Mathematical Model and Plant Investigation to Characterize Effect of Casting Speed on Thermal and Solidification Behavior of an Industrial Slab Caster

Vikas SINGH1)* and Suchandan Kumar DAS2)

1) R&D, Tata Steel Ltd., Jamshedpur, 831001 India.
2) CSIR-National Metallurgical Laboratory, Jamshedpur, 831007 India.

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Development of a validated 3D transient mathematical model for modeling the fluid flow and solidification process in an industrial continuous slab caster has been demonstrated. The model couples thermo-fluid aspect of mold and sub-mold region by utilizing a standard Enthalpy-porosity method. Extensive plant level measurements of mold heat fluxes and thermocouples data, breakout shell thickness profile, and macrostructures were carried out to evaluate proper input of heat transfer and other conditions for the model. A suitable validation of the model is established with slab surface temperature and solidified shell thickness profile as measured from a breakout shell in the caster plant. An insight is drawn for an industrial slab caster from the model results analysis for a range of operating parameters of casting speed and SEN submergence depth as employed in the caster. Evolution of a solidified shell thickness profile is simulated. Slab surface temperature mapping is drawn from the model and discussed its variation originating due to fluid flow inside the solidified shell. Casting speed is shown to have a dominant effect as temperature rise of order of 50°C are observed as it is increased from an average plant value of 1.4 m/min to peak of 1.8 m/min. Similar effect is also reflected in the solidified shell thickness profile as shell thickness gets thinner by an order of 6 mm in the sub-mold region due to increase in casting speed from an average to peak value. The effect of SEN submergence depth is also outlined.

KEY WORDS: mathematical model; slab caster; casting speed; heat transfer; solidification; solidified shell thickness; SEN submergence depth.

1. Introduction

To remain competitive in today’s world-wide market for continuously cast steel products, steel producers are finding that it is ever more important to implement model based process control and to develop a more thorough technological understanding of their casting process. Accurate prediction and control of heat transfer and solidification in steel caster operation allows more flexibility by giving operators ability to change casting speed while keeping critical process parameters within required range. Such control capability also results in more uniform cast steel quality throughout an entire casting sequence from startup to shutdown.1,2) Furthermore, due to the unreliability of temperature sensors, and the lack of good sensors for important process parameters such as solidification end-point and liquid pool depth, computer-based models are often the only available option. To increase productivity of a continuous slab caster, high-speed casting is desired.

Casting speed, which is directly related to caster productivity, is one of the most important parameter for the continuous steel casting. Appropriate setting according to the operating conditions, the steel grade being cast and the caster parameters is crucial to produce steel slabs with the desired quality and structure, and also to minimize the occurrence of defects. In addition, the produced steel’s properties can be further optimized.3) The importance of the proper setting of the casting speed is obvious on the parameters like the entire temperature distribution (e.g., the surface and core temperatures of the steel slab that are very often required to fit a certain range of temperatures, e.g., due to the straightening), the iso-solidus and iso-liquidus curves that characterize the solidification process e.g. the shell thickness along the slab4) or the metallurgical length. High speed casting is also reported to cause breakout and other surface defects in the caster due to active flow of liquid steel and low solidified shell thickness in the mold.

Numerical modeling of continuous casting has been the scope of many studies5) and is of great interest to help the caster engineers to adjust their process parameters like cooling conditions or casting speed. Modeling of solidification phenomena in a caster is fairly complex and computationally expensive. Earlier, crude empirical correlations...
were used to predict the solidification behavior, however, solidification inside the caster is a 3-dimensional (3D) phenomenon and shell thickness changes accordingly. Over the year, sustained efforts have been made by various investigators around the world to develop better understanding of the various strongly coupled multi-physics phenomenon of continuous slab caster to achieve improvements in both quality and productivity, however capturing the right inputs for the model from an operating caster is key to draw any meaningful conclusions from such modeling work. With the progressive advancement of the computing power, increasingly complex models are being developed to characterize the melt flow, heat transfer and solidification behavior in a multi scale framework.

In the present work, a 3D transient model has been developed for the slab caster mold to analyze the heat transfer and solidification behavior within the mold of an industrial slab caster. The influence of increased casting speed on slab surface temperature field and solidified shell profile has been examined for a low carbon steel grade as a function of Submerged Entry Nozzle (SEN) submergence depth pertaining to non-isothermal flow conditions. The heat flux boundary condition has been generated from the plant data for mold cooling and Savage-Prichard correlation is utilized with suitable customization. Plant measurements were carried out on break out shell samples from the operational slab caster to successfully validate the model predictions.

2. Development of Solidification Model of Operational Slab Caster

A validated 3D transient solidification model for slab caster of Tata Steel has been developed to characterize solidification behavior incorporating the influence of increased casting speed and submergence depth of SEN in the mold. Slab caster solidification phenomena involves coupling of both heat transfer and fluid flow inside the mold which needs a multi-physics treatment. In this study, an “Enthalpy-porosity technique” has been employed to formulate the process model. The main advantage of this technique is that it allows a fixed-grid solution of the coupled momentum and energy equations to be taken without resorting to variable transformations.

2.1. Model Assumptions and Governing Equations

The following model assumption has been invoked:

(i) The effect of argon injection and overlying mold powder addition on the mold flow dynamics is negligible. This implies that the flow field is not altered because of argon injection and overlying mold powder addition.

(ii) Boussinesq approximation is invoked for buoyancy term in the momentum equation.

(iii) Shell pull velocity is equal to casting speed.

(iv) Heat capacity and thermal conductivity are considered to be independent of temperature for the range of the study.

(v) Heat generation due to any phase transformation during solidification is neglected.

(vi) The slag layer on top of molten steel is assumed to diminish the radiative heat transfer considerably.

(vii) Effect of mold oscillation on heat transfer and fluid flow behavior is ignored.

(viii) Local surface temperature variations due to effect of slab support rolls and spray is averaged.

The solidification model governing conservation equations are as follows:

Continuity equation
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad \text{...... (1)}
\]

Momentum equation
\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p + \nabla \cdot (\mathbf{T}) + \rho \mathbf{g} + \mathbf{S} \quad \text{...... (2)}
\]

where, \( S = \frac{(1-\beta)^2}{(\beta^3 + \varepsilon)} A_{\text{mush}} (\bar{v} - \bar{v}_p) \quad \text{...... (3)} \)

and \( A_{\text{mush}} = \frac{\mu}{\lambda^2 + (6 \times 10^{-3})} \quad \text{...... (4)} \)

Energy equation
\[
\frac{\partial (\rho H)}{\partial t} + \nabla \cdot (\rho \mathbf{v} H) = \mathbf{\nabla \cdot (k_e \nabla T)} + \nabla \cdot (\rho \beta \mathbf{v} \mathbf{H}_f) \quad \text{...... (5)}
\]

, where \( \mathbf{VH} = \beta \mathbf{V H}_f \quad \text{...... (6)} \)

\[ H = h + \beta \mathbf{V H}_f \quad \text{...... (7)} \]

\[ h = h_{\text{eff}} + \int_{T_{\text{ref}}}^{T} C_p \beta T \quad \text{...... (8)} \]

\[ k_e = k_1 + \frac{C_p \mu_1}{Pr} \quad \text{...... (9)} \]

\[ \beta = \begin{cases} 0 & T < T_i \\ \frac{T - T_i}{T_i - T_c} & T_i < T < T_c \\ 1 & T > T_c \end{cases} \quad \text{...... (10)} \]

The boundary conditions for the slab caster model and all pertinent input data have been generated from extensive plant level measurements and described here.

a. Inlet: The entry point of the SEN was used as inlet surface. Inlet velocity corresponding to the desired casting speed for molten steel was calculated by the volumetric flow balance. Uniform distribution of velocity and temperature across the inlet surface was applied. The incoming liquid steel temperature was set as 1 830 K. The inlet conditions for the turbulence variables for SST k-omega model were taken semi-empirical correlations as below.

\[ k = \frac{3}{2} \frac{(u_m l)^2}{l}, \text{ where } l = 4\% \quad \text{...... (11)} \]

\[ \omega = \frac{k^{1/2}}{C_p l} \quad \text{...... (12)} \]

where \( l = 0.07 d_{\text{in}}, \text{ } d_{\text{in}} \) is SEN entry bore diameter.

b. Meniscus: It was treated as free surface with conditions...
as below. Heat losses by radiation are taken into account through Stefan’s law.

\[
\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = \frac{\partial T}{\partial z} = 0, \quad w = 0 \quad \text{..............(13)}
\]

c. SEN walls: No slip condition along with adiabatic thermal condition was applied.
d. Mold and sub-mold walls: Pull velocity concept has been employed to take downward shell movement into account. In the mold, heat flux profile is applied as per customized Savage-Prichard heat flux correlation whereas in sub-mold a combined convective and radiative thermal boundary condition has been applied to the wall.
e. Outlet: With a fully developed flow assumption at outlet, following conditions used:

\[
\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = \frac{\partial w}{\partial z} = \frac{\partial T}{\partial z} = 0 \quad \text{..............(15)}
\]

2.2. Numerical Solution Procedure

The approach utilizes standard solution procedures for the enthalpy-porosity technique. In this technique, the melt interface is not tracked explicitly. Instead, a quantity called the liquid fraction, which indicates the fraction of the cell volume that is in liquid form, is associated with each cell in the computational domain. Based on an enthalpy balance as per Eq. (5), the liquid fraction computation is done at every iteration. The mushy zone is a region in which the liquid fraction lies between 0 and 1. The mushy zone is modeled as a “pseudo” porous medium in which the porosity decreases from 1 to 0, as the material solidifies. When the material has fully solidified in a cell, the porosity becomes zero hence velocity also drops down to zero.

The 3D simulation is done using the segregated pressure based, transient solver using an implicit, control-volume-based finite volume scheme to discretize the conservation equations. Non-uniform meshing is used for SEN-mold & sub-mold regions as depicted elsewhere. Fine grid has been taken near the wall and SEN having more than 1.5 million cells. The discretized finite volume equations yield a set of linear simultaneous equations for all cells which is solved through a least-square cell method. In this study, the second order upwind scheme is used as the discretization scheme for momentum, first order for the turbulence kinetic energy and dissipation rate, whereas for energy the “Quadratic Upstream Interpolation for Convective Kinematics” (QUICK) scheme\(^{27}\) is been used and the “Pressure Staggering Options” (PRESTO) scheme\(^{27}\) is used for pressure interpolation. For the discretization of time first order implicit scheme is employed. Standard pressure discretization scheme interpolates the pressure on the faces using the cell center values. On the other hand, PRESTO actually calculates pressure on the face, gives more accurate result since interpolation errors and pressure gradient assumptions on boundaries are avoided. The velocity pressure coupling in momentum equations is handled using the SIMPLE algorithm.\(^{27}\) SST k-ω turbulence model has been used to take care of turbulence for the present analysis.

\[
\begin{align*}
\text{Table 1. Parameters used in solidification modeling.} \\
\text{Parameter} & & \text{Value} \\
\hline
\text{Mold width, mm} & 1300 \\
\text{Submergence depth, mm} & 160, 240, 320 \\
\text{Casting speed, m/min} & 1.4, 1.8 \\
\text{Mold computational length, m} & 5 \\
\text{Mold thickness, mm} & 215 \\
\text{SEN bore, mm} & 75 \\
\text{Port size, mm}^2 & 55 \times 100 \\
\text{Superheat, K} & 25 \\
\text{In temperature, K} & 1830 \\
\text{Solidus, K} & 1796 \\
\text{Liquidus, K} & 1805 \\
\text{Steel} & \text{Low carbon (0.04% C)} \\
\end{align*}
\]

The fluid flow is solved in transient manner up to 150 sec using the transport equations as given earlier; afterward a pseudo steady state is achieved. Multiple monitor points are used for establishing fluid flow development in the computational domain before starting solidification module. The time step is maintained at less than 0.01 sec. The convergence criterion for the momentum equation was established when the sum of residuals for flow \textit{i.e.} the residual error of the mass source term, must be less than 10e-5 and for the energy variables, the relative error must be less than 10e-9. The solidification model was run until a pseudo steady temperature field is obtained and solidified shell thickness is no more changing which is approximately after 300 seconds of calculation for this analysis. The parameters used for the simulation is depicted in Table 1.

3. Plant Level Measurements & Data Generation

Right boundary condition is crucial for correct prediction of the solidification along with the suitable models. Hence, amount of heat transfer through slab surface in the mold and sub-mold region was captured through plant data. Extensive plant level measurements were carried out to customize the model for an operational slab caster at Tata Steel. Mold cooling water temperatures along with mold thermocouple data was mapped to assess thermal profile across the mold. Mold cooling water temperature data is captured from the operating plant. The water temperature is registered at inlet and outlet of both the mold plates of narrow and wide faces. Large number of data was collected for varying operating conditions. Accordingly, the coefficients in the Savage-Prichard correlation were customized for the particular casting conditions.

3.1. Mold Heat Flux Profile Assessment

In order to customize the slab caster solidification model for the operating plant, it is imperative that realistic plant data are generated through careful measurements which can be used as input into the model. Measurement of mold heat transfer profile through primary cooling parameter is one of important input to the model. Water is used to extract heat from the mold and runs through each face of the mold. \(\Delta T_w\)
i.e. inlet and outlet temperature of water through mold can be used to calculate the total heat extracted from each face of the mold. $\Delta T_w$ data provides total heat extracted from the mold but does not give the distribution across length of the mold. Savage-Prichard correlation gives idea about the distribution; however different set of coefficient may represent the real plant conditions. The correlation coefficients can be evaluated by the plant data like the total heat extraction from the mold and water flow rates through each mold face. Thus, the customized correlation provides the distribution for Tata Steel operating slab caster plant. For the purpose, $\Delta T_w$ data was collected for various conditions with varying SEN submergence depth, casting speed, and steel grades. A large number of data was collected from the operating plant. Owing to normal operating variations in the plant, the plant data captured is categorized in two scales viz. Low and High encompassing both lower and higher operating ranges. The definition of data ranges are depicted in Table 2.

Table 3 shows data set of the operating conditions for which $\Delta T_w$ has been collected and organized for calculating coefficients for customized Savage-Prichard correlation. Figure 1 shows a typical set of $\Delta T_w$ data as obtained from the operating industrial slab caster. Variation in the data is attributed to normal operational variation of the plant. Such data was also collected for other conditions of the slab caster viz. steel grades, SEN submergence depths. It is clear from the data that mold cooling water $\Delta T_w$ increases with casting speed. As mold cooling for the narrow faces and wide faces are independent of each other, hence it is also reflected in the $\Delta T_w$. This data is useful in calculating the total heat extraction from each face of the mold as explained below. However, in reality the local heat flux varies from top of the mold to mold exit and for real prediction the model requires to capture this. The variation in local heat flux can be explained by Savage-Prichard expression as given below.

Local heat flux (q) distribution is given by Savage-Prichard expression:

$$ q = A - B \sqrt{\frac{Z}{u_c}} \quad \cdots \cdots \cdots \cdots \cdots (16) $$

Where, $Z$ is casting length along the mold and A & B are empirical constants.

Average heat flux (Q) across mold surface is related with q by:

$$ Q = \int_0^Z q \, dz / z \quad \cdots \cdots \cdots \cdots \cdots (17) $$

From Eqs. (16) & (17):

$$ Q = A - 0.5068 * B \sqrt{\frac{Z}{u_c}} \quad \cdots \cdots \cdots \cdots \cdots (18) $$

$\Delta T_w$ data from plant quantifies Q as:

$$ Q = F_u * C_p * \Delta T_w / A_{mold} \quad \cdots \cdots \cdots \cdots \cdots (19) $$

Calculations using Eqs. (17) & (18) provide with real heat flux profile for the model by computing coefficient A & B for wide and narrow mold face. The coefficients computed for modeled conditions (#1 & 2 in Table 3) are

For wide mold: $A = 2.209$, $B = 0.145$

For narrow mold: $A = 2.18$, $B = 0.09$

It is also demonstrated that heat transfer profile is directly proportional to mold embedded thermocouple temperature. The above heat flux is calculated based of several sets of data analysis.

3.2 Analysis of Plant Mold Heat Flux Profiles

Figure 2 shows the calculated mold heat flux profiles for various sets of parameters as given in Table 3. It can be seen in the figure that heat flux profile not only depends upon casting speed as given in the Savage-Prichard relation but also upon SEN submergence depth, steel grade as well. The various data sets given in the figure provide useful insight about the heat transfer dynamics of the caster mold. Now, by comparing the data set of steel grade low carbon1 where submergence depth is high and casting speed is varying from low to high, it can inferred that the two cases has almost same heat flux near the meniscus negating the influence of casting speed. Another set of data for steel grade low carbon1 with low submergence depth and varying casting speed indicates the same i.e. the near meniscus heat flux is not affected much by casting speed variations. While looking at data set where submergence depth is varying with rest
of the parameters constant, can give effect of submergence depth. Again with steel grade low carbon1, for low casting speed and varying submergence depth from low to high, it can be concluded that higher submergence depth has lower near meniscus heat flux and is quantifiable in the modified Savage-Prichard relation. A similar observation can also be made for steel grade low carbon2 at any casting speed in the figure. The finding is also in line with fluid flow in the caster mold. As submergence depth increases, the submeniscus velocity decreases resulting in lower heat transfer near meniscus.

Effect of casting speed is visible on heat flux down the mold. Considering data set for steel grade low carbon1 with high submergence depth and varying casting speed from low to high, it can be seen from the figure that the rate of heat flux decrease is more for lower casting speed. To check on consistency, another data set of steel grade low carbon2 with low submergence depth and varying casting speed can be looked into; here the rate of heat flux decrease is more for lower casting speed as well. Similar observations, thus conclusion can be made for the rest of such cases irrespectively of steel grade or SEN submergence depth.

Effect of steel grade has its effect both on meniscus heat transfer as well as down the caster mold. To highlight its effect, the data set having steel grade high carbon and low carbon1 can be compared. As can be seen from the figure, high carbon steel grade has higher meniscus heat transfer than that of the low carbon steel grades. This is mainly due to the fact that the high carbon steel grade has wider liquidus to solidus range, thus mushy region is thicker than that of the low carbon steel grades. Hence, for the high carbon grade, initial shell formation near meniscus enables better surface contact due to the ferro-static pressure causing increased heat transfer. While at lower mold region, better surface contact due to the ferro-static pressure causing carbon grade, initial shell formation near meniscus enables that of the low carbon steel grades. Hence, for the high liquidus to solidus range, thus mushy region is thicker than that of the high carbon steel grade has wider meniscus heat transfer as well as down the caster mold. To highlight its effect, the data set having steel grade high carbon and low carbon1 with high submergence depth and varying casting speed can be looked into; here the rate of heat flux decrease is more for lower casting speed as well. Similar observations, thus conclusion can be made for the rest of such cases irrespectively of steel grade or SEN submergence depth.

3.3. Primary Dendrite Arm Spacing (PDAS) Measurements to Calculate Mushy Constant

Enthalpy porosity method employs a mushy zone constant to take care of the phenomena inside the mushy region as given by Eq. (3). The constant is an input to the solidification model and is suitably calculated from plant measurements. Gu and Beckermann gave a correlation that links PDAS measurements in the slab from an industrial slab caster to mushy zone constant. PDAS in a solidified shell depends on the cooling rate as experienced by the local solidified shell and varies from the surface of the slab to the core of the slab. Thus a variation can be captured by carefully measuring PDAS across thickness of the slab under specified conditions. To evaluate the cast structure of a low carbon grade, macrostructure was revealed by taking out samples from a fully solidified shell. Bechét-Beauchard etchant was used to properly reveal the primary dendrites. The variation of PDAS along caster thickness was measured to add to the model development. Figure 4 shows the macrostructure of the steel slab caster taken at an off-centered position (350 mm from narrow face). The left most edge is wide face of the slab while right most edge represent centerline parallel to wide face of the slab. Coarsening of PDAS is observed as seen from near wide face towards core of the slab. The measurement of PDAS is done by digital optical microscope at several points at varying shell thickness values of 4, 10, 15, 18, 30, 40, 70, 95 mm from wide face. 50 measurements at each location are done to have a representative value of PDAS. A typical measurement corresponding to 4 mm shell thickness from wide face is shown in Fig. 5. The figure indicates an average value to 0.16 mm of primary arm dendrite spacing. Figure 6 shows measured PDAS values corresponding to various shell thickness. It can be observed that large variation is present near surface. The variation in PDAS diminishes inside core of the slab. The small values near slab surface are indication of chill zone as pointed out in various literature. This variation in PDAS has to be reflected in mushy zone constant for taking the reality into account. With the use of Gu and Beckermann correlation, mushy constant is suitably calculated for proper input in the solidification model.
4. Results and Analysis

4.1. Validation of the Model with Surface Temperature and Breakout Shell Thickness Profile

The validation of the model can be done in two possible ways, one by comparing surface temperature of the slab, secondly by carefully measuring slab thickness of a breakout shell. To capture heat transfer in sub-mold region, slab surface temperature data were utilized and accordingly heat transfer coefficients were evaluated based on trial and error method to match the slab surface temperature data. Thus, the model was validated preliminary with surface temperatures measurements in region near the mold using a two color pyrometer. Figure 7 shows a good match with the plant temperature measurement for a typical operating condition of 160 mm SEN submergence depth and 1.4 m/min casting speed at middle of narrow face.

Many breakout shells were collected and measurements done with an ultrasonic based technique. At the time of breakout, the casting speed gets drastically reduced to a much lower 0.6 m/min. This requires measurement data to be corrected for the casting speed before comparison with the model results. To have a one to one match with the model results the meniscus and breakout shell top was suitably adjusted to have one scale. Moreover, care is also required in shell thickness measurement as some liquid steel flows over and solidifies after the breakout has happened. To correct for this phenomenon, the solidified shell sample was macro-etched to reveal shell thickness after the over flow of break out steel melt. The macrostructure analysis shows the added shell thickness that corresponds to the amount of liquid steel solidified over top of the normal solidified shell before the breakout happened. The casting direction is shown by the arrow with slab top surface on left side while deposition on inner (melt side) surface is shown on right side of the Fig. 8. This shows that our physical measurement post breakout will be overestimated by 2–3 mm. After taking these inputs and projecting for casting speed 1.4 m/min by the parabolic law, the breakout shell measurement and the model predictions are compared and shown in Fig. 9. Similar measurement is also shown in literature. Hence, a good match between plant breakout sample and solidification model prediction is achieved. A wave like variation in shell thickness profile due to molten metal and solidification shell front interaction is also captured by the model.

The validated model is then used for parametric investigation with various submergence depth viz. 160, 240, 320 mm with different casting speed of 1.4, 1.8 m/min. The present numerical investigation of heat transfer and solidification
analyzes the temperature and shell thickness profile inside the mold and sub-mold region. Slab temperature mapping and shell thickness profile from the model can be useful for number of further analysis like prediction of right taper in the mold etc.

### 4.2. Slab Surface Temperature

Variations in slab surface temperature are presented here for varying condition of different SEN submergence depths with casting speed. Figure 10 shows a typical slab surface temperature for wide and narrow face for submergence depth 240 mm with casting speed 1.4 m/min. Sharp temperature gradients exist near the meniscus. A “W” thermal pattern is visible on the wide face of the slab as a signature of typical double role fluid flow in the mold as result of using two port SEN. It can be observed that the temperature decreases along the casting direction with some variations along width and at the corner temperature is under predicted due to two-way cooling. Though, the model under predicts the corner temperature as it treats a perfect corner numerically while in real situation the corners may be a bit rounded due to shrinkage phenomena as a result of solidification progress.

For a quantitative comparison, surface temperature is plotted on several lines along the casting direction (Z in the Fig. 10) i.e. distance below the free surface. Figure 11 shows the predicted slab surface temperature along middle, and quarter line of wide & narrow face for the submergence depth of 160 mm and casting speed of 1.4 m/min. A large variation in surface temperature at meniscus is observed due to heavy turbulence at the meniscus. As melt jets coming out of SEN are directed towards narrow faces, meniscus experiences a higher temperature. Spatial temperature variation on narrow face is insignificant inside the mold but it starts increasing in the secondary cooling zone of the slab caster. The two way cooling adds to this variation on the narrow side. While on the wide face of the mold, the fluid flow causes some spatial variation inside the mold. Though, the variation quickly vanishes as slab moves from meniscus towards mold exit.

It can be seen in the figures that the temperature profile trend is almost same for all the locations considered. Steep temperatures gradients are observed in the mold region compared to sub-mold regions. The surface temperature rises as slab comes out of the mold region indicating a change in heat transfer mechanism from primary cooling to secondary spray cooling. The surface temperature change in the mold regions is uneven though overall declining trend is observed along the casting direction. Since the solidified shell is still thinner within the mold hence fluid flow inside the mold cavity may influence outside surface temperature. The temperature across wide and narrow face at a particular casting length remains within the range of maximum 100–120°C difference.

For parametric study, temperature along the casting length on middle and quarter lines of wide and narrow faces is compared. As can be seen from Figure 12, effect of SEN submergence depth is insignificant on overall temperature profile across the slab surface, though there is minor influence in the mold region as a lower temperature of the order of 10°C for was observed at mold exit for higher submergence depth. The reason for this may be revealed by analysis of solidification profiles later in the discussions.

A distinct shift in the temperature profile was observed for low and high casting speed of the order of 50–60°C. The temperature shifted to higher values as casting speed was increased from 1.4 to 1.8 m/min. The trend is consistent for all the studied SEN submergence depths. The reason lies in the fact that residence time of the steel is less for higher casting speed as it decreases the time for the heat extraction from inside the mold, hence higher slab surface temperature is predicted for higher casting speed. At mold exit the increase in temperature due to increase in casting speed are 40, 45 and 60°C for the submergence depth of 160, 240 and 320 mm respectively on middle line of the wide face. Quarter line temperature exhibits the same trend though a different number, not shown here for sake of brevity.

Narrow face temperature at mold exit remains a little lower than that of wide face. This is due to net balancing of higher heat supplied by liquid steel stream coming straight from SEN ports and impinging on narrow face and applied higher heat flux on narrow face. Looking at Figure 13, effect of casting speed is dominant and distinct as similar to wide face trend. Narrow face shows some influence of change in SEN submergence depth as higher submergence depth leads to few degree lower temperature (~3–5°C) in sub-mold region. The temperature difference due to submergence depth widens even more with increase in casting speed.

### 4.3. Solidified Shell Thickness

Shell growth in the mold and sub-mold region is an important criterion to decide on any changes being made for the caster operation. Sufficient and consistent shell growth is essential to avoid any breakout situation. Keeping the objective in mind, the effect of SEN submergence depth is analyzed with high casting speed of 1.8 m/min and compared with an average casting speed of 1.4 m/min in the caster. The investigation reveals some interesting findings.

Since the liquid fraction ranges from 0 to 1, where 0 represents complete solidification and 1 represents full molten steel. Numerically here, a liquid fraction less than or equal to 0.1 is assumed to be a solidified shell. A typical modeling result is shown in Figure 14 for evolution of shell profile in the mold and sub-mold region. In the 3D figure, the SEN is
Fig. 10. Slab surface temperature (K) for the SEN submergence depth of 240 mm and casting speed of 1.4 m/min.

Fig. 11. Predicted slab surface temperature along the casting length.

Fig. 12. Predicted slab surface temperature along the casting length on the middle line of wide face for submergence depth of 160, 240, 320 mm with casting speed of 1.4, 1.8 m/min.

Fig. 13. Predicted slab surface temperature along the casting length on middle line of the narrow face for various parameters.

Fig. 14. Graphical representation of solid fraction (Blue) and liquid steel fraction (Red) as a solidification model result.

Fig. 16. Comparison between Shell thickness (t) and Vorticity (ω) profile for narrow faces.

Fig. 17. Comparison of shell thickness profiles for different SEN submergence depth with low and high casting speeds.
shown at the top and liquid fraction is represented in a scale of 0 to 1 on the horizontal planes at an interval of 1 meter distance. The evolved solidification profile subtly matches with a dog bone shape, thicker at the corner regions due to two-way cooling and middle of the wide face, and gradually reducing towards corners. As model solution progresses, the solidification thickness grows from top of the mold and becomes constant until a pseudo steady state is achieved as depicted in the figure. So the solidified shell in mold always remains thinner as compared to sub-mold region. The solidified shell thickness can be quantified from the model results and plotted from top to bottom along casting direction to have solidified shell thickness profiles.

Figure 15 shows the predicted shell thickness profile at the middle plane of narrow and wide mold faces. It can be seen from the figure that the narrow face has overall thicker shell thickness as compared to the wide face. The reason lies in heat extraction rate for the two sides. In the mold region, solidification starts earlier in wide face than narrow face due to lower fluid flow velocity between SEN and wide face. This also leads to higher early shell growth near wide face in the mold. Moreover, shell growth in narrow face is delayed due to high turbulence near narrow face meniscus which causes a local mixing effect. It has been observed that the shell thickness profile is following a definite trend that is different than the theoretical parabolic profile of the shell. This is due to the interaction of fluid flow and solidification growth. It has been suitably customized for the Tata Steel slab caster and predictions for an industrial caster. Savage-Prichard correlation is suitably customized for the Tata Steel slab caster through careful measurements of mold water cooling data and thus calculation of actual mold heat flux profiles for various operating conditions as employed in the plant. The model is able to capture the interaction of fluid flow inside the solidified shell and evolving shell growth process. The effect of an increase in casting speed is demonstrated on slab surface temperature and solidified shell thickness as higher casting speed causes a reduction in shell thickness by 1–2 mm range. Similar extent of thinning can also be observed for other submergence depths as well.

5. Conclusions

A 3D transient mathematical model has been developed by taking inputs from the slab caster plant data to model the actual plant conditions and hence draw meaningful insights and predictions for an industrial caster. Savage-Prichard correlation is suitably customized for the Tata Steel slab caster through careful measurements of mold water cooling data and thus calculation of actual mold heat flux profiles for various operating conditions as employed in the plant. The model is able to capture the interaction of fluid flow inside the solidified shell and evolving shell growth process. The effect of an increase in casting speed is demonstrated on slab surface temperature and solidified shell thickness as higher casting speed causes a reduction in shell thickness by 1–2 mm at the mold exit. The range of SEN submergence depth studied has subtle effect on slab surface temperature as due to change in fluid flow inside the mold cavity local surface temperature is affected like in case of SEN submergence depth of 240 mm, it is predicted to have comparatively

![Graph showing predicted shell thickness along casting direction at middle lines for the 160 mm SEN submergence depth and 1.4 m/min casting speed.](image)
lower temperature by 10°C and thicker shell formation at mold exit region than that of 160 mm submergence depth. Difference in the shell thickness between 160 mm and 240 mm submergence depth SEN for 1.4 m/min casting speed is found to be in order of 2 mm at the mold exit.

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List of symbols

- \( A_{\text{mold}} \): Area of the mold, m²
- \( A_{\text{mush}} \): Mushy region constant
- A, B: Empirical constants, kW/m², kW/m² s⁰.²
- \( C_{p} \): Empirical constant, 0.09, specified in the turbulence model
- \( C_{p}^\prime \): Specific Heat in constant pressure, J/(kg-K)
- \( D_{in} \): Inlet diameter, m
- \( F_{w} \): Water flow rate in the mold, Kg/s
- \( g \): Gravitational force, m/s²
- h: Enthalpy, J/kg
- \( h_{ref} \): Reference enthalpy, J/kg
- H: Total Enthalpy, J/kg
- I: Turbulence intensity
- k: Turbulence kinetic energy, J/Kg
- \( k_{l} \): Laminar thermal conductivity, W/(m.K)
- \( k_{e} \): Effective thermal conductivity, W/(m.K)
- l: Turbulence length scale, m
- \( P \): Pressure, Pa
- \( P_{r} \): Turbulence prandtl number
- q: Local heat flux, kW/m²
- Q: Average heat flux across mold surface, kW/m²
- S: Source term
- \( S_{\text{sen}} \): SEN submergence depth, mm
- t: Time, s
- T: Temperature, K
- \( T_{c} \): Solids temperature, K
- \( T_{l} \): Liquidus temperature, K
- \( T_{ref} \): Reference temperature, K
- \( \Delta T_{w} \): Differential temperature of inlet and outlet of mold water, K
- \( u \): Velocity x-axis component, m/s
- \( u_{in} \): Inlet velocity, m/s
- \( u_{c} \): Casting speed, m/min
- v: Velocity y-axis component, m/s
- \( v \): Velocity, m/s
- \( \bar{v} \): Roll velocity, m/s
- w: Velocity z-axis component, m/s
- \( \alpha \): Near zero constant to avoid division by zero
- \( \lambda \): Primary dendrite arm spacing, m
- \( \mu \): Dynamic viscosity, Kg/(m.s)
- \( \mu_{l} \): Turbulent viscosity, Kg/(m.s)
- \( \rho \): Density, Kg/m³
- \( \tau \): Shear Stress vector, Pa
- \( \tau^{\prime} \): Specific Dissipation Rate, J/(Kg.s)

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