

Role of Thermal Driven Buoyancy Flow on Solidification Process of Continuous Slab Caster

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ABSTRACT: The main objective of present work is to study the effect of thermal driven buoyancy flow (also called as natural convection) on solidification process of continuous slab caster. A three dimensional fluid flow, heat transfer and solidification model is developed and result obtain from model are combined with non-dimensional formula to discuss the role of thermal driven buoyancy force. Result shows the importance of thermal driven buoyancy flow, inertial flow from SEN jet and flow through porous media. The strength of thermal driven buoyancy flow depends upon the characteristic velocity, temperature difference and porosity of mushy zone. The most effect zone of thermal buoyancy flow is centre of the mould, region away from the meniscus, and mushy zone.

KEYWORDS: Continuous slab casting, thermal driven buoyancy flow, solidification, mushy zone.

I. INTRODUCTION

Metal casting process used in various manufacturing industry to get different shapes and components and alternative method to it is continuous casting. The continuous casting is more advantageous than conventional casting in terms of productivity, yield and quality assurance. For this reason, many research done to understand the process and improve the productivity. One of the research areas is thermal driven buoyancy flow. In tundish thermal driven buoyancy flow are studied which cause change in flow pattern [1-2].

Similarly, in continuous casting temperature difference created due to heat transfer and solidification. So what about the thermal buoyancy flow in mould and sub mould region of casting?

X. Huang *et al* [3]. were the first to study the effect of thermal buoyancy with modified Froude number and concluded that inertia force is more important than thermal driven buoyancy flow. They came to this result because of not considering the mushy region. Yang *et al* [4] predict that thermal buoyancy is important in mushy region but due to neglecting the effect of inter dendritic flow the thermal buoyancy flow result gets misreported. Saul Garcia *et al* [5]. Investigated the effect of buoyancy force over inertia force and concluded that thermal buoyancy is 10% of inertia force. They got this result because of not considering the mushy region.

In present research work the analysis of thermal driven buoyancy flow are carried out by developing three dimensional fluid flow and solidification model and result are discuss through non dimensional formula. It is expected this will provide better understanding in developing the mathematical model for continuous casting.

II. MATHEMATICAL FORMULATION

Before presenting the governing equation for fluid flow and heat transfer in continues casting some of the assumptions considered in model are: 1) Material considered homogeneous and isotropic.2) fluid is Newtonian, incompressible with Boussinesq approximation, and the fluid flow is laminar in the liquid region.3) Multiphase fluid flow in the mould

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region and secondary cooling zone not considered.4) Thermodynamic and transport properties of steel are invariant.5) Turbulent is approximated using SST K-ε model of turbulence from various pervious acceptable work [6-8).

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_j)}{\partial x_j} = 0 \quad \dots\dots\dots (1)$$

Momentum Equation:

$$\frac{\partial(\rho u_i)}{\partial t} + \rho u_j \frac{\partial u_i}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{\partial p}{\partial x_i} - \rho \beta' (T_{ref} - T) \quad \dots\dots\dots (2)$$

Energy Equation:

$$\frac{\partial(\rho H)}{\partial t} + \frac{\partial(\rho u_j H)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\alpha \left(\frac{\partial H}{\partial x_j} \right) \right] \quad \dots\dots\dots (3)$$

$$H = h + \Delta H$$

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

The liquid fraction, β can be defined as,

$$\beta = 0 \quad \text{if} \quad T < T_{solidus}$$

$$\beta = 1 \quad \text{if} \quad T > T_{liquidus}$$

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \quad \text{if} \quad T_{solidus} < T < T_{liquidus}$$

Mushy region refers to a region in which metal is neither pure liquid nor pure solid and temperature lies between liquidus and solidus. As liquid jet of molten metal strike the mould wall, there exist a chilled zone and at the centre of mould there exist a equiaxed crystal zone and in between there exist columnar dendrites. Both equiaxed crystal and columnar dendrites block the fluid flow. Some of the columnar dendrites get cut off by fluid flow and some remain attached to solid shell. A microscopic model is required to simulate the above phenomena but due to lack of computational power, mushy zone considered as a porous media and porosity equal to liquid fraction that is keep on changing with solidification. For mushy zone Kozeny- Carman equation is applied given by:

$$\frac{\Delta P}{L} = \frac{180 \mu (1-\beta)^2}{\varphi^2 D_p^2 \beta^3} v \quad \dots\dots\dots$$

(4)

ΔP/L Is constant for the particular plane, φ², D_p² is constant throughout the porous media, then the velocity v is given by:

$$v = k \frac{\beta^3}{[1-(0.001+\beta)]^2} \quad \dots\dots\dots$$

(5)

For mushy zone velocity, vary according to equation 5. The term 0.001 is added to avoid divisible by zero.

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III. MODEL CONSIDERATION

A numerical model was developed for continuous slab caster and solved on CFD commercial software FLUENT. Table 1 shows the geometrical parameter and steel properties of simulated model. Twine bore SEN is used with casting direction is negative Z-axis. Figure 1 shows the computational mesh for the given caster that has around 1700000 cells in structured mesh. This mesh was refining around the mushy zone for particular plane created to study thermal buoyancy force effect.

It is not easy to calculate the mould heat flux due to gap between mould and shell. Local heat flux are obtain by measuring the mould water volume and temperature at inlet and outlet. Savage Prichard in 1954 reported following relation for heat flux in mould [9]:

$$q = 2.67 - 0.33 \sqrt{\frac{z}{u}}$$

..... (6)

The values of heat transfer below the mould from the strand surface to environment calculated by three modes: conduction, convection and radiation. Therefore, to predict the combine heat transfer coefficient trial and error method has adopted by knowing the spray cooling water volume from plant data

Table 1: Geometrical parameter and operating condition of simulated caster

PARAMETER	VALUES
Mold & model domain width (mm)	1.56 L
Mold length (mm)	L
Mold & model domain thickness (mm)	218
Model domain length (mm)	5000
Casting speed (m/min)	1.8
Density (kg/m ³)	7200
Specific heat (j/kg k)	682
Thermal conductivity (W/m K)	34.6
Laminar viscosity (kg/m s)	0.006482
Thermal expansion coefficient (1/K)	0.0001197
Pure solvent melting heat (j/kg)	271954
Solidus temperature (K)	1796
Liquidus temperature (K)	1805
Superheat temperature (K)	25
Casting temperature (K)	1830

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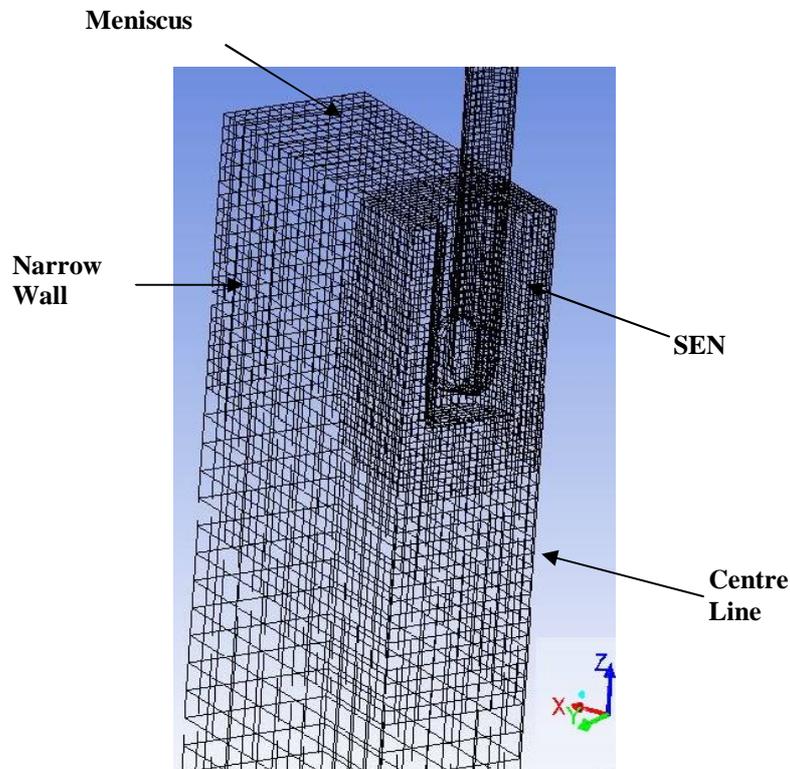


Fig 1: Grid and Coordinate of given Caster

IV. RESULT AND DISCUSSION

1. Verification of Calculated Result

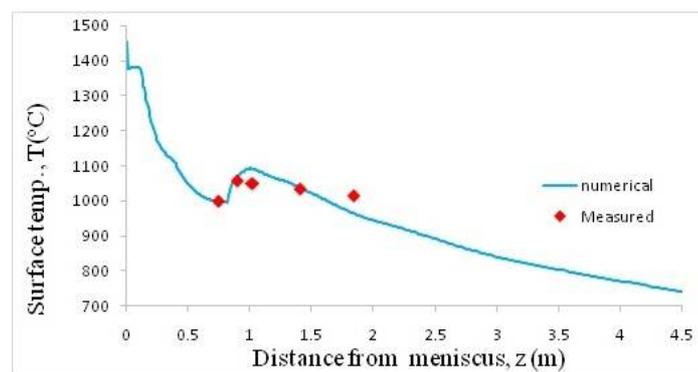


Fig 2: Comparison between Numerically Simulated and Measured Surface Temperature for given Slab Caster

Figure 2 shows the comparison between numerically simulated temperature and measured surface temperature in a given slab caster of a Tata Steel plant. It can be seen that the pattern for surface temperature given by simulated model is similar to the measured surface temperature from the plant data and can be used to validate the model.

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2. Relative Importance Thermal Driven Buoyancy Force and Inertia Force by Jet Impinging.

In present work, Gr/Re^2 (called as Richardson Number) are consider to determine the importance of buoyancy driven flow and forced flow from SEN impinging jet, given by [10]:

$$\frac{Gr}{Re^2} = \frac{gL_c\beta^l\Delta T_c}{u_c^2} = \frac{BUOYANCY\ FORCE}{INERTIAL\ FORCE}$$

In slab caster solidification are mainly in downward along the longitudinal direction and Sform narrow wall towards centre of the mould and thermal driven buoyancy occurs in lateral direction. L_c is width of the mould and u_c is the local velocity of convective heat transfer.

To study the effect of thermal driven buoyancy flow in mould; a plane is created at 800 mm downward form the meniscus perpendicular to the casting direction. Due to symmetry in the model any one half of the plane is considered that is from centre line towards narrow wall. The plane consist of three zones first liquid zone, where steel is in liquid form having liquid fraction 1. Next to, it is mushy zone whose liquid fraction varies from 1 to 0. Next to mushy zone is the solid zone where steel is in solid phase. Solid zone is not considered in study.

When Gr/Re^2 ratio tends to zero it means inertial force is dominant over and when it is above 1 thermal force is dominant. Considering this, Gr/Re^2 ratio for liquid zone and mushy zone are shown in figure 3 and figure 5.

In liquid region; at the centre line of the plane Gr/Re^2 ratio is below zero ($Gr/Re^2 = 0.952$, $u_c=0.19$ m/s, $\Delta T_c= 24.53$ K) which indicate the dominancy of inertia force over buoyancy force. Moving in lateral direction towards narrow wall Gr/Re^2 ratio increasing and reach to a peak value ($Gr/Re^2 = 71.94$, $u_c=0.022$ m/s, $\Delta T_c= 23.77$ K). The velocity at the centre line of the plane is quite high due to recirculation of the steel flow as shown in figure 4.

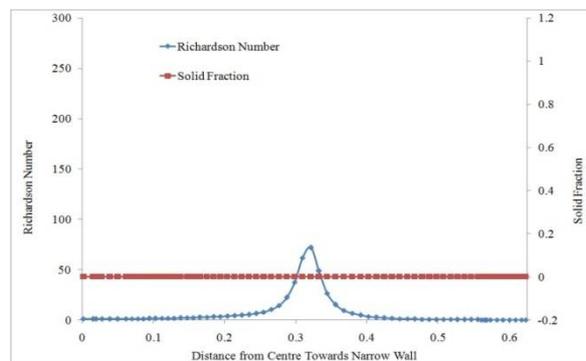
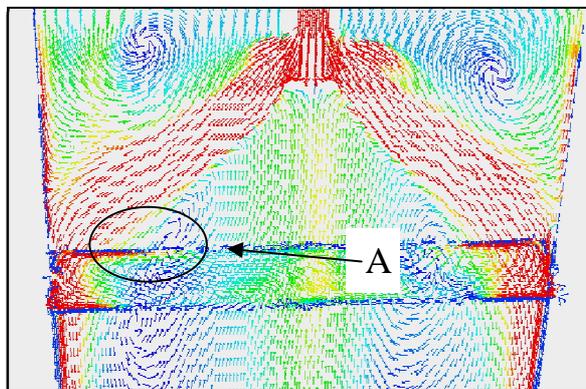


Fig 3: Richardson Number and Solid Fraction at 800 mm from Meniscus in Liquid Region **Fig 4:** Velocity Vectors at Mid Plane and Plane at 800mm from the Meniscus.



In between, centre line and narrow wall where Richardson number reaches to peak value, velocity become very low. The lower recirculation again gets re-circulate (denoted by **A** in figure 4) and velocity reaches almost to its dead point.

Near to end of liquid region, Gr/Re^2 ratio again goes below zero as jet from SEN increases the velocity in this region. Therefore, along the plane Richardson number is below zero; leaving a little portion where Richardson number is quiet high then it can be say that in liquid region the inertia force is dominant over thermal buoyancy force.

In mushy region, Kozeny- Carman equation are applicable. According to Kozeny- Carman equation variation of velocity in mushy region are given by **equation 5**. Figure 6 shows the variation of velocity in mushy region. It indicates that velocity of steel flow dropping very rapidly. As 2% of liquid converted to solid, velocity decreases from 0.38 m/s to 0.00097 m/s. This cause Gr/Re^2 ratio to increase instantly to a value of 35216.23 and it is keep on increasing in mushy region (See figure 5). Which means in mushy region thermal buoyancy is dominant over inertia force and buoyancy force is responsible for the motion of fluid in mushy region.

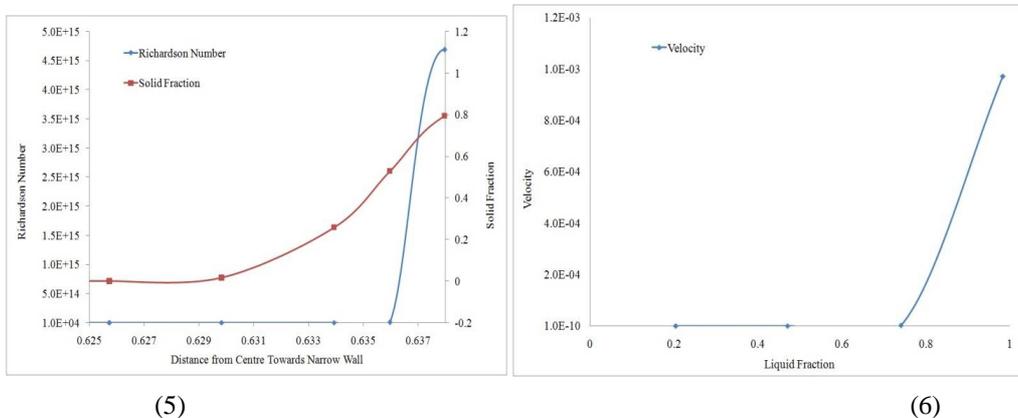
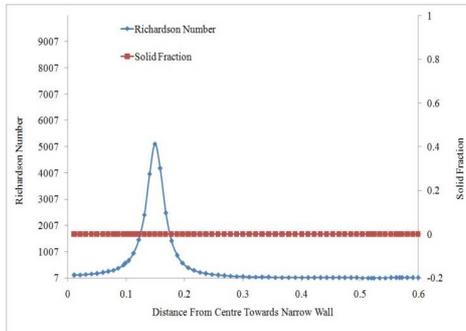


Fig 5: Richardson Number and Solid Fraction at 800 mm from Meniscus in mushy Region **Fig 6:** Velocity in Mushy Region for Plane at 800 mm

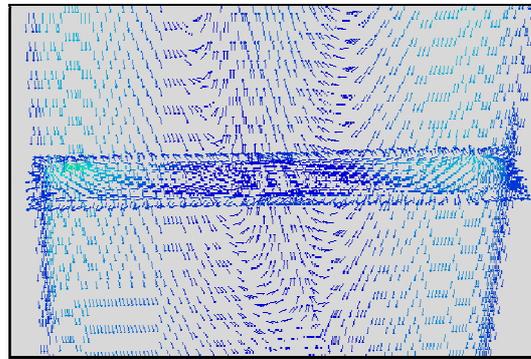
The temperature of mushy region is low compare to the liquid zone due to which the density of the of fluid is high, which cause the fluid to move in downward direction under the action of gravity because of which fluid particles get some momentum and ultimately increased in velocity. Therefore, we can say that thermal buoyancy decaying the delay of velocity. In liquid region density of liquid is low due to which it moves in upward direction and inertia force is in downward direction. These two forces are in opposite direction. Therefore, thermal buoyancy speeds up the decay of velocity. However, due to the recirculation fluid moving in the upward direction so thermal buoyancy supporting the inertia and increasing the speed.

To investigate the buoyancy effect outside the mould, a plane created at 3000 mm downward from the meniscus perpendicular to casting direction. Figure 7 shows the change in Gr/Re^2 ratio along the plane in lateral direction for liquid zone. Gr/Re^2 ratio in liquid region is above 1 from centre of plane ($Gr/Re^2 = 114.3$, $u_c=0.018$ m/s, $\Delta T_c=24.93$ K). It reaches to the peak Value ($Gr/Re^2 = 5114.17$, $u_c=0.0027$ m/s, $\Delta T_c=24.83$ K) near to centre. After this, it starts decreasing but remains well above the 1 till the end of the liquid region. These phenomena can be explain with figure 8. The right side recirculation slightly shifted towards left and two circulations mixed due to which the Gr/Re^2 ratio reach to peak value as velocity is very low. However, it is observed that at 3000 mm from meniscus the velocity gets very low due to which for complete liquid region Gr/Re^2 ratio is above 1.

For mushy region, variation of velocity are according to equation 5 shown in figure 9. It shows that when 1% of liquid converts to solid, velocity drop from 0.04 m/s to 0.0048 m/s which is almost 100 times velocity gets drops in the start of mushy zone. Due to which the Richardson number reach to high value ($Gr/Re^2 = 1675.57$, $u_c=0.0047$ m/s, $\Delta T_c=25.02$ K) and it is increasing in the mushy region (shown in figure 10) with decreasing velocity. It means that away from the meniscus, in liquid region as well as in mushy region thermal buoyancy force is predominant over inertial force.

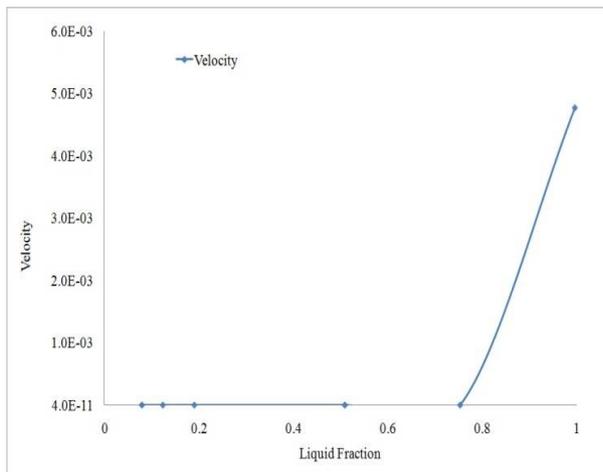


(7)

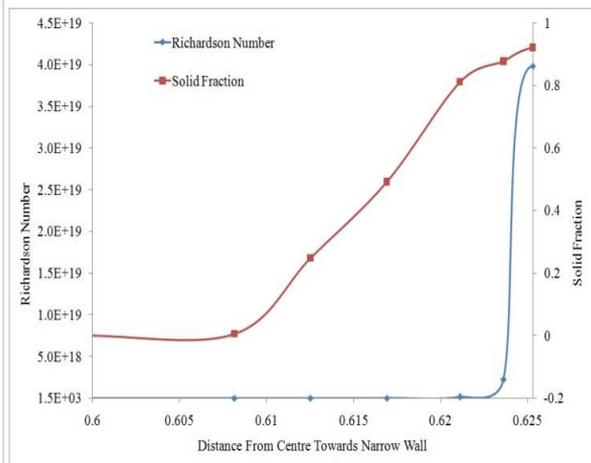


(8)

Fig 7: Richardson Number and Solid Fraction at 3000 mm from Meniscus in Mushy Region. **Fig 8:** Velocity Vectors at Mid Plane and Plane at 3000mm from the Meniscus.



(9)



(10)

Fig 9: Velocity in Mushy Region for Plane at 3000 mm **Fig 10:** Richardson Number and Solid Fraction at 3000 mm from Meniscus in mushy Region.

A line was drawn along the axis of jet. Along this line Richardson number are plotted for liquid zone and mushy zone. Figure 11 shows that Gr/Re^2 ratio in liquid zone are below 0 from start of port to the end of liquid zone. It means that along the jet the inertial force is dominant over buoyancy force.

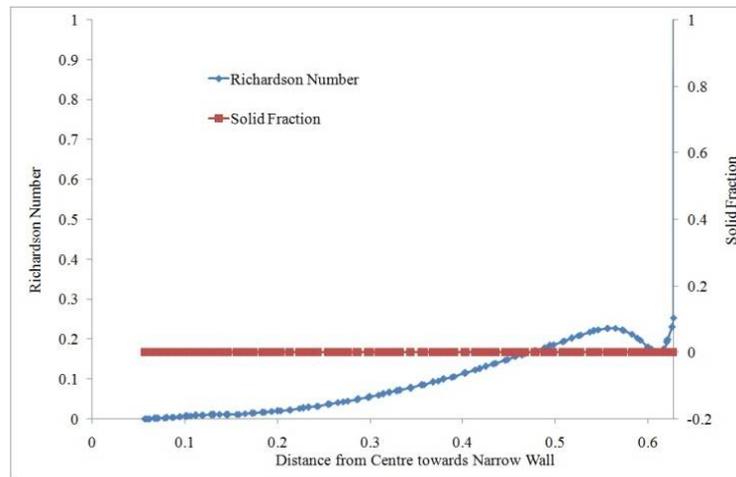
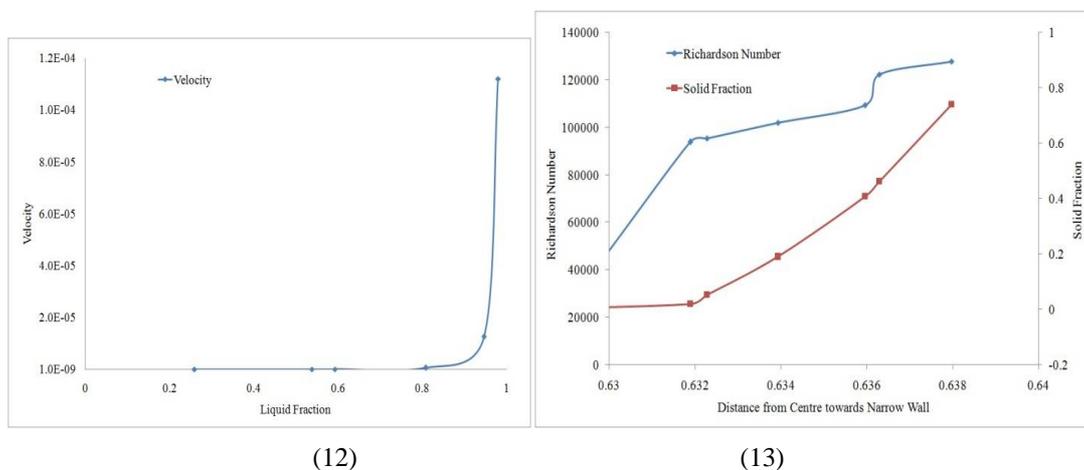


Fig 11: Richardson Number and Solid Fraction at 3000 mm from Meniscus in Liquid Region



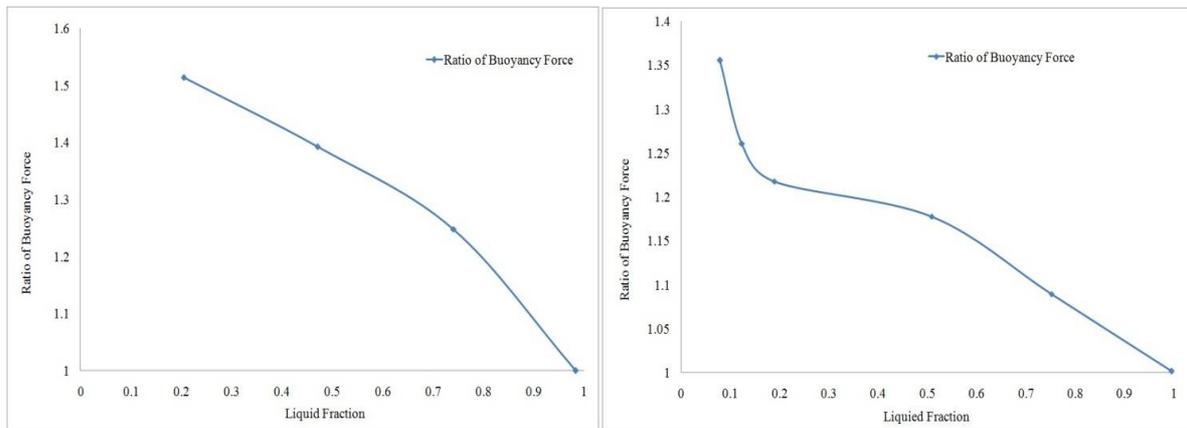
(12)

(13)

.Fig 12: Velocity in Mushy Region Along Jet **Fig 13:** Richardson Number and Solid Fraction along the Jet in mushy Region.

However, in mushy region velocity of jet suddenly drop to a value of 0.00011 m/s from 0.35 m/s when 2% of liquid phase changes to solid phase and change in velocity along mushy region shown in figure 12. In mushy region velocity drop continuously that cause Richardson number to increase throughout the mushy region indicated in figure 13 from start of mushy region towards end of it. From the above analysis, it can be seen that in mushy region only thermal driven buoyancy flow play an important role compare to the inertial force and buoyancy force is responsible for the motion of the fluid in mushy region.

Thermal buoyancy force plotted along the mushy region mushy region for the plane at 800 mm, 3000 mm downward from meniscus and along jet also. Figure 13, 14 and 15 indicate the ratio increase in buoyancy force along the mushy region. All the three figure shows same Patten of increasing in buoyancy force along the mushy region with little change in magnitude. It is observed that increasing buoyancy force ratio is almost 50% in mould region as in mould ΔT is more due to force convection Along the jet buoyancy force increase is 36% which shows the same agreement with the result from Saul Garcia et.al.



(13)

(14)

Fig 13: Thermal Buoyancy Force Ratio along the mushy region for plane at 800 mm **Fig 14:** Thermal Buoyancy Force Ratio along the mushy region for plane at 3000 mm.

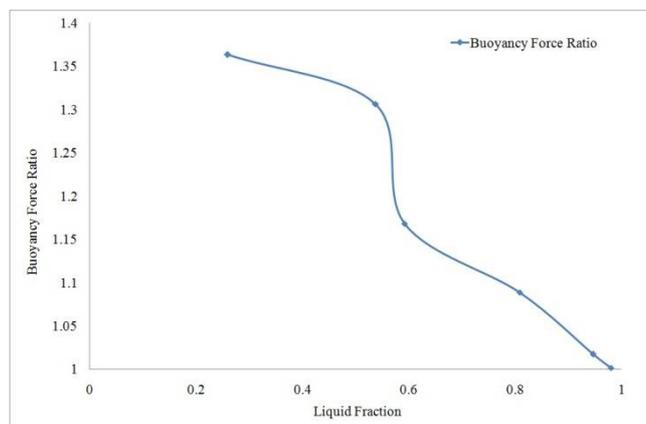


Fig 15: Thermal Buoyancy Force Ratio along the mushy region for jet region.

V. CONCLUSIONS

A 3-D fluid flow and solidification model has developed to study the effect of thermal driven buoyancy flow and conclusions derived from thee result are as follows:

1. It is observed that in mould region, inertial force is dominant over thermal buoyancy force in liquid zone. However, for mushy zone thermal driven buoyancy force is predominant and it is responsible for the motion of fluid in mushy region.
2. It is also observed that, region away from the meniscus thermal driven buoyancy force is dominant in both liquid zone as well as mushy zone.
3. Along the jet, inertial force is more important in liquid zone while in mushy region thermal buoyancy force play important role.
4. It is observed that for mushy region, anywhere in mould and sub-mould region thermal buoyancy play important role and there is almost 50% increasing in buoyancy force in mould region and 36 % increasing in jet region.

So we can conclude that thermal driven buoyancy flow play very important role in steel flow behavior, consequently they always considered otherwise it will lead to certain grade of inaccuracy in obtaining the result.

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VI. NOMENCLATURE

g	Acceleration due to gravity (m/s^2)
u_i, u_j	Velocity of steel flow along three dimensional coordinate
H	Total enthalpy of material (J/Kg)
ΔH	Latent heat content of the cell (J/Kg)
C_p	Specific heat of solid and liquid (J/Kg K)
h_{ref}	Reference enthalpy (J/Kg)
$T_{solidus}$	Solidus temperature (K)
$T_{liquidus}$	Liquidus temperature (K)
P	Effective pressure ($Kg/m s^2$)
T	Temperature (K)
v	Velocity in mushy region
z	Cast length or distance below the meniscus (m)
u	Casting speed (m/s)
Gr	Grashof Number
Re	Reynolds Number
ρ	Density of solid and liquid (Kg/m^3)
β	Liquid volume fraction
α	Thermal diffusivity (m^2/s)

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