluid in the system. The dimensionless groups that are relevant to a particular system can be obtained by examination of the dimensionless Navier Stokes equation. According to Szekely et al [41], the Navier Stokes equation using dimensionless variables can be written as

\[
\frac{\partial \mathbf{u}^*}{\partial t^*} + \frac{\partial (\mathbf{u}^* \cdot \mathbf{u}^*)}{\partial x_j^*} = \frac{1}{Re} \frac{\partial}{\partial x_j^*} \left( \frac{\partial \mathbf{u}^*}{\partial x_j^*} + \frac{\partial \mathbf{u}^*}{\partial x_i^*} \right) - \frac{\partial \sigma^*}{\partial x_i^*} + \frac{1}{Fr}
\]

(4.1)

Using the above formulation, it was then postulated that for dynamic similarity between the water model of the thin slab casting mold and its prototype, the Reynolds number (Re) and the Froude number (Fr) should be the same in the model as well as the prototype. Re and Fr are respectively defined as:

\[
Re = \frac{\rho \cdot U \cdot L}{\mu}
\]

(4.2)

\[
Fr = \frac{U^2}{g \cdot L}
\]

(4.3)
In the above equations, $U$ and $L$ are the characteristic velocity and length of the system, $g$ is the gravitational acceleration, $\mu$ is the fluid viscosity and $\rho$ the fluid density. Since the kinematic viscosity ($\mu/\rho$) of the water at the room temperature and that of the molten steel at $1600^\circ$C is nearly same (within 10%), it can be shown from Reynolds number similarity that

$$U_m \approx \left( \frac{1}{\lambda} \right) U_p$$  \hspace{1cm} (4.4)

where $\lambda$ is the scale factor, and the subscripts $m$ and $p$ refer to the model and prototype respectively. Similarly, the Froude similarity between a model and a prototype yields:

$$U_m = \sqrt{\lambda} \cdot U_p$$  \hspace{1cm} (4.5)

It is very obvious from Eqs. 4.4 and 4.5 that satisfying both the Reynolds and Froude similarity criteria in a water model at the room temperature is only possible with the use of full scale model i.e. $\lambda=1$ by maintaining the same velocity in the model and the prototype. In a reduced scale model ($\lambda<1$) only one of the two criteria can be satisfied. Sahai and Emi [42] found that most of the researchers have chosen the Froude similarity criterion in which reduced velocity is used in the model in accordance with Eq. 4.5. Sahai and Emi [42] stated that Reynolds number is important in the laminar flow systems but in the turbulent flow systems the turbulent Reynolds number is naturally satisfied so long as one operates in the turbulent flow regime. On the other hand Froude number similarity being the ratio of the inertial and gravitational forces is not very important for modeling isothermal systems. However, Froude number provides relationships between the
prototype and its reduced scale model in terms of various scale factors. Thus, it becomes a very convenient method of modeling flow aspects in a thin slab casting mold. In the water modeling experiments of thin slab caster the flow was always highly turbulent. Therefore, in the present work Froude number similarity criterion was satisfied.

4.3 Design of Water model

The water model design was debated as to be either tapered or parallel (same as that in the caster). The tapered design was considered as it was argued that it can better model the mold fluid flow because it takes into the account the presence of the solidified shell in the real caster. The argument that goes against this is that in the real caster the volume of molten steel is reduced as we go down the caster. This is because some of the molten steel solidifies and forms the shell, which we wanted to model using the tapered mold. If a tapered water model is used then the amount of liquid does not decrease because there is no solidification or outflux of water on the sidewalls. Therefore if a tapered mold is used then the fluid flow will be faster than it should be because of the decrease in the cross-sectional area. So, it was concluded that the parallel wall water model is the best design for water modeling.
4.4 Water model setup

A schematic diagram of the water model setup is as shown in Fig. 4.3. The model is a half scale model made out of plexiglass. The picture of the model is as shown in Fig. 4.4. The half scale water model was based on the design used for thin slab casting presently used by the industry. The design was supplied by the sponsors, FOSECO Inc. The dimensions and the drawings of the half scale model are shown in Fig. 4.5. For constructing the curved portion in the plexiglass model an Aluminum plate was machined using CNC machine to serve as a die. The plexiglass was then heated and set into the required shape by pressing on the machined Aluminum piece.

The plumbing connections of the water model were set up with the pipes of 1 1/2in. diameter. The tracer concentration at the outlet was measured with the help of Brinkmann PC 910 colorimeter. The colorimeter was first calibrated and then used to measure the outlet concentration. The output from the colorimeter was also sent to an attached computer, which read the readings and helped in the analysis of experiments. The software used for this purpose was SMART-D. The software acquires the transmittance value from the colorimeter through a data acquisition card and using the calibration coefficients, converts these values into concentration and generates C-curves. A C-curve generated by SMART-D for a water modeling experiment is as shown in Fig. 4.6.
Figure 4.3: Schematic of the water model setup.
Figure 4.4: Picture of the water model.
Figure 4.5: Dimensions and the drawings used for constructing the water model.
Figure 4.6: C-curve generated by SMART-D software.
From this C-curve data generated by the water modeling experiments, the F-curves were generated using the equation:

\[ F = \int_{0}^{t} Cd\theta \]  
(4.6)

where, \( \theta \) is the dimensionless time, \( F \) refers to the dimensionless concentration for step input and \( C \) refers to the dimensionless concentration for the pulse input.

### 4.5 Experimental procedure

The water model was run at the flow rate of 22 gallons/min. (0.00139 m³/s) which corresponds to the casting rate of 4.61 m/min. in the real system. It was not possible to operate the water model at the flow rate of 23.75 gallons/min. because the flow rate of incoming water in the water holding tank was less than 23.75 gallons/min. and slightly greater than 22 gallons/min.. Therefore, if the flowrate of 23.75 gallons/min. would have been used, the water level in the water holding tank would slowly go down and would be empty by the time the water level in the plexiglass mold stabilizes.

The following steps were taken for conducting water modeling experiments:

1. A syringe with water soluble dye, described in section 4.2, was inserted in the pipe carrying water to the SEN. The syringe was inserted about 12 inches above the nozzle. About 5ml of dye was taken when only flow visualization experiments were performed. For conducting the RTD experiments, the dye was diluted to
one-eighth of its original concentration and 10ml of it was used for each experiment.

2. Water was then allowed to fill the water holding tank.

3. The water flow was then started by switching on the pump and the valve at the outlet of the mold was closed to allow the water level to go above the SEN ports.

4. The valve at the outlet of the mold was then opened such that the water level in the mold was constant. Also, the submergence depth of the SEN was kept constant at the desired value (generally 5 in.).

5. The valve at the outlet of the pump was then adjusted such that the flow rate of 22 gallons/min. was observed.

6. Steps 4 and 5 were repeated till a steady state was achieved. It was concluded that the steady state has been achieved when the level of the water in the mold did not change for about 5 to 10 mins.

7. The dye was then injected in the water model and the fluid flow profiles were recorded using the video camera. The Smart-D software was switched on to starts recording the concentration of the dye, passing the colorimeter probe, 7 seconds after the dye was injected into the mold. The 7 second period was the time taken by water to travel from the bottom of the mold to the drain, where the probe of the colorimeter was installed.

A major problem encountered during initial runs of the water model was the presence of air bubbles in the incoming stream of water to the mold (at the outlet of SEN). Initially, it was postulated that the joint of the SEN and the pipe (that brings in the water from the
pump) causes air entrainment. After carrying out a number of tests and experiments it was concluded that the above stated joint was not the cause of air entrainment. It was found that the air entrainment occurred through joints in the SEN. The joints in the SEN were not air tight and so they were the reason for air entrainment. Therefore, in the present work the joints of the SEN were sealed with rubberized silicone to stop air entrainment in the water model. The joints were further sealed by a duct tape, which was put over the dried silicone. Rubberized silicone was used instead of adhesive as it can be taken off easily when the experiments are over. This led to the desired condition of no bubbles (or almost zero bubbles) in the water model.
CHAPTER 5

RESULTS AND DISCUSSION*

Results of the mathematical model, and the water modeling experiments, described in previous chapters are presented and discussed in this chapter. The finite element software, calculations of velocity, temperature and composition in the mold and the strand are performed by solving fluid flow, heat transfer and mass transfer equations. The predicted velocity profiles are compared with available experimental data in the literature. The mathematical modeling results are then verified using the water modeling technique described in chapter 4 and a new SEN for thin slab casting was designed after analyzing the results from mathematical and water modeling. A part of the discussion is also based on the literature survey and various brainstorming sessions.

5.1 Flow Pattern

Fluid flow equations as described in chapter 3 are solved to get the longitudinal symmetry plane velocity profiles in the top 4 m portion of the strand. The SEN design

* The figures of this chapter are placed towards the end of the chapter.
used for these simulations was provided by FOSECO Inc. and is shown in Fig. 5.24. The mesh used to calculate the fluid flow profile is shown in Fig. 5.1. The fluid flow profile generated is as shown in Fig. 5.2. In this figure the velocity vectors are drawn at every node. This figure shows how the flow leaves the nozzle as a strong jet, traveling across the mold to impinge upon the narrow face, then splitting vertically into two streams. One of the stream flows upward along the narrow face towards the meniscus and flows along the metal slag interface back towards the nozzle. The other stream flows downward along the narrow face. A part of it flows down and a part of it flows back in the upward direction along the longitudinal symmetry plane symmetric plane to create a lower recirculation zone. The extent of the lower recirculation zone is greater than the upper recirculation zone. Figs. 5.3 and 5.4 depict the contours of turbulent kinetic energy and dissipation in the continuous casting mold.

5.2 Temperature

The temperature contours in the molten steel due to extraction of heat by the mold walls are as shown in Fig. 5.5. The isotherms near the SEN exit shown in the Fig. 5.5 clearly outline the path of the hot steel and show how the flow carries heat to narrow face wall. As the jet moves, it cools and heat diffuses radially away from it due to the conductivity of molten steel. When the stream impinges the narrow face, it splits to flow both in upward and downward directions. As these two streams flow along the mold walls, they continue to cool against the solidifying steel shell. The steel flowing downward quickly
loses its remaining superheat and produces a cold liquid pool below the impingement point.

Significant temperature gradients occur in the solidified shell. These temperature gradients were calculated by modeling the temperature profiles inside the mold in the thickness direction. The assumption in creating this model was that the velocity of molten steel was taken to be 5 m/min. at the top of the mold and the bottom was treated as the outlet. The left side boundary was taken to be the symmetric boundary and fixed value of temperature was assigned at each node at the symmetric boundary line. The values of temperatures assigned at the symmetric boundary were calculated from the longitudinal symmetry plane temperature profiles. The temperature profiles are taken at a distance 1 m from the symmetric boundary towards the mold wall. The heat transfer coefficient on the mold wall was taken to be 500 W/m²/K [43, 44]. The outline of the shell in the narrow side of the mold is shown in Fig. 5.6. The temperature profiles at the top portion and at the bottom portion of the slab in the thickness direction is shown in Fig. 5.7 and 5.8 respectively. The red line (left most temperature contour) of 1798K depicts the liquidus temperature of steel and has solidified shell to its right and molten steel to its left.

5.2.1 Effect of Thermal Buoyancy

To investigate the importance of the thermal buoyancy forces, one simulation was performed to solve for the coupled velocity and temperature fields including this effect (Fig. 5.9). Comparison of velocity profiles in Figs. 5.2 and 5.9 illustrate the finding that
thermal buoyancy forces are not very important in the mold, producing no significant change in either the velocity or temperature fields. This result is expected, because the inertia of the liquid entering rapidly through the nozzle exceeds the thermal buoyancy forces. Later, when the jet has slowed enough to be affected by secondary forces, its superheat has been dissipated and there is little temperature difference to drive the flow. The dominance of the inertial forces on the flow in the upper liquid pool can be seen through evaluation of the modified Froude number. This dimensionless quantity represents the ratio between inertial and thermal buoyancy forces,

\[
\frac{BuoyancyForce}{InertialForce} = \frac{g \cdot l \cdot \beta \cdot \Delta T_0}{u^2}
\] (5.1)

where,

- \(g\) = acceleration due to gravity, 9.8 m/s\(^2\)
- \(l\) = characteristic length, 0.925m
- \(\beta\) = thermal expansion coefficient of molten steel, 10\(^{-4}\) K\(^{-1}\)
- \(\Delta T_0\) = temperature difference, K

and

- \(u\) = velocity, m/s

Inserting a typical velocity of 0.3 m/s in the above equation yields a value of 0.3 for the condition when maximum temperature difference was 25 K. Therefore in some places where \(u > 0.3\) m/s the inertial force dominates the buoyancy force and also when \(u < 0.3\) there \(\Delta T_0 \ll 25\) K, the ratio in equation 5.1 is much less than 1. So in this system the inertial forces are much higher than the buoyancy forces due to temperature differences.
Thus, it appears reasonable that the jet position, which controls the overall flow pattern and accompanying heat transfer in the mold, should not depend on buoyancy phenomena.

5.3 Validation

To validate the simulated fluid flow profiles, to determine that the simulated fluid flow profiles in our mathematical model are valid, the fluid flow solution is compared to the experimental measurements stated in the literature [45]. The geometry and the boundary conditions of the simulated mold were changed according to the continuous casting conditions with which the simulated results were compared. Two cases were modeled. In one case the submergence depth was much more than the other case. The double roll pattern existed in the case where submergence depth was 300 mm (Fig. 5.10) whereas single roll pattern existed in the case where submergence depth was small (almost zero).

The velocity vectors of the longitudinal symmetry plane plane from Fig. 5.10 and Fig. 5.11 came out to be similar to that of Fig. 5.12 and 5.13 respectively. This proves that the mathematical modeling parameters are reasonable and similar models with slightly different parameters can be assumed to give correct fluid flow profiles.
5.4 Intermixing

The mathematical model of steel grade transition (i.e. intermixing) in the thin slab casting process was developed. From mathematical calculations, it is expected that the convective flux is much greater than the diffusive flux. This is because the velocities are so high in the system that the flux due to convection is much greater than diffusion. Contours of the normalized concentration of the species at a certain time after the grade change are as shown in Fig. 5.14. The mass transfer equation, Eq. 3.5 was solved to get these concentration contours. The values of velocity in Eq. 3.5 were found by solving the turbulent Navier-Stokes equations, Eqs. 3.2 and 3.3. The velocity solution was not considered to be dependant on the solute concentration in the molten steel. The mixing behavior was qualitatively found to be as expected. In this case the concentration of species was raised from 0 to 1 at time, t=0. The dimensionless concentration at the outlet versus time (F-curve) is shown in Fig. 5.15.

5.5 Effect of casting conditions on intermixing

The dependence of mixing on casting parameters such as casting speed, submergence depth and casting angle were studied.
5.5.1 Casting Speed

The influence of casting speed on mixing in the strand was investigated by changing the input velocity of molten metal. Casting speed (in the steady state domain) has little qualitative effect on the flow pattern in the strand. The magnitudes of the velocities simply change proportionally. This is because the flow inside the mold is turbulent. However, casting speed has a significant effect on both mixing in the strand and solidification. A slower casting speed increases the time needed to reach the normalized concentration of 1. This effect is shown in Fig. 5.16. It was found that the weight of intermixed steel is almost the same for all the casting speeds. This is as shown in Fig. 5.17. This is because the thin slab casting mold is a highly turbulent system and therefore, the change in input velocity changes the velocities in the system proportionally and so when the amount of waste metal is calculated then the velocity factor is eliminated as it has changed proportionally with no change in the nature of flow.

5.5.2 Submergence Depth

Changing the nozzle submergence depth changes the impingement point on the narrow face wall in direct proportion. Also, the change in submergence depth is expected to show a change in the surface velocities at the meniscus.

A change in submergence depth is not expected to bring about any significant change in the intermixed grade. Since the submergence depth changes the velocity at the meniscus
but not at the outlet. This is because the change in fluid flow pattern and mixing only effects the upper portion of the strand. And also, the flow pattern remains almost the same. This was observed in Fig. 5.18. The intermixed tonnage is as shown in Fig. 5.19. Fig. 5.19 shows that the waste tonnage is almost constant for each case of 10-90\(^1\) and 20-80\(^2\) respectively.

### 5.5.3 Casting Angle

Casting angle significantly effects the fluid flow pattern. Changing the jet angle changes speed with which the new grade is transported to the meniscus. However, there is no measurable change along the longitudinal symmetry plane in the slab. This is because the change in fluid flow pattern and mixing only effects the upper portion of the strand. The waste or intermixed grade tonnage is shown in Fig. 5.20 for different casting angles. This shows that waste tonnage is not affected by casting angle and almost constant for different cases of 10-90 and 20-80 respectively.

### 5.6 Coupled intermixing in both tundish and mold

The coupled effect of intermixing in both tundish and mold was studied by using the concentration profiles at the outlet of tundish as the concentration at the inlet of the mold. This means that at the inlet of the mold the transient boundary condition was used. The

\(^1\) 10-90 is the steel between the dimensionless concentration of 0.1 and 0.9 of the new grade of steel.

\(^2\) 20-80 is the steel between the dimensionless concentration of 0.2 and 0.8 of the new grade of steel.
mixing in the tundish was studied at FOSECO Inc. using water modeling techniques. The concentration profiles at the outlet of the tundish from the water modeling experiments were input as transient boundary conditions at the inlet of the math model of the mold. Figure 5.21 shows the normalized concentration at the outlet of calculation domain with respect to time. It is noted that the “Fwfo” (refilling tonnage = 7.3 tonnes) system takes the least amount of time to reach the normalized concentration of 1 whereas “Fzfo” (refilling tonnage$^3$ = 25.9 tonnes) takes the most. Fig. 5.22 is the plot of waste tonnage with respect to refilling tonnage of the tundish. From the Fig. 5.22 it can be deduced that the lower the refilling tonnage or amount of steel in the tundish, the lower will be the wastage.

### 5.7 New SEN design

A new Submerged Entry Nozzle was designed to improve the quality of thin slabs produced by thin slab casting technique. SEN was designed by identifying the problems that occur due to the bifurcated nozzle and the other SEN designs, being currently used. The characteristics of the ideal SEN were identified and these characteristics served as the design criteria. The new SEN was designed by modifying a currently used SEN design. The mathematical modeling and water modeling techniques were used to model the fluid flow that is expected to occur in the real thin slab caster. Firstly, mathematical model was used to design the new SEN and then water modeling experiments were done on the design that was predicted by math modeling. Water modeling is necessitated by

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$^3$ Refilling tonnage is the amount of steel remaining in the tundish when refilling of tundish is started.
the fact that the mathematical model predicts the fluid based on theoretical equations and is two dimensional in nature. Therefore, the mathematical model may involve inaccuracies in predicting the fluid flow behavior in the real system. Besides validation, fluid flow due to finer changes in the SEN design was studied using the water modeling technique as it is more reliable technique than mathematical modeling to model the fluid flow in the real system.

5.7.1 Bifurcated SEN

In the continuous casting of steel, the bifurcated nozzle is a widely used popular design for the SEN. The fluid flow in a bifurcated nozzle is a complex phenomenon, as shown in Fig. 5.23. The SEN design being presently used by Nucor Steel Co. for thin slab casting is shown in Fig. 5.24. The computer model results of fluid flow inside the SEN are shown in Fig. 5.25(b). The fluid flow profile in Fig. 5.23 shows that most of the molten steel flows out of the lower part of the port and the top part of the port is the area of relatively stagnant flow, where the fluid actually recirculates back to the SEN. But this stagnant area can be eliminated by improving upon the nozzle design. For example, in Fig. 25(b) no stagnant or recirculation area can be seen inside the SEN. The bifurcated nozzle also leads to complexity in the fluid flow inside the mold. Figure 3.1 shows the schematic flow patterns in the liquid pool in the continuous casting mold. Molten steel from the tundish is delivered to the mold using bifurcated SEN. The molten metal stream exits the SEN ports and strikes the solid steel shell along the narrow face of the mold. Upon impact with the narrow face, the metal stream splits into two portions. The upper portion
of this stream flows along the narrow face towards the meniscus. It then flows horizontally along the metal-mold slag interface until it meets the corresponding molten metal stream from the other side of the SEN. It then merges back with the SEN exit stream. The lower portion of the two streams goes down along the narrow face. A part of it keeps going down and another part of it goes upwards towards the SEN. This is the lower recirculation zone shown in Fig. 3.1. The solidified steel shell is withdrawn continuously at a constant speed. Therefore, the shell profile as seen at different intervals of time remains constant. The flow in the liquid pool in the continuous casting mold is assumed to be a steady state phenomena at all times.

The main disadvantages of the bifurcated nozzle are as follows:

1. **Nozzle clogging:** Nozzle clogging occurs in the vertical bore and sometimes in the exit holes. Clogging changes the flow pattern in the mold, and thereby deteriorates the cleanliness of slab influencing the quality of slab produced. Sometimes nozzle clogging occurs at the exit holes because of the stagnant area present in the upper region of the port.

**Reducing / Eliminating Nozzle clogging:**

a) This can be done by keeping inclusions away from SEN walls. One of the ways to do this is by inducing whirls inside the SEN. The whirling motion inside the SEN will keep inclusions away from the walls due to the centripetal force on the inclusions. Therefore, the inclusions will to deposit on the SEN walls.
b) The exit stream should utilize full port area of SEN. This eliminates the prospects of the presence of a stagnant region in the upper portion of a mold, which might lead to nozzle clogging.

2. **Surface waves** cause
   - mold flux entrapment
   - unstable meniscus and uneven shell growth
   - uneven mold flux layer leading to lubrication problems
   - uneven heat flux leading to longitudinal cracking

   **Reason:** High velocities of the molten steel in the mold and at the surface of the molten steel are primarily responsible for the presence of surface waves.

   **Elimination/Reduction of Surface waves:** By reducing velocity of molten steel at the surface as much as possible.

3. **Vortex** at meniscus
   - mold flux entrapment

   **Reason:** High velocities of the molten steel in the mold and the surface are mainly responsible for the presence of vortex at the meniscus.
Elimination/Reduction of Vortex: By reducing the velocity of molten steel at the meniscus.

4. **Inclusion Floatation:**
   - decreased floatation at high velocity of molten steel.
   - the exit jet from SEN acts as a barrier, which cannot be crossed by most of the inclusions.

**Reason:** High velocity of the molten steel in the mold.

Increased inclusion floatation can be achieved by decreasing the SEN exit stream velocity.

5. **Shell thinning and breakout:** Due to impact of SEN exit stream on the strand shell, the shell becomes thinner and hotter on the narrow sides. Therefore, shell thinning and breakouts are greatly influenced by the velocity of exit stream. The impingement point also greatly influences the shell thinning. The impingement point should be inside the mold and high enough to have uniform and maximum heat flux as possible.

Elimination/Reduction: The lower the velocity of the molten steel in the mold better the strand shell. Generally, the higher the impingement point the lower the chances of shell breakout.
6. **Trapped bubbles:** Bubbles of injected Argon gas can become entrapped in the steel shell. The bubbles collect alumina inclusions while in the liquid steel. When the steel shell solidifies around the trapped bubbles, “pencil-pipe defects” are formed.

**Solution to most of the above problems** is the reduction of the velocity of molten steel in the mold, especially at the meniscus. But the reduction should be such that the heat transfer at the surface is adequate, so that the problem of meniscus freezing does not arise. Wada *et al* [46], Teshima *et al* [3] and Kubota *et al* [4] proved that there is an optimum range of surface stream velocity, which does not cause the powder slag entrapment.

The positive results of reducing the velocity have also been observed in the case of ElectroMagnetic Braking (EMBR) [27, 47]. In this technique, opposite electromagnetic forces are applied to the SEN exit stream. This results in reduced velocities in the mold as shown in Fig. 5.26. This figure shows both the fluid flow profiles without EMBR and also with EMBR. The case B shows that the application of EMBR results in lower velocities in the mold. The authors of this process claim when EMBR is applied, the quality of steel slabs is significantly better than that of the case when no EMBR was applied.
5.7.2 Ideal SEN

On studying the various disadvantages of the bifurcated nozzle, and various defects in the slab due to different conditions inside a given thin slab caster [2, 5, 24 . . 34], the characteristics of the ideal SEN were identified. The defects in the thick slab casting were also considered in studying these characteristics. The effect of techniques like EMBR that have helped in improving the quality of continuous casting mold were also studied for formulating the characteristics of ideal SEN. The understanding of these characteristics helped in identifying criteria for designing innovative SEN designs for improving the fluid flow conditions inside the mold and hence, improving the quality of slab produced. The various characteristics of an ideal SEN are as follows:

1. The exit stream should go through the whole port of the SEN.
2. The velocity of molten metal at SEN exit should be as low as possible.
3. There should be no stagnant region inside the SEN and no nozzle clogging should take place.
4. There should be no vortex at the meniscus.
5. The velocity of liquid steel at the meniscus should be as low as possible with enough heat input such that meniscus freezing doesn’t take place.
6. The lifespan of SEN should be as long as possible.
5.7.3 Limitations on the SEN design

Some of the SEN design limitations are as follows:

1. The SEN should fit in the mold.
2. In context of manufacturing of SEN, the design should be as simple as possible.
3. The cost of SEN should be as low as possible.
4. The SEN should be designed such that its wear and tear should be minimum, which leads to as long life of the SEN as possible. Materials more resistant to erosion should be used at places where the erosion of the SEN is expected to be maximum.

5.7.4 Current SEN designs

Various SEN designs are used by the steel industry for thin slab casting. Most companies use some variation of bifurcated two port nozzle. Its advantages and disadvantages have already been discussed. Another SEN design used by ARMCO has a three port nozzle and is shown in Fig. 5.27. The nature of flow pattern in the mold due to three port nozzle is different from that of the bifurcated nozzle. The fluid flow in the mold due to three port SEN is expected to have six recirculation loops as compared to four in the case of bifurcated nozzle. This is shown in Fig. 5.28(a). The computational modeling results (Fig. 5.28(b)) of the three port nozzle qualitatively match the nature of fluid flow illustrated by the authors of the ARMCO design. The authors of this design claim that the meniscus is calm, stable, hot and there are no flux entrapments [31, 32]. They also claim
that surface quality of the slab produced is good and there are no longitudinal, transverse and corner cracks on the slab surface. The reason of the above stated advantages might be that the velocity of molten steel in the mold is lower than what it would be in the case of bifurcated nozzle with the same SEN exit area. This is because a part of the volume of the liquid steel flowing through the side ports goes through the port in the middle of the SEN. This results in lesser fluid going through the same area and hence, lower SEN exit velocities and hence lower velocities in the mold.

Few designs have been suggested in the literature. One of them is use of dams inside the SEN, as shown in Fig. 5.29 [48]. But detailed information is not available on these designs. Also, this kind of design has a big drawback that it may not be easy to manufacture, and the SEN life is expected to be less than what it would be without the baffle. This is expected because of excessive wear and tear on the dam.

5.7.5 Basis for the new SEN design

A lot of brainstorming was done in the creation of a new innovative SEN design. The aim of the thought process was to create a SEN design, which has the characteristics as close to that of an ideal SEN as possible. Also, the SEN has to be within the limitations that it should fit inside the mold and the design should be simple. The bifurcated nozzle design supplied by FOSECO Inc. (Fig. 5.24) was the basis for the new SEN design. It was sought to improve this design by reducing the exit velocity of the fluid from the SEN. Melt flow through various SEN designs was predicted by mathematical models. The
mathematical modeling results of the bifurcated nozzle design (Fig. 5.24) are shown in Figs. 5.25(a) and 5.25(b).

5.7.6 Evolution of the new SEN design

5.7.6.1 Mathematical modeling

A couple of designs conceived initially are shown in Figs. 5.30 and 5.31. The presence of baffles inside the nozzle helps to distribute the fluid equally through out the nozzle cross-section. The computer modeling plot of the fluid flow vectors for the design shown in Fig. 5.30 is shown in Fig. 5.32. This plot shows that there is no significant improvement in fluid flow inside the mold. Moreover, these designs are not easy to manufacture and will have a relatively smaller lifespan than the SEN currently being used because of the wear and tear of the baffle. The baffles are expected to wear out much faster than any other part of the nozzle because the molten steel flowing through the bore of the nozzle strikes the baffles and then changes its direction. Also, the baffles have to be as thin as possible for good results.

Another design of a nozzle with a hole in the center and a baffle inside the nozzle was conceived. The idea of the baffle as stated in the earlier case is to help to distribute the fluid through out the cross-section of the nozzle. The presence of the hole, as depicted in Fig. 5.33 is to allow a certain amount of fluid flowing through it so that a smaller amount of molten metal flows through the side ports. This helps in reducing the velocity of fluid
flowing out of side ports of the SEN. Figure 5.33 shows reduction of the velocity of fluid flowing out of the SEN. But due to the presence of the baffle, this design is also difficult to manufacture and will have a shorter lifespan due to the wear and tear of baffle.

A couple of more SEN designs were conceived. These designs, as shown in Figs. 5.34 and 5.35, have the elongated dams that run to the end of the ports. This design will increase the total area of the ports as the increased area will be fully utilized by the molten steel exit stream. Hence the exit velocity of the fluid from SEN will be reduced. This design should be relatively easy to manufacture. From this design another design was conceived (Fig. 5.36) which further led to our final design from the side ports. This design is based on the fact that if the volume of the fluid going through the side ports is reduced then the exit velocity of the molten steel will also be reduced. To achieve this, a fluid collecting well is made inside the SEN and the fluid collected from this well is passed through the central ports. This means that the well helps in forcing a certain amount of fluid through the central port. The design shown in Figs. 5.36, 5.37 and 5.38 did not work because the streams from the central ports\(^4\) merged with that of the side ports\(^5\) and did not have much effect on the velocities.

In the next case, the side port was shifted to the right as shown in Fig. 5.39. This change did not show much affect on velocity profile as compared to the one observed in Fig. 5.37. The velocity vector plots can be seen in Figs. 5.40 and 5.41.

\(^4\) In case of SEN having more than two ports, the ports which are towards the center are termed as central ports.
Another nozzle with ports at different angles was designed. In this case, the side port was at the angle 30° from the vertical and the central port was at an angle of 15° from the vertical. Velocity profiles are as shown in Figs. 5.42 and 5.43. It showed a slight decrease in velocities of the molten steel in the mold but indicated that the separation of the streams of the central and side ports will reduce the velocity of the molten steel in the mold. This separation was achieved by putting the central port at an angle of 15° from the vertical and side port at an angle of 55° from the vertical. The depth of the well was increased and the width of the side port was decreased. Figs. 5.44, 5.45 and 5.46 show the changes in the geometry and the fluid flow profiles in the SEN and the mold, respectively. This is a good design and significant improvement over the currently used bifurcated SEN design because the velocities are significantly reduced as compared to that of the bifurcated nozzle design. The nature of fluid flow due to this nozzle design resembles that of the three port nozzle used by ARMCO, Mansfield (now AK steel) [31, 32]. The fluid flow profile in this design has six recirculation loops, similar to the loops as in ARMCO’s design. This has an added advantage over ARMCO design as the central stream has relatively less penetration depth compared to the three-port nozzle used by ARMCO (Fig. 5.28(b)).

It was tried to improve upon the previous design (Fig. 5.44) by tweaking the parameters of the side and central ports. For example, as shown in Fig. 5.47 the central port was made wider and shifted towards the center and the angle of the side port was decreased to 43° from the vertical. But the fluid flow profile in this case was not the same as in the

\[5\] Side ports are the ports of SEN which are away from the center and shoot molten steel to the narrow walls.
previous case. Also the side port of the nozzle was changed so that it has larger width to reduce the velocity of the liquid going through the side port. But the velocity profiles were not good as the streams from the side ports merged with the stream from the central port. This is shown in Figs. 5.48 and 5.49. It is undesirable that the velocity flow profile in the mold has a large penetration depth and also, there is relatively little movement of molten steel in the upper region of the mold.

In another case central port of the design shown in Fig. 5.44 was made wider by 5 mm but the resultant flow in the mold did not improve because the side port exit stream merged with the central port exit stream, thereby creating a large penetration depth and relatively no movement of liquid steel at meniscus, which is highly undesirable.

So it was again sought to take these two streams apart by increasing the angle of the side port and limiting the width of central port to 27.5 mm. The angle of side port was changed to 60° from the vertical (Fig. 5.50). The computer model plots (Figs. 5.51 and 5.52) show that the side port exit stream still merged with the central port exit stream, though in this case the merger was a bit delayed as compared to the previous case. There is a possibility that on increasing the angle between the side and central exit streams, the streams will not merge. But that may not be a useful design as the impinging velocity on the nearest wall will be greater leading to higher velocities at the meniscus, which is undesirable.
The increase in the width of central port was tried to increase the amount of liquid steel going through the central port. But it was found that if the width of central port is increased then the angle of side port from the vertical has to be increased to separate the streams from the central and side ports. Another effort was made to force more volume of liquid steel to flow through the central port. This was done by increasing the length of the well wall by 5mm as shown in the Fig. 5.53. The results are as shown in Figs. 5.54 and 5.55. The results are not an improvement over the SEN design shown in Fig. 5.54. So it was concluded that for this kind of a design, the design shown in Fig. 5.54 is the optimum SEN design predicted by mathematical modeling.

The angle of side port was changed from $50^0$ to $65^0$ to find out the window of design in which the nozzle design shown in Fig. 5.54 is good for producing better quality of steel slabs. Figs. 5.56 and 5.57 show the fluid flow in the system when the angle of the side port is changed to $50^0$ from the vertical. The rest of the geometric parameters remained the same. In this case the molten steel coming out of the SEN is divided into two streams in the symmetrical half of the mold. The symmetrical half of the mold has three recirculation loops. This is similar to the molten steel flow in Fig. 5.58 (side port of SEN at the angle of $55^0$ from the vertical). Also the same kind of fluid flow was observed when the angle of the side port was increased to $65^0$ from the vertical (Fig. 5.58). But in this case a large part of the stream of the liquid steel coming out of the central port was going straight down the strand. The close up of the fluid flow in SEN shows that when the angle of side port is $65^0$ (Fig. 5.59) the fluid flowing through the central port is much more than the case when the angle of side port is $50^0$ (Fig. 5.56). If the angle of side port
is increased then more liquid steel will flow through the central port leading to deeper impact of the stream coming out through central ports. This kind of flow is not good for the quality of steel slabs produced because it is expected to reduce the inclusion floatation. So the upper limit of the angle of side port was taken to be $65^0$ from the vertical. For the lower limit, as seen in the Fig. 5.19 where side port angle was $43^0$. The streams from the central and side ports merged in this case, whereas in the case when the side port was at an angle of $50^0$ from the vertical the streams were separated. So it can be concluded that the limiting angle when the two streams separate lies between $43^0$ and $50^0$. Therefore, the new SEN design is suitable to operate when the angle of the side port lies between $50^0$ and $65^0$.

### 5.7.6.1.1 Study of velocity profiles with change in casting parameters

The width of the mold was varied from 0.941 m (36 inches) to 1.85 m (72.83 inches) to investigate changes brought to the nature of fluid flow on changing the width. The fluid flow in the 36 inch wide mold is shown in Fig. 5.60. The fluid flow in the 50 inch wide mold and 72.83 inch wide mold is shown in Figs. 5.61 and 5.46 respectively. On comparing these velocity vector plots it was found that the nature of fluid flow in the symmetrical half of the mold remains same i.e. the exit flow from the SEN bifurcates into two different streams, one going straight down and the other hitting the side wall of the mold. The stream that hits the sidewall gets further divided into an upward and a downward flow along the mold wall. There are three recirculation loops in the symmetrical half of the mold for each case. It was observed that the width of these
recirculation loops is dependant on the width of the mold. The greater the width of the mold, the greater the width of the recirculation loops.

The effect of casting speed on the nature of fluid flow for the new SEN design was studied. Figs. 5.62, 5.46 and 5.63 show the fluid flow in the mold for the casting speeds of 4, 5 and 5.85 m/min., respectively. It was observed that there is no difference in the fluid flow except for the fact that on changing the casting speed the velocity of the fluid changes proportionally.

To improve upon the new SEN design the surfaces were curved instead of sharp corners. The molten steel flow in the curved SEN is shown in Fig. 5.64 and the steel flow in the mold is shown in Fig. 5.65. In this case the fluid flow in the mold is much better as the SEN exit velocity of the molten steel at the side port is reduced and therefore, is expected to produce better quality of slabs.

5.7.6.2 Water modeling

The water modeling was necessitated by the fact that the mathematical model is a two dimensional model which predicts the casting conditions in the longitudinal symmetry plane of the caster. Also the mathematical model has the limitation of being the time-averaged model of a turbulent system. So it is expected that the fluid flow profiles predicted through mathematical modeling may not be exactly the same observed in the real caster. So water modeling, being more reliable, is conducted after mathematical
modeling to get the correct results. The mathematical modeling is used because it is economical and easier to make small changes in mathematical model and analyze its effects. Minor changes in the new SEN design from mathematical modeling were made and the effects due to these changes were studied using water modeling.

A series of experiments were done on the water model described in the previous chapter. The flow profiles were visualized using water colored dye as tracer and were recorded using a digital camcorder. The water model due to physical restrictions could not be run at 23.75 gpm (5 m/min. of casting rate in the prototype). Instead 22 gpm of flow rate of water was used which corresponds to the casting rate of 4.61 m/min.

The fluid flow profiles for the nozzle shown in Fig. 5.24 matched well with that of the mathematical modeling results. The impingement point on the narrow face wall of the stream coming from the SEN is predicted to be 1m below the meniscus by mathematical modeling. The impingement point came out to be 0.5m below the meniscus in the half scale water model. This shows that in the full scale system the impingement point is 1m. This matches very well with the results of the math modeling. Also, a small dead zone was found near the meniscus on the narrow face. This dead zone was also observed in the water model.

Water modeling experiments were also performed on another nozzle design (Fig. 5.67) currently being used for thin slab casting. Intermixing experiments were also performed
using the two different nozzle designs (Figs. 5.24 and 5.67) currently being used for thin slab casting. The resulting F-curves (as described in previous chapter) for the two nozzle designs are shown in Fig. 5.68.

The new nozzle design designed by using mathematical modeling techniques was built for conducting water modeling experiments on it. The technical drawing of the half scale nozzle used for water modeling experiments is shown in Fig. 5.69. On performing the water modeling experiments it was found that the fluid flow profiles are not the same as predicted by the mathematical model. The flow profile observed in the water model is as shown in the schematic of Fig. 5.70. To get the central streams to merge the nozzle was changed to as in Fig. 5.71. This change did not get the central streams to merge. Therefore, the overall angle of the central ports was changed from 15° to 10° from the vertical. This helped in getting the central streams to merge. The changes in the nozzle design are as shown in Fig. 5.72. In both Figs. 5.71 and 5.72 the dotted lines represent the original design as shown in Fig. 5.69 whereas the solid lines denote the design being represented by that figure. The fluid flow profiles observed in the water model were close to the expectations. One problem was that the central streams had the tendency to go to one side of the mold rather than coming straight down this led to the dead zone in one part of the mold. This dead volume in some experiments would be in one half of the mold and in some experiments on the other half. This is as shown in the Fig. 5.73. It was sought to reduce or eliminate the dead volume by making a hole in the middle of the central divider used in the original SEN design shown in Fig. 5.69. The change is as shown in Fig. 5.74. The idea behind this change was to reduce the dead volume by directing the fluid towards
every part of the mold. But this change did not reduce the dead volume. On the contrary, the dead volume increased. The increase in the dead volume was easily perceived by the naked eye.

Reduction in the dead zone was achieved by reducing the angle of the central divider to 10\(^0\) from the vertical and the outer walls of the central ports were kept at 15\(^0\) from the vertical. This nozzle design is shown in Fig. 5.75. Further reduction in dead volume was achieved by reducing the angle of side ports from 55\(^0\) to 45\(^0\) from the vertical. The change in the nozzle is as shown in Fig. 5.76. The Residence Time Distribution (RTD) experiments were performed on these nozzles. These RTD’s were compared with the RTD’s of SEN currently being used for thin slab casting (N1 and N2). The comparison of the C-curves (Fig. 5.77) and F-curves (Fig. 5.78) show that the new SEN design (N4) has less dead volume and better intermixing than other nozzles. The comparison is tabulated in Table 5.1.
Table 5.1: The comparison of various SEN designs using water modeling experiments. The nozzles N1, N2, N3 and N4 refer to nozzle designs shown in Figs. 5.67, 5.24, 5.69 and 5.76 respectively.

### 5.7.7 Advantages of the new SEN design ("N4-Final Design")

The new SEN design ("Final Design") has the following advantages over the SEN designs being currently used by the steel industry for thin slab casting of steel.

1. The impingement point is higher (by about 14 in. in real caster) and therefore, the probability of shell breakout decreases considerably.
2. Due to the higher impingement point and greater angle of the nozzle with respect to the vertical, it is expected to have better heat transfer to the meniscus. So mold flux is expected to be in the molten state.
3. The meniscus is very stable and quiet. Therefore, it is expected that the problem of mold flux entrapment will not arise.

4. The system is more stable and predictable. The oscillation has decreased considerably and the oscillation frequency has decreased. The streams coming out of the side ports are very stable and don’t seem to be oscillating.

5. The dead volume is less than that in the case of other SEN designs.

6. The off-grade tonnage is expected to decrease on the use of the new SEN design.

5.7.8 Characteristics of the new SEN design ("N4-Final Design")

- The new SEN design is derived from the bifurcated two port SEN design. The design is evolutionary in nature and not a revolutionary one. The design was made such that the resulting SEN design has characteristics as close to that of an ideal SEN as possible.

- The new SEN design is shown in Fig. 5.69.

- The new design aims upon reducing the exit stream velocity from SEN. This will lead to lower molten steel velocities in the mold. Thereby, improving the properties of the system and the quality of steel slab produced.

- The volume of liquid metal flowing through the side ports is reduced in order to decrease the SEN exit velocity of molten steel.

- The reduction of the volume of liquid metal flowing through side ports is attained by diverting some part of liquid coming from the central bore to a well which collects the molten metal and flows it out into the mold through central ports.
• As it can be seen in Fig. 5.45, the well acts like an overflowing container. Due to this and also, because of the geometry of the nozzle the velocity of the molten steel along the exit cross-section is more uniform.

• The presence of well stabilizes the flow because the oscillation of the central/stagnation point does not matter much as long as it does not go out of the range of the well. It can also be stated that the well acts as the absorbing media of the turbulence in the system. It dampens the oscillation and therefore induces stability in the flow.

• There is a divider inserted at the bottom of the well.

• The divider acts like a barrier to the stream coming out of the bottom of the well and does not allow it to go straight down into the mold and have a large penetration depth.

• The divider divides the fluid in the well into two streams that eventually come out of the bottom of the nozzle at an angle with the vertical. The two central streams after coming out of the bottom of the nozzle recombine but before that their velocity is reduced because each of the central stream expands just after coming out of the nozzle.

• Due to the reduced velocity of the central stream the penetration of the central stream in the mold is minimal.

• Separation of the side streams and the central streams from each other was achieved. For this the angle of separation between the side ports and central ports should be greater than 30°.
• For optimal design the side port (or the upper port) angle should range from $35^\circ$ to $45^\circ$ from the horizontal. The central port (or the lower port) should be at the angle of $80^\circ$ to $90^\circ$ from the horizontal.

• About 60-65% of molten metal comes out of the side ports (or the upper ports) whereas 35-40% of molten metal comes out of the central ports (or the lower ports).

• Due to this new nozzle design there are six recirculation loops in the mold whereas due to a bifurcated nozzle there are four recirculation loops. The recirculation loops are shorter in the case of the new nozzle design.

• The water modeling results have shown that the intermixing is much better in the mold due to this new SEN design. This means that the off grade tonnage is reduced on using the new SEN design.

• The off-grade tonnage is greatly reduced in a slab caster on using the new SEN design.
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Central port
(width= 0.02m)

Figure 5.36
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Central port
(width= 0.02m)

Side port

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Central port
(width = 0.025m)

Figure 5.44
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Central port (width= 0.03m)

Figure 5.47

Central port (width= 0.0275m)

Figure 5.50
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Central port
(width= 0.025m)

Figure 5.53
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CHAPTER 6

SUMMARY

A mathematical model has been developed to calculate the molten steel flow profiles in a thin slab caster under steady state conditions. The fluid flow is highly turbulent in the mold. The mathematical model calculations show good agreement with available experimental measurements for the fluid flow in a continuous casting slab. So the mathematical modeling results for the thin slab caster are assumed to be close to the real conditions.

The fluid flow results were used to calculate the temperature profiles in the mold. The temperature and the velocity of the impinging jet on the narrow face are very high. Therefore, at the point of impingement slab thinning or breakage might occur. A simple mathematical model was developed for solidification taking place in the thickness dimension of the mold. The temperature gradients in the solidified shell are significant and may lead to the development of thermal stresses in the mold which might cause defects like longitudinal cracking.
A mathematical model was developed to calculate the mixing in the strand and the slab during steel grade transition in the continuous slab casting process. The model was based on turbulent fluid flow and mass transfer models. The intermixing was studied for both conditions, “flying tundish” and coupled intermixing in tundish and mold. The effect of various casting parameters on the intermixing was studied. It was found that increase in casting speed reduces the time needed to reach a given concentration in the strand. But it was also found that the waste tonnage remains almost the same for different casting speeds. Also, the effect of casting angle and submergence depth on the intermixing in the slab was studied. The results show that the intermixing does not depend at all on the submergence depth and the casting angle.

The problems associated with bifurcated SEN were discussed and the characteristics of ideal SEN were defined. The SEN designs being used currently for thin slab casting were also studied. A new innovative SEN was designed based on the fact that lower the SEN exit velocities in the caster, the lower the velocity of molten steel in the caster and hence, better the quality of thin slabs produced. The new SEN design (“Final Design”) is expected to provide better stability, intermixing and solidification characteristics in a thin slab caster than that of the SEN designs currently being used.
REFERENCES


37. FIDAP 7.0 manuals, 1993.


