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Research Paper

EFFECT OF CASTING SPEED ON CONTINUOUS CASTING OF STEEL SLAB

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A three dimensional mathematical model has been developed to study the effect of degree of superheat and casting speed in continuous casting of steel slab. Study is based on investigation of heat transfer and solidification behaviour of steel within mold and Secondary Cooling Zone (SCZ). The Computational Fluid Dynamics (CFD) software Ansys Fluent 13.0 has been used to solve the discretized equations with realizable k-ε turbulence model. For solidification, Enthalpy-Porosity technique was used which treats the mushy region (partially solidified region) as a "pseudo" porous medium. Liquid fraction of steel in the mushy region has been traced to find the solidified shell thickness. However, calculations were made to find the temperature distribution and metallurgical length at different degree of superheat and casting speed. Result shows that superheat has a little effect on temperature distribution and metallurgical length of strand while casting speed has a significant effect. High casting speed may cause inadequate thickness of the solidified shell at the mold exit to withstand the Ferro-static pressure of the molten metal below the mold. It may also leads to breakout due to sticking of solidified shell and mold because of lack of slag film for lubrication between the two.

Keywords: Solidification, Continuous casting, CFD, Heat transfer, Mathematical modelling

INTRODUCTION

Continuous casting is the primary method in production of steel billets, blooms or slabs.The process starts by transferof molten steel from ladle through tundish to the water cooled copper mold by submerged entry nozzle, whereby molten metal get solidified into "semis" and subsequently pulled/rolled out into final product. The cooling intensity of the mold should be high enough so that steel get solidified to sufficient depth (Choudhary *et al.*, 1993; Meng and Thomas, 2003; and Amimul Ahsan, 2011) around the inner surface of the mold, forming a solid shell with molten metal in centre of strand.Moreover the solid shell formed should have an adequate amount of thickness to withstand the ferro-static pressure (Mazumdar and Ray, 2001) of the molten metal.Cooling rate has also a great influence on the formation of various defects within the

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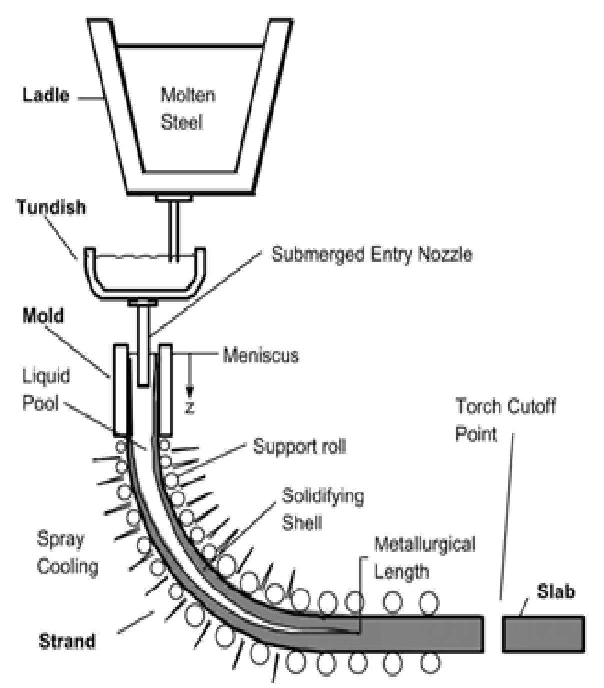
cast product (Lee *et al.*, 2000; Meng and Thomas, 2003; Li and Thomas, 2004; Thomas, 2006; Hibbeler *et al.*, 2009; and Hadala *et al.*, 2011). So an appropriate control of the strand cooling and shell growth is to be made tohave defect free products.

Atthe exit of the mould, strand enters to the secondary cooling zone. Secondary cooling zone have rollers to support the strand and assist in bending and straightening. Water sprays are present to extract the heat from the strand. These sprays are grouped as spray zones according to cooling rate required which is controlled independently by valves. Later, strand moves to radiation zone (Versteeg and Malalasekera, 2012) where it cools naturally and cut off after particular length for further processing.

Many authors have investigated cooling and solidification models (Lee *et al.*, 2000; Mazumdar and Ray, 2001; Meng and Thomas, 2003; Gonzalez *et al.*, 2003; and Amimul Ahsan, 2011) for the continuous casting in mold. It is very difficult to measure the data and process experimentally, so mathematical modelling remains a reliable tool for obtaining required information and preventing costs of experimental investigations in order to increase the productivity and quality.In the present work, a precise heat transfer model simulating the solidification process within mold and secondary cooling zone of continuous castinghas been developed. An enthalpy-porosity technique (ANSYS FLUENT) has been used using CFD softwareAnsys Fluent 13.0. In this technique, liquid fraction is calculated,which indicates the fraction of cell volume that is in liquid form. A mushy zone region is formed in which the liquid fraction lies between 0 and 1. This mushy zone is modelled as a “pseudo” porous medium where porosity decreases from 1 to 0 as the material solidifies. When the material has fully solidified in a cell, the porosity becomes zero and hence the velocities also drop to zero. Hence it can be said that the pull velocity is included for the movement of the solidified material as it is continuously withdrawn at casting speed.

In the present work degree of superheat and casting speed has been considered as the two process parameters which are varied to see their effect on the solidification behaviour of the cast product. Variation of degree of superheat is inevitable as when the next ladle starts pouring into the tundish and then further into the mold. Casting speed is important as high speed casting is required to improve productivity and production yield. High speed

Figure 1: Schematic of Steel Continuous Casting Process



casting is also reported tocause breakout (Meng and Thomas, 2003; and Li and Thomas, 2004) and other surface defects (Hakaru *et al.*, 1984; Harada *et al.*, 1990; Yeo *et al.*, 1996; and Thomas, 2006) in the cast due to active flow of liquid steel and low solidified shell thickness in the mold. Hence, in the present investigation, temperature distribution, metallurgical length and solid shell thickness at narrow and wide face has been calculated by varying the process parameters values.

MATHEMATICAL FORMULATION

Heat Transfer

Energy conservation equation for solidification can be defined as

$$\rho\frac{\partial H}{\partial t} + \rho\nabla.(\bar{u}H) = \nabla(k_{eff}\nabla T) + Q_L$$

where, H is the enthalpy of the material and can be computed as the sum of sensible heat (h) and latent heat content (ΔH),

$$H = h + \Delta H$$

Sensible enthalpy and latent heat content are defined as,

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dT$$

$$\Delta H = L\beta$$

where, L = latent heat of material, β = liquid fraction,

h_{ref} = reference enthalpy, T_{ref} = reference temperature,

k_{eff} = effective conductivity, c_p = specific heat, ρ = density,

$\bar{u}$ = velocity, Q_L = source term.

The source term Q_L, has two terms in it; explicit latent heat term and convective term. In a single phase solidification model Q_L can be expressed as

$$Q_L = \rho L\frac{\partial f_s}{\partial t} + \rho L\bar{u}_{pull}.\nabla f_s$$

The latent heat has been released from the mushy zone. In the continuous casting the solidifying shell is pulled out at a constant casting velocity $\bar{u}_{pull}$. That means the zone having solid fraction "f_s" equals to one, will move downward with the casting speed. It is to be noted that sum of liquid fraction "β" and solid fraction "f_s" is always 1. The liquid fraction can be calculated by determining the temperature as

$$\beta = \begin{cases} 0 & if\ T < T_{solidus} \\ \dfrac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} & if\ T_{solidus} < T < T_{liqidus} \\ 1 & if\ T > T_{liqidus} \end{cases}$$

Governing Equations

The continuity equation can be expressed as

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0$$

While, transient Navier-Stokes equation for momentum conservation can be expressed as

$$\frac{\partial}{\partial t}(\rho u) + \rho\nabla(uu)$$

$$= -\nabla P + \nabla\{\mu_{eff}(\nabla.u)\} + \rho + S$$

where, $\mu_{eff} = \mu_l + \mu_t$ is the effective viscosity due to turbulence and k-ε model is used for this, μ_l is the dynamic viscosity and μ_t is the turbulent viscosity. In the enthalpy-porosity technique mushy zone is treated as porous medium and the porosity of every cell is set equal to the liquid fraction in that cell. The porosity equals to zero if the zone is fully solidified, which extinguishes the velocity in that zone. Thus the momentum sink term "*S*" was added to the right hand side of the Navier-Stokes equation. The presence of this term allows the newly solidified material to move downward at constant pull velocity. The momentum sink can be expressed as

$$S = \frac{(1-\beta)^2}{(\beta^3-\xi)} A_{mus\,h}\left(\bar{u} - \bar{u}_{pull}\right)$$

where, ξ is a small number (0.001) just to prevent zero in denominator, A_{mush} is mushy zone constant. The mushy zone constant measures the amplitude of the damping; the higher this value, the steeper the transition of the velocity of the material to zero as it solidifies. Very large value may cause the solution to oscillate. In the momentum sink term, the relative velocity between the molten liquid and the solid is used rather than the absolute velocity of the liquid.

For simulating turbulence, the realizable k-ε turbulence model was used, which is found to be very much suitable. The turbulence viscosity is given by

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$

The two partial differential equations for turbulent kinetic energy (k) and dissipation rate (ε)(9)are given by

$$\rho\frac{\partial k}{\partial t} + \rho(\nabla k u) = \nabla\left(\alpha_k \mu_{eff} \nabla k\right) + G_k + \rho\varepsilon + S_k$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho(\nabla \varepsilon u) = \nabla\left(\alpha_\varepsilon \mu_{eff} \nabla \varepsilon\right) + C_{1\varepsilon}\frac{\varepsilon}{k} G_k - C_{2\varepsilon}^{*}\rho\frac{\varepsilon^2}{k} + S_k$$

Sinks are added to all of the turbulence equations in the mushy and solidified zones to account for the presence of solid matter. The sink term (11) is very similar to themomentum sink term.

$$S_k = \frac{(1-\beta^2)}{(\beta^3-\varepsilon)} A_{mus\,h}\varphi$$

where φ represents the turbulence quantity being solved (k, ε, ω, etc.), and the mushy zone constant, Amush, is the same as the one used in equation above α_k and α_ε are the inverse effective Prandtl numbers, $C_{1\varepsilon}$ and $C_{2\varepsilon}^{*}$ are the model parameters, G_k is the generation of the turbulence kinetic energy due to mean velocity gradients.

$C_1 = 1.44$, $C_2 = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$(9)

BOUNDARY CONDITIONS AND ASSUMPTIONS

The following assumptions were made during formulation of the solidification model to simplify the governing equations:

- Liquid steel as Newtonian incompressible fluid.
- Only two dimensional heat transfers (lateral direction) is considered.
- Convective boundary condition has been taken into account for extraction of heat from mold and strand.
- Density and specific heat of steel are invariant.
- Mold oscillation, bending of strand, effect of segregation, etc., have been ignored.
- Perfect contact between the shell and mold is considered as shrinkage due to solidification is ignored.

- No slip boundary condition prevails at the walls.

Based on the above assumptions, the material properties and standard boundary conditions used for analysis in present work are listed in Table 1.

Table 1: Material Properties and Boundary Conditions

Material Property, Boundary Conditions	Value
Steel Density, $kg.m^{-3}$	7200
Viscosity of Liquid Steel, $kg.m^{-1}.s^{-1}$	0.0067
Thermal Conductivity, $W.m^{-1}.k^{-1}$	41
Specific Heat, $J.kg^{-1}.K^{-1}$	750
Latent Heat, $J.kg^{-1}$	272000
Liquidus Temperature, K	1800
Solidus Temperature, K	1770
Casting Speed, m/s	1.0, 1.2, 1.4
Liquid Steel Superheat, K	15, 20, 25
Mushy Zone Constant	100000

Inlet

The mold is fed by a simple rectangular inlet port with velocity inlet of the molten steel. The velocity component at the inlet is only in z-direction (casting direction) while, inlet velocity was obtained by balancing the inlet flow rate with the casting speed. However, inlet temperature (T_{inlet}) of the molten steel was fixed according to the superheat (ΔT) provided to the steel above the liquidus temperature (T_L). The inlet temperature can be expressed as:

$$T_{inlet} = T_L + \Delta T$$

Wall

To avoid the computational difficulties associated with the heat extraction from steel through cooling water flowing within mold, heat transfer by convection (2, 12) has been considered for the mold walls.The walls with solid shell were set to move with casting velocity along the casting direction. In secondary cooling zone, different heat transfer coefficients were quantified for four sections modelled with consideration of different cooling rateswhile moving down the strand.

Outlet

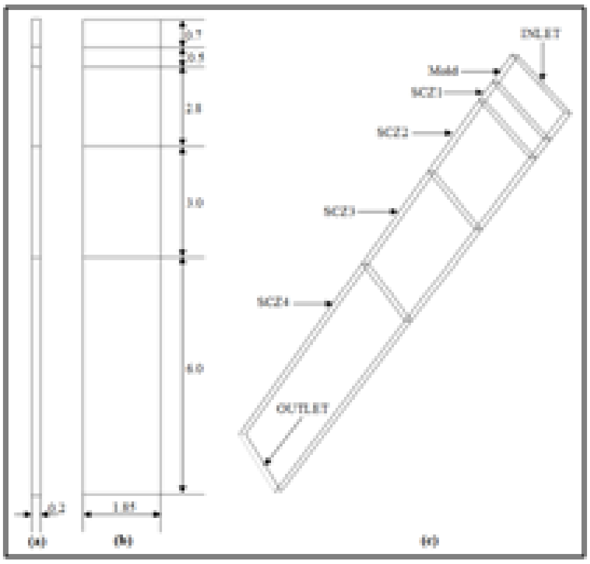
Since, the solidified shell is pulled out with a specified constant velocity, so a velocity inlet boundary condition at the exit. The velocity at the outlet is equal to the casting speed toward casting direction.

COMPUTATIONAL PROCEDURE

The computational domainand the grid were created using Gambit. The model has total strand length of 12 m including mold with a circular inlet of radius 79 mm at the topand its other dimensions are shown in Figure 2. As shown in the figure, geometry has been broadly divided in two parts: mold and Secondary Cooling Zone (SCZ). SCZ is further subdivided into four sections, as cooling rate varies while moving down the strand. Second order implicit scheme and realizable k-ε turbulence model were used to solve the fluid flow equations by finite volume method. For solidification, instead of tracking liquid-solid front explicitly, enthalpy-porosity technique has been used as explained above. The solution was executed in transient state with time step of 0.01 second. To avoid divergence during calculation, reduced under relaxation factor has been used. The solution convergence has been achieved with momentum residuals < 10^{-4} and energy residuals < 10^{-7}.

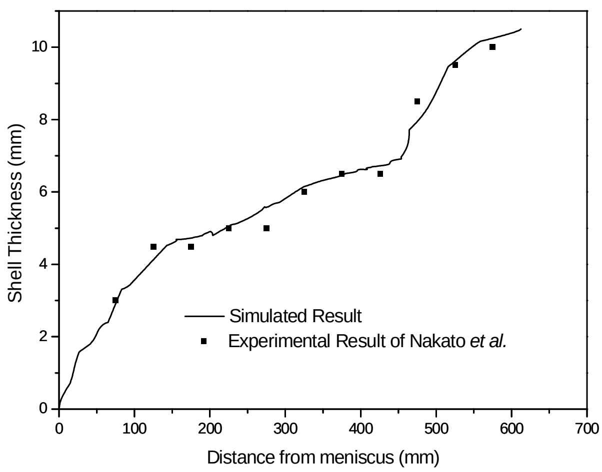
In order to check the accuracy of present work, model is validated with the calculation

Figure 2: Model Geometry (a) Thinner Side (b) Wide Side (c) Isometric View



of solid shell thickness at the narrow wall of the model of Nakato *et al.* as shown in Figure 3. Form the figure, it can be seen that there is a good match between them for solid shell thickness.

Figure 3: Validation of Model



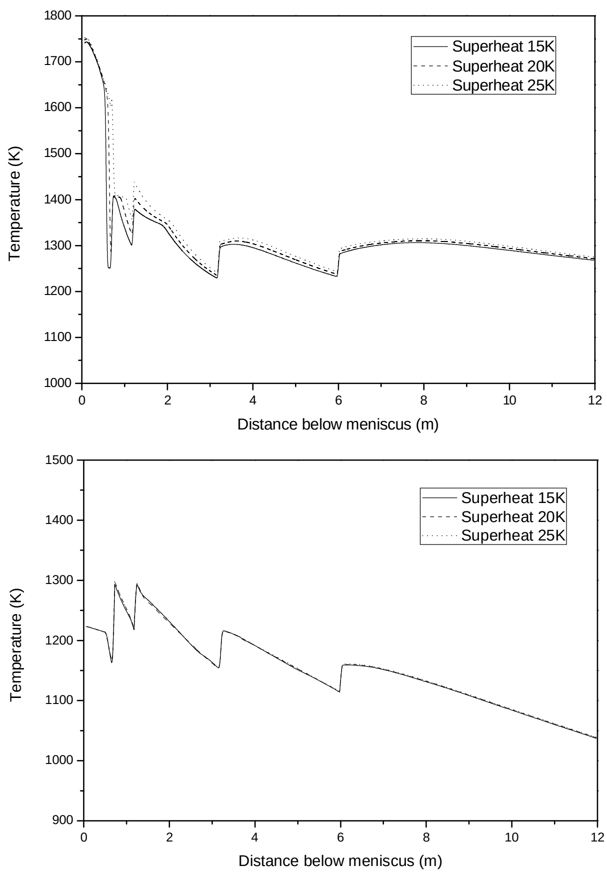
RESULTS AND DISCUSSION

Model calculations of temperature and solid shell thickness are performed with solidification and melting model. The temperature distributions were calculated at the centreline of the faces of the strand and solid shell thickness at the symmetric plane of two axes along the casting direction. The liquid fraction having value less than 0.5 is considered to be solidified.

Effect of Superheat

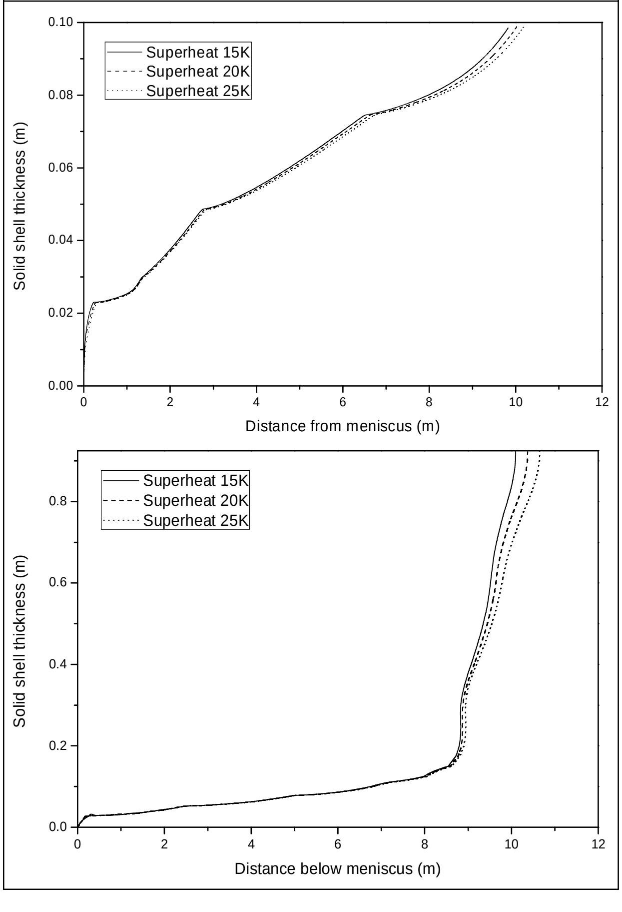
In the first part of investigation, effect of superheat has been studied by the temperature distribution and solid shell thickness. Figures 4a and 4b shows the temperature distribution at the broad face and narrow face respectively of mold and SCZ. As heat loss from the mold is very high, a sharp drop of temperature can be seen in the mold region, while along SCZ

Figure 4: Temperature Distribution at Different Superheat (a) Broad Face (b) Narrow Face



heat loss reduces down the strand consequently the increase and decrease in strand temperature results from the change in cooling conditions. On the other hand, temperature drop in broad (near) face is observed less as compared to narrow (far) face because of difference in heat flux at the two surfaces. It can also be seen that the change in superheat has a very little effect on slab temperature and solid shell thickness, as shown in Figures 5a and 5b. Thus small change in degree of superheat may not affect the process significantly. But large changes may reduce solid shell thickness at the mold region and hence breakout and other defects can occur.

Figure 5: Solid Shell Thickness at Different Superheat (a) Thin Section (b) Wide Section



Effect of Casting Speed

To study the effect of casting speed in continuous casting of steel, investigation has been performed with three different casting speeds. Figures 6a and 6b shows the temperature distribution at broad and narrow face of the strand for different casting speed. It can be noticed that change in casting speed affects the temperature distribution significantly which in turns affect the solid shell thickness in mold and SCZ, as shown in Figures 7a and 7b. It was observed that the metallurgical length of the strand increases with increase in casting speed and at the speed of 1.4 m/s metallurgical length of the strand

Figure 6: Temperature Distribution at Different Casting Speed (a) Broad Face (b) Narrow Face

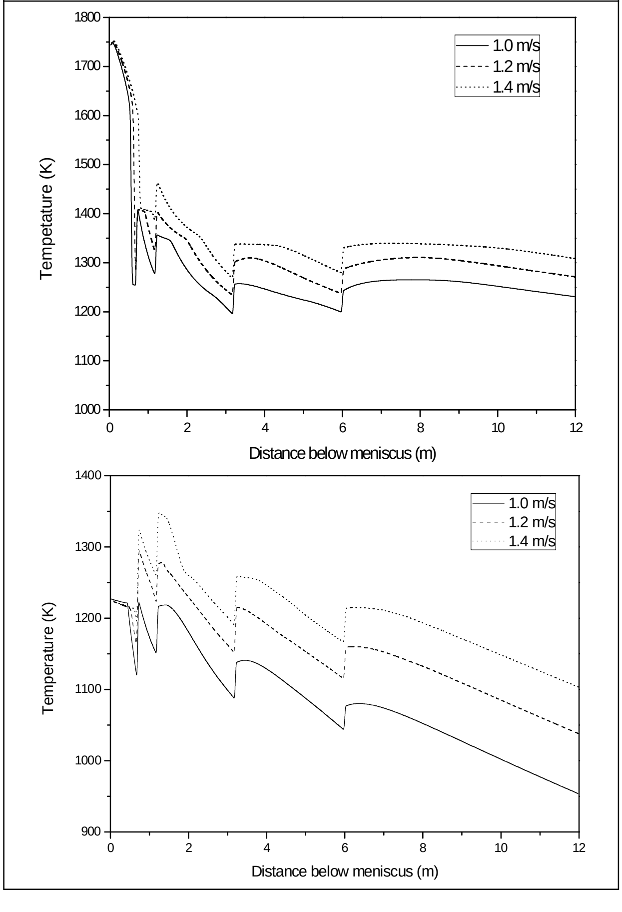
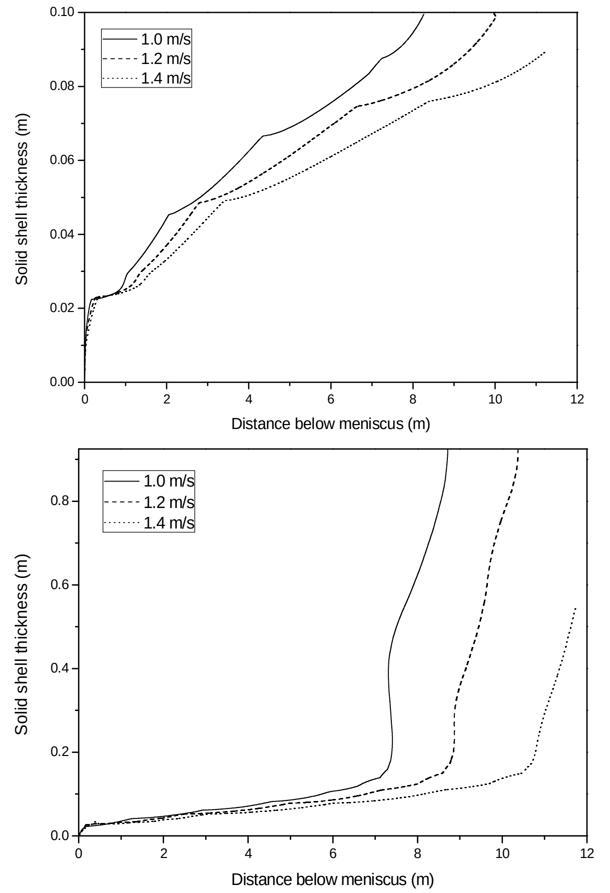


Figure 7: Solid Shell Thickness at Different Casting Speed (a) Thin Section (b) Wide Section



became more than the computational domain and could not get solidified completely at the caster exit. Significant decrease in solid shell thickness at the mold exit was observed which may cause breakout at mold exit. Due to high casting speed bulging, inner and surface cracks and other defects may be found in final cast. So the casting speed is to be limited to prevent the formation of any defect.

CONCLUSION

A three dimensional numerical model has been developed to study the solidification of continuous casting of steel slab. The temperature distribution and solid shell thickness has been calculated to study the effect of superheat and casting speed. It was observed that small change in degree of superheat will not affect the process and has very little effect on the metallurgical length. The change in casting speed has more pronounced effect on the chance of formation of defects such as bulging, cracks, etc. Casting speed can be increased or decreased by properly maintaining the cooling in the mold and secondary cooling zone.

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