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Computational Investigation of Solidification Behaviour of Steel Billet of Square Cross Section in Continuous Casting

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Abstract
The purpose of this paper spotlights the solidification behavior of continuous casting process of a rectangular steel billet with square cross section. The parametric investigation of solidification process during continuous casting is carried out by mathematical modelling of solidification and melting process. The solidification-melting model united with volume of fluid (VOF) model. The simulation was done with computational package Ansys Inc. FLUENT 19.0 R3 software. The validation of the model was done for present study. The solidification behaviour is analyzed by estimating the temperature, velocity and liquid fraction inside the mould at different pouring temperatures and different inlet velocities. The uniform velocity and temperature profiles are observed with increased in inlet velocity at constant pouring temperature. The uniform temperature and velocity distribution inside the mould suggested the uniform solidification propagation which was justified by liquid fraction profile inside the mould. The temperatures of the wall also effect the propagation of solidification. The better solidification behavior is observed at .0175 m/s inlet velocity and 1803 K pouring temperature at 1118 K constant wall temperature. It can be illustrated from the present study that the modelling of this study is used to recognize the affect of pouring velocity and temperature on solidification process inside the mould. The temperature, velocity and liquid fraction variation inside the mould are achieved and used to optimize the pouring velocity and temperature for better casting product.
Keywords Solidification, Pouring, Temperature, Liquid fraction, Volume of fluid

1. Introduction

The manufacturing of any product to desire shape and size through the molten metal was done through the casting process. Therefore, to meet out the industries demand. The casting processes entailed the combination of phase change heat transfer and fluid flow at macroscopic point of view. The successful casting operation needs knowledge of moulds and patterns design, liquefied metal melting and pouring and solidification and further cooling to surrounding temperature. In order to get good qualities, imperfection free casting appropriate melting of the metal is crucial. The appropriate gating systems are used to recover the difficulties during pouring of molten into the mould cavity. The pouring temperature and pouring time or pouring rate are the two main considerations during pouring takes place. The structural character of cast material and controls the properties of casting are decided by solidification process.

The researchers are committed toward process improvement for the manufacture of high eminence casting goods at low costs. The continuous casting is one of important casting processes that make over molten metal into solid on a permanent basis and consist of a variety of significant industrial processes. It is generally well-organized way to solidify large volumes of metal into simple shapes for succeeding processing (Jadayil, 2011). The flow characteristics in continuous casting are affected by residual flow due to the filling stage. The faster liquid metal solidifies
in the case of the reverse flow condition than in that of the secondary flow direction (Im et al., 2001). The analysis of
solidification systems with general implicit source based enthalpy method was used for a broad choice of enthalpy temperature relationship and the efficient analysis of metallurgical solidification phenomenon (Swaminathan and Voller, 1992). The problem of dendritic growth during solidification was discussed by (Yinheng et.al.,1995). They observed separation that establish in steel castings and their upshot of an upward flow of inter-

dendritic liquid. The inter-dendritic liquid can liquefy the solid and a channel is formed and continuous grow with increase in the temperature. The approximation of the convective flux was done with the volume of fluid method. The complex phase change process associated with modelling of general casting exertion that entail filling and additional coupled phenomena (i.e. solidification, segregation) (Swaminathan and Voller,1994). The solidification behaviour by modelling of the joined effect of buoyancy-driven flow and the residual flow of filling process was done to simulate concurrent mould filling and solidification of a pure metal. The residual flow affects the development and shape solidification edge during primary stages of solidification (Pathak et.al. 2022).

The defects in Aluminium casting were varying the pouring rate of molten material. The pouring rate increases face defects appreciably, while on the other hand when the pouring rate is increases, there are much less defects appeared internally (Jadayil,2011). The decreasing in solidification rate caused fewer pores, bigger pores and an increase in solidification rate resulted in finer microstructure (Vander, 2005). After machining of aluminium-silicon alloy castings, the porosity creation is big dilemma. These defects are minimized by altering gating system design, controlling at some stage in filling and by using tolerable chills (Kakas et.al., 2008).

The entirely implicit behaviour of the field equations and the boundary situations was estimated by numerical method. The testing of numerical method against several diffusion forms for which analytical solutions moderately existing was done by (kim and kaviay, 1992).

The casting process with various effects i.e. heat and phases transfer on thermal arrest time and turbulence flow were done with the help of CFD. The simulation was done by means of volume of fluid model combination with the solidification model. The heat transfer is very low for the short time of thermal arrest. It produced imperfections in products and a highly increasing in the heat alternation increases the solidification time (Nguyen and Huang, 2012). The mould filling problems are analysed with finite element approach by an implicit-flow and explicit-front tracking. Two inter-dendritic flow models are used to simulate the effect of solidification (Ravindran and Lewis, 1998; Vijayaram et al., 2006). The discharge of latent heat of fusion during conversion of liquid phase to solid phase in casting was studied. Proper casting design and gating system is necessary to eradicate and eliminate these defects. The imperfect sites in the castings are identified by time-temperature contours in simulation process. The feeding flow model was developed to estimate shrinkage defects for casting alloys. The shrinkage imperfections are illustrated by VOF free surface model. The short and long freezing range causes internal and external shrinkage respectively (Reis et al. 2008). The vertical wall of the inclusion is retained at constant heat flux on one side and constant temperature on the other whereas horizontal walls are kept adiabatic and applied heat transfer is a significant parameter which controls the heat transfer and fusion velocity (Mbaye and Bilgen, 2001). The studied was done to simulate the moving boundary which coupled heat transfer equation and two phase Stefan condition. As the casting speed increases, the molten flow foliage the mould quicker and the solid thickness ingoing the secondary cooling arena is decreased. The numerical study of continuous casting was done with precise modelling of flow of molten, heat transfer, solidification and configuration of the shell by solidification and pairing (Thomas,2001; Amratav et al.,2021). The quality cast steel billet of continuous costing affected by cooling rate, speed of casting and pouring temperature. Therefore the optimization of this parameter is required for suitable casting (Khurram et al., 2022). The better quality of steel sheets product is present choice of casting by conventional continuous casting method. However the Endless Strip Production (ESP)-Thin Slab Caster (TSC) advance is now extremely competitive (Roderick et al., 2022). The temperature and solidification of fluid flow are used to compare the behaviour of casting with and without mold electromagnetic stirring. The heat transfer of superheat enlarges close to the solidification face because of high rotating flow, therefore it causes to an increase in the temperature and a decrease in solidification thickness in that region (Gupta et al., 2022).

The heat elimination from billets strands in the continuous casting was simulated. The model covenants with the non-symmetric cooling situations of a billet caster. The plugged nozzles are used in the secondary cooling system (SCS). The approach is adaptable as it consents pleasantly the changes of various casting machines, including the use of altered types of water spray nozzles. The general heat removal rate enhances at low slab casting speed because of longer residence times under cooling effects in the SCS (Adan et al., 2021). The excessive change in flow patter is observed in presence of EMS. There was presence of horizontal recirculation flow region below the meniscus (Bin et al., 2020). The CFD simulation of vertically upwards continuous casting was done (Jones et al., 2021). The oxygen free copper casting was done for different casting speed. The faster casting speeds produced high temperatures. The temperature within the die is increased which act as an indicator for the occurrence of casting defects and will persuade the final microstructure. The study for behaviour of initial solidification and heat transfer at different positions of the mold was done by (Junde et al., 2021). The thickness of the total slag on the cross section is larger at the corner than extreme from the corner. The primary solidification and heat transfer are considerably pretentious by the thickness of the slag as well as the heat set off from the upper backflow. The simulation of slab mold friction behavior with varied mould turn structures in continuous casting suggested that the liquid slag thickness diminishes step by step form the meniscus to the mould exit. The liquid slag vanishes when the temperature of the slag is lesser than its melting temperature (Sheng et al., 2019). The thermo-mechanical model of the mould with turbulent flow model in presence of variable heat transfer, suggested various taper profiles for the corner and the off-corner regions of the mould periphery. Further the modified taper profile which is suitable for retain minimum air gap between the billet and the mould and create definite for smooth process and demur defects in billet casting (Chakraborty et al.,2019). The postponed solidification end near the 1/4 width of slab is observed because of liquid flow from a flooded entry nozzle injected to the strand's narrow face (Jiang et al.,2019). The optimization of residence time, homogenizing the temperature and elimination of insertions by floatation of molten metal based on flow state of molten steel in tundish was done. The overall velocity of the flow field, turbulent intensity and molten steel surface velocity increase as the casting speed is doubled (Huang et al., 2019).

The above literature studies focused the solidification behaviour of continuous casting process but less number of studies related to computational studied of liquid flow with solidification at different contentions i.e. pouring temperature, inlet velocities, cooling jet/surrounding convective condition and mould wall temperature etc.

This study is done for the solidification behaviour of liquid metal in a cavity during continuous casting process through mathematical modeling. The governing equations are solved with a computational solidification/melting model joined with volume of flow model. The effect of pouring velocity, temperature and wall temperature are used to analyze the solidification progression by estimating the temperature, velocity and liquid fraction profiles inside the cavity throughout solidification.

2. Mathematical Modeling

2.1 Solidification Model

The fluid flow problems is explained by this model during solidification and/or melting of metal (e.g., pure metals and binary alloys) on one temperature or a range of temperatures. The enthalpy-porosity formulation is used for modeling the phase change process (Amratav et al., 2021; Ansys, 2019).

2.2 Energy Equation

The enthalpy (H) is calculated by the summation of the sensible enthalpy (h) and the latent heat (ΔH) of material as mentioned in equation (1)

$$H = h + \Delta H \qquad (1)$$

$$H = h_{ref} + \int_{T_{ref}}^{T} C_p dT \qquad (2)$$

Equation (3) is used as energy equation for solidification/melting problems.

$$\frac{\partial(\rho H)}{\partial t} + \nabla.(\rho v H) = \nabla.(k\nabla T) + S \qquad (3)$$

2.3 Momentum Equation

The enthalpy-porosity processes take concern of the mushy section as a porous medium. The liquid fraction of the cell is equivalent to the porosity in each cell. The porosity is equal to zero in fully solidified regions, which smothers the velocities in these regions. Equation (4) is used to specify the momentum sink owing to the compact porosity in the mushy region.

$$s = \frac{(1-\beta)^2}{(\beta^3-\varepsilon)} A_{mush}(v - v_p) \quad (4)$$

2.4 Model of Liquid Fraction

Equation (5) is used to calculate the liquid fraction (β) as discussed by[19]:

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \quad (5)$$

$$\text{if T less than } T_{solidus}, \text{ then } \beta = 0$$
$$\text{if T more than } T_{solidus}, \text{ then } \beta = 1$$

The latent heat is estimated by equation (6)

$$\Delta H = \beta L \quad (6)$$

2.5 Turbulence Model

The turbulence equations are added by sinks in the mushy and solidified region to describe the occurrence of solid material (Ansys, 2019).

$$s = \frac{(1-\beta)^2}{(\beta^3+\varepsilon)} A_{mush}\, \varphi \quad (7)$$

2.6 Contact Resistance at Wall Model

The estimation of wall heat flux (q) is done by equation (8)

$$q = \frac{T - T_w}{(\frac{1}{k} + R_c(1-\beta))} \quad (8)$$

2.7 Volume of Fluid (VOF) Model

The VOF model is used for two or more immiscible fluids. In this model a single set of momentum equations and tracking the volume fraction of each of the fluids in the province (Amratav et al., 2021; Ansys, 2019).

The q_{th} fluid's volume fraction in the cell is signified as a_q and subsequent situations are specified[1]:

(i) If cell is vacant (of the q_{th} fluid) then a_q= 0

(ii) If cell is filled (of the q_{th} fluid) then a_q= 1

(iii) If cell encloses the edge between the q_{th} fluid and one or more former fluids then 0 <a_q< 1

2.8 Volume fraction Model

The following of the edge(s) between the phases are consummated by the explanation of a continuity equation for the volume fraction of one or more of the phases. The continuity equation for q_{th} phase has the subsequent form given in equation (9):

$$\frac{1}{\rho_q}[\frac{\partial}{\partial t}(a_q\rho_q) + \nabla.(a_q\rho_q v_q) = s_{a_q} + \sum_{p=1}^{n}(m_{pq} - m_{qp})] \quad (9)$$

2.9 Momentum Equation

All over the domain, a single momentum equation is simulated, and the consequential velocity field is collective among the phases. The momentum equation is reliant on the volume fractions of all phases through the properties (density (ρ) and viscosity (μ)) given in equation (10),

$$\frac{\partial}{\partial t}(\rho v) + \nabla.(\rho v v) = -\nabla P + \nabla[\mu(\nabla v + \nabla v^T)] + \rho g + F \quad (10)$$

The energy equation given in equation (11), also shared along with the phases.

$$\frac{\partial}{\partial t}(\rho E) + \nabla.(v\,(\rho E + P)) = \nabla.(k_{eff}\nabla T) + S_h \quad (11)$$

$$E = \frac{\sum_{q=1}^{n} a_q\rho_q E_q}{\sum_{q=1}^{n} a_q\rho_q} \quad (12)$$

3. Numerical Simulation

The governing equations beside with the other modelling equations have been computed using a computational solidification/melting model of ANSYS (Version 19R3). The methods for liquid zone and variable space grid method for solidified shell are front-fixing or Boundary Immobilization Method (BIM). The heat of solidification should be taken into consideration when setting up the energy balance. There is no alteration of volume on solidification as it is supposed that physical properties of the material remain constant all over the process. Variable space grid method (VSG) is used as the solidified shell thickness is varying continuously, for this region. Solutions for moving boundary problems obtained through finite difference methods. The implicit method is used to solve the resulting matrix. The convergence criteria for all variables (i.e., mass, velocities and turbulence extents) are set as the standardized and in general residue value which is equal to 10^{-5}.

The geometry used in this study is a square cross sectional of rectangular steel billet as stated in Table 2. The liquid metal enters through the inlet of mould shown in Figure 1 (a). The steel as a material is used for solidification and the thermo physical properties and input parameters of slab caster are given in Tables. 1 and 2, respectively (Moghadam and Hosseinzadeh, 2015)

.

Table 1 Properties of steel

Thermophysical properties	**Solid**	**Liquid**
c (J/ kg°C)	430	825
ρ (kg/ m^3)	7400	7400
k (W/ m°C)	33	39
Liquids Temperature (K)		1723
Solidus Temperature (K)	1698	
L_f (J kg^{-1})		260000
T_{in} (K)	1803	
Solid wall temperature (K)	1118.35	
Ste	1	

Table 2 Geometry of the rectangular billet

Section Size (mm x mm)	280mm x 280mm
Length H (mm)	670
Inlet velocity v (m/s)	0.0125
d (mm)	2
k (W m^{-1}°C^{-1})	315

The simulation is done for the grid independence test and the validation of the model at following boundary conditions that was specified by (Moghadam and Hosseinzadeh, 2015): pouring velocity at the inlet of mould is 0.0125 m/s on the wall. The no-slip condition is defined and outlet of billet and solid wall temperature is 1118.35 K. The meshed geometry is shown in Figure 1 (b).

The grid independence test is done as per above specified conditions. The temperature variation for solidified shell with different grid sizes 36.0 mm, 38.0 mm, 40.0 mm, 42 .0 mm and 44.0 mm along the normal to axis from the centre of mould is shown in Figure 2(a) The minimum variation in temperature is observed at 42 mm grid size along the normal to the axis from center of the mould. Therefore the validation of the model was done for the 42 mm size of grid with same conditions as specified by (Moghadam and Hosseinzadeh, 2015) given in Figure 2(b) . At the centre about 100 ^{0}C and 100 mm (outer surface) away from the centre less than 50 ^{0}C temperature difference is observed. However the behavior of temperature difference is similar to the work of (Moghadam and Hosseinzadeh, 2015). Hence the model is validated and further study was done at 42 mm size of grid for 2000 second time steps.

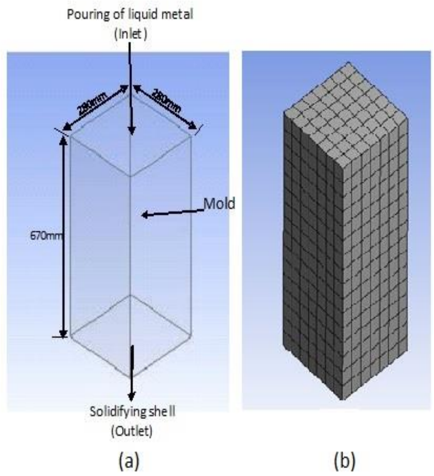
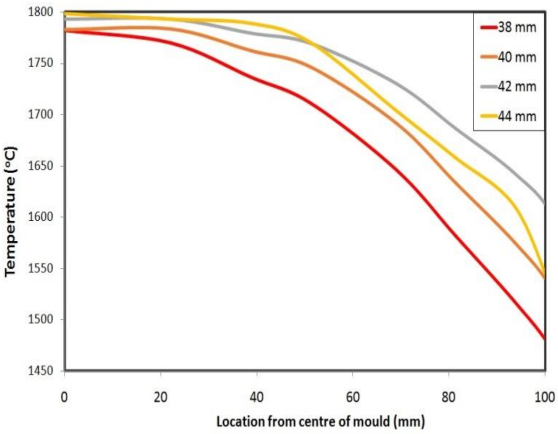
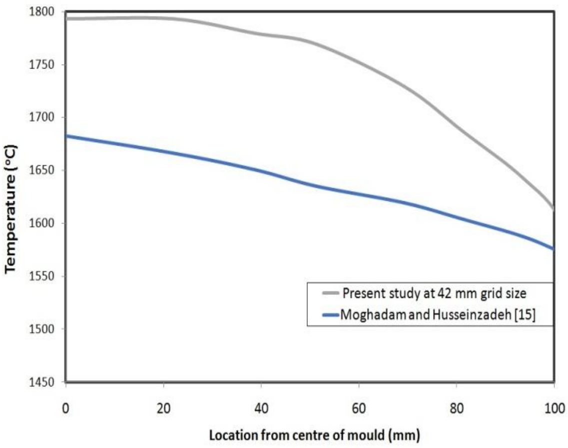


Figure 1 Schematic of continuous casting of rectangular billet (a) geometry with dimension in mm (b) meshed geometry



(a)



(b)

Figure 2 Temperature variations along the normal to axis from the centre of mould at Ste=1, casting speed 0.0125 m/s and time step 2000 s for (a) different grid (b) present study at grid sizes 42 mm (Moghadam and Hosseinzadeh, 2015)

4. Result and Discussion

This section is used to discuss the cause of inlet velocity on the solidification in continuous casting process. The temperature contour for different pouring temperature with varying inlet velocity, at the constant time (2000 sec.) and same solid wall temperature 1118.35 K is given in Figure 3.

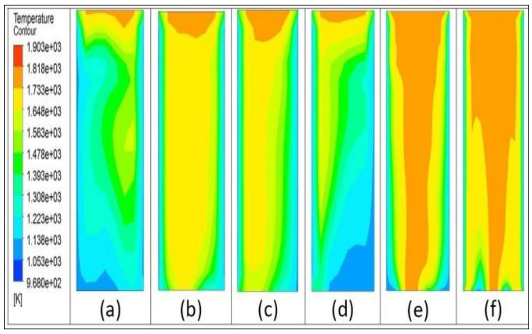


Figure 3 Temperature variation for velocities (a) 0.0075 ms^{-1}, (b) 0.010 ms^{-1}, (c) 0.0125 ms^{-1}, (d) 0.015 ms^{-1}, (e) 0.0175 ms^{-1} (f) 0.02 ms^{-1}at pouring temperature 1753 K

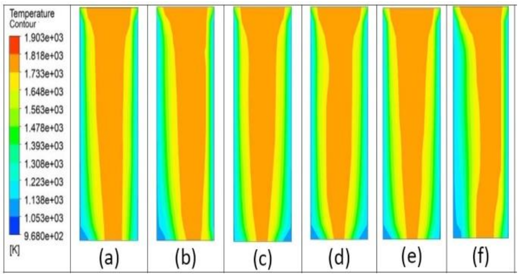


Figure 4 Temperature variation for velocities (a) 0.0075 ms^{-1}, (b) 0.010 ms^{-1}, (c) 0.0125 ms^{-1}, (d) 0.015 ms^{-1}, (e) 0.0175 ms^{-1} (f) 0.02 ms^{-1}at pouring temperature 1803 K

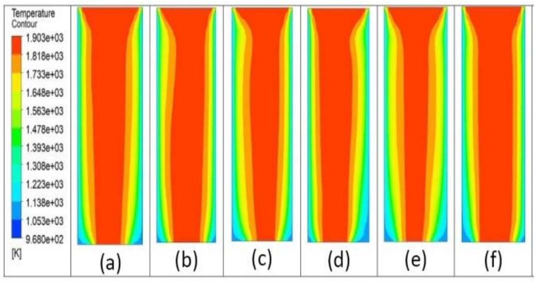


Figure 5 Temperature variation for velocities (a) 0.0075 ms^{-1}, (b) 0.010 ms^{-1}, (c) 0.0125 ms^{-1}, (d) 0.015 ms^{-1}, (e) 0.0175 ms^{-1} (f) 0.02 ms^{-1}at pouring temperature 1853 K

Figure 3 shows the temperature profile at different inlet velocity at 2000 second for 1753 K pouring temperature. As velocity increased from 0.0075 m/s to 0.0175 m/s, the informality in temperature distribution increases and better contour is observed at 0.0175 m/s further increase in velocity up to 0.02 m/s the informality in temperature distribution is decreased. It was observed because of solidification propagation affected by the flow velocity. Further the pouring temperature increased from 1753 K to 1853 K, the temperature inside the mould increases and region of solidification decreases, however the temperature distribution is more uniform at all poring temperature than 1753 K at all inlet velocity shown in Figures. 3,4 and 5. The more uniform profile is achieved at velocity of 0.0175 m/s at 1803 K as given in Figure 4 with higher solidified region. At the lower velocity the profile is not uniform which increases the chances of defects in the casting. The higher region of liquid inside the mould at higher temperature in Figure 5 is cussed the inclusion of air and further create the defect in the casting. The liquid metal near to the mould walls solidifies faster than in the center part because constant mould walls temperature 1118.35 K is maintained in the continuous casting process through the water cooling.

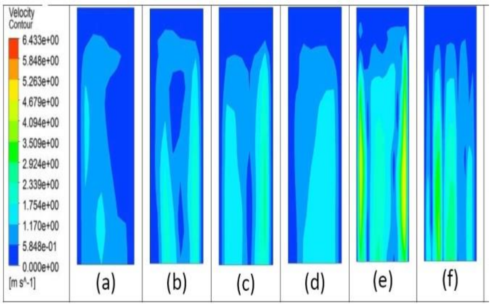


Figure 6 Velocity variation for velocities (a) 0.0075 m/s, (b) 0.010 m/s, (c) 0.0125m/s, (d) 0.015 m/s, (e) 0.0175 m/s(f) 0.02 m/s at pouring temperature 1753 K

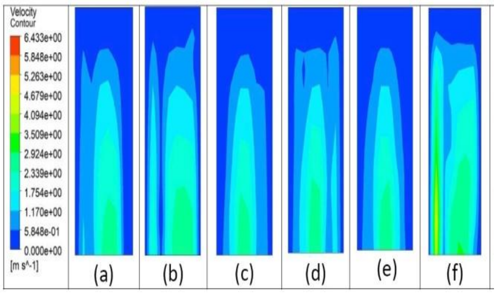


Figure 7 Velocity variation for inlet velocities (a) 0.0075 ms^{-1}, (b) 0.010 ms^{-1}, (c) 0.0125 ms^{-1}, (d) 0.015 ms^{-1}, (e) 0.0175 ms^{-1} (f) 0.02 ms^{-1}at pouring temperature 1803 K

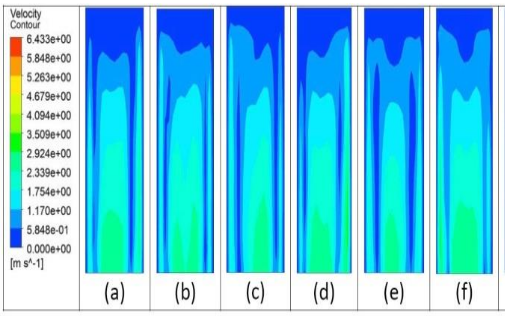


Fig.ure 8 Velocity variation for inlet velocities (a) 0.0075 ms^{-1}, (b) 0.010 ms^{-1}, (c) 0.0125 ms^{-1}, (d) 0.015 ms^{-1}, (e) 0.0175 ms^{-1} (f) 0.02 ms^{-1}at pouring temperature 1853 K

Figures 6,7 and 8 shows the velocity variation inside the mould at different inlet velocity for variable pouring temperature 1753 K to 1853 K. The increased in velocity from 0.0075 m/s to 0.02 m/s, the more uniform velocity contour observed at pouring temperature 1803 K for inlet velocities 0.0125 m/s and 0.0175 m/s given in Fig.ure 8. This is because of uniform temperature distribution inside the mould as discussed in the Figures. 3,4 and 5. The non-uniform nature in velocity profile is caused the defects in casting. The higher temperature region supports the uniform velocity but required more time for the solicitation which pro the gas inclusion and causes defect in the casting. Therefore the uniform velocity profile at pouring temperature 1803 K for inlet velocities 0.0175 m/s is more suitable.

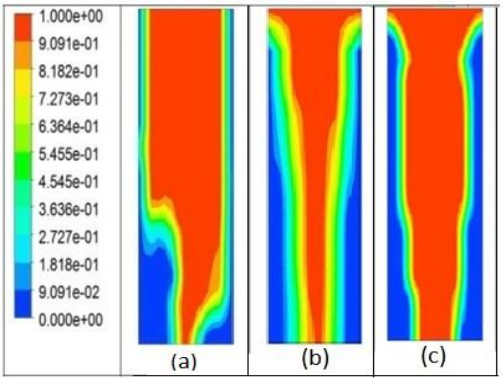


Figure 9 Liquid Fraction variation for pouring temperature (a) 1753 K (b) 1803 K (c) 1853 K at velocities 0.0175 ms^{-1}

Further, the solidification behavior is analyzed by estimating the liquid fraction inside the mould. The contour of liquid fraction for different inlet velocity and pouring temperature to same time duration is shown in Figure 9. The solidification in non uniformly proceeded with raise in velocity from

0.0075 to 0.02 m/s at 1753 K pouring temperature shown in Figure 6. Further increase in pouring temperature solidification propagated from wall to the centre side uniformly compare to 1753 K at different inlet velocity. Beyond 1803 K more liquid fraction is observed and the propagation of solid region has less uniform structure as given in Figures 9(a), 9(b) and 9(c). This is because of due higher pouring temperature; solidification time is increased and initiates the reversal of the liquid flow that can be verified with velocity profile given in Figure 4. Therefore at 1803 K and 0.0175 m/s inlet velocity better liquid fraction profile is observed as shown in Figure 9. This behaviors support the similar view as discussed in temperature variation (Figures 3, 4 and 5) and velocity variation (Figures 6, 7 and 8).

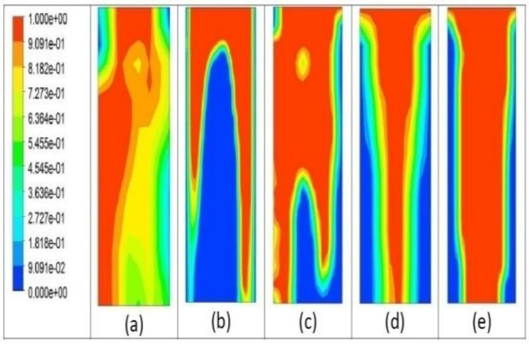


Figure 10 Liquid Fraction variation for different solid wall temperature, (a) 968 K, (b) 1018 K, (c) 1068 K, (d) 1118 K, (e) 1168 K at pouring temperature 1803 K and inlet velocity 0.0175 ms^{-1}

Further studied was done at 1803 K and 0.0175 m/s inlet velocity to understand the effect of wall temperature from 968 K to 1168 K. The liquid fraction profile is given in Figure 10 for different wall temperature. The wall temperature is increased from 968 K to 1068 K the liquid fraction profile is non uniform given in Figure 10. This is because of higher temperature difference between the liquid and wall surface, which not support the uniform propagation of solicitation from wall to centre of the mould. Beyond 1068 K wall temperature uniform profile is observed at 1118 K and 1168 K. But at 1168 K, the velocity profile less uniform and more liquid fraction is observed than 1118 K. Therefore for the wall temperature also effect the solidification behavior and 1118 K is the better wall temperature for 1803 K pouring temperature with inlet velocity of 0.0175 m/s

5. Conclusions

This paper focused a numerical simulation of continuous casting process of a rectangular steel billet with square cross section. The solidification behavior is analyzed by estimating the temperature, velocity and liquid fraction inside the mould for pouring temperature (1753 K to 1903 K) and different inlet velocities. The investigation of solidification process is carried out by means of solidification/melting model tied with volume of fluid model. The simulation was done with computational package Ansys Inc. FLUENT 19.0 R3 software. The uniform temperature and velocity distribution inside the mould are observed with increase in pouring temperature and further increase in pouring temperature informality disturbed. The uniform velocity profile is observed with increased in inlet velocity at constant pouring temperature. The uniform velocity and temperature profiles suggested the better propagation of solidification that was analyzed by liquid fraction profile. The temperatures of the wall also effect the propagation of solidification from wall to the centre of the mould. The better solidification behavior is observed at 0.0175 m/s inlet velocity and 1803 K pouring temperature at 1118 K constant wall temperature.

Nomenclatures

A_{mush} Mushy zone constant
B Liquid volume fraction
C_p Specific heat at constant pressure.
E Energy
E_p Each phase is based on the specific heat of that phase
F External body force.
H Enthalpy
h_{ref} Reference enthalpy
k Thermal conductivity
k_{eff} Effective thermal conductivity.
l Distance between the wall and the location
L Latent heat of material.
m_{pq} Mass transfer from phase p to phase q
m_{qp} Mass transfer from phase q to phase p
P Static pressure
Rc Contact resistance

S Source term
S_h Heat source
T Temperature at location within the cell
T_{ref} Reference temperature,
T_w Temperature of wall
v Fluid velocity
v_p Solid velocity due to the pulling of solidified material out of the domain
ρ Density
ε Small number (0.001) to avoid division by zero
φ Turbulence parameter

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