Numerical study of thermal driven buoyancy flow effect on solidification process of continuous slab caster

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Abstract. The main aim of the present research is to study the role of thermal driven buoyancy flow in solidification process of continues slab caster. A 3-D fluid flow, heat transfer and solidification model was developed. The result from the model combined with non-dimensional number to study the effect of thermal driven buoyancy flow on fluid flow and temperature distribution. For mushy region Kozeny-Carman is applicable. Observations show the relative strength between thermal driven buoyancy flow and steel flow through mushy region. It is observed that buoyancy force in mould and sub mould region depend on the characteristic flow velocity, temperature difference and porosity of mushy zone. The most effect zone of thermal driven buoyancy flow is mushy zone and centre of mould where inertial flow is inferior. The convection flow creates by thermal buoyancy cause appearance of local turbulence.

KEY WORDS: continuous slab casting, thermal driven buoyancy flow, solidification, mushy zone.

1. Introduction

Recognizing the importance of continuous casting in industry, researches are done to understand the process and improve the productivity. The advantage of continuous casting is better yield, saving energy and manpower. The quality problems of continuous cast product are eliminated with development in work. In recent year, with increase in the power of computer and reduction in computational cost, allows the researcher to access some of the unknown phenomena of continuous casting. One of the unknown parameter is thermal driven buoyancy flow. In tundish, thermal driven buoyancy flow has been studied1-2). This cause change in flow profile. Similarly, in mould and sub mould region the temperature difference is created due to the heat transfer and solidification so, what about the thermal driven buoyancy force?

First the X. Huang et al.3) investigated the importance of thermal buoyancy force with modified Froude number and came to conclusion that inertia force are more important than thermal buoyancy force in controlling the flow pattern. They got this result because of not considering the mushy region in to account to reduce the complexity in the model. Aboutalebi et al.4) developed a 2-D fully coupled fluid flow, heat and solute transport model and studied the effect of thermal driven buoyancy force on the predicted velocity distribution in slab caster, but in 2-D model the predicted heat transfer of slab...
strand affect the accuracy in prediction of the thermal buoyancy. Sual Garcia-Hernandez et al.\(^5\) investigated the effect of buoyancy force and come to the result that in jet region buoyancy force is 10\% of the inertial force but they neglected the porosity of the mushy region.

In present study a steady three dimensional fluid flow and solidification model is developed and result are discuss with the help of non dimensional formula to study the effect of thermal driven buoyancy flow on fluid flow and solidification. This will provide awareness to the role of thermal buoyancy flow in developing the mathematical model for continuous casting of steel.

2. Mathematical Formulation

2.1. Assumptions

The 3-D transport equation is derived based on of assumptions.

- The fluid is Newtonian, incompressible with Boussinesq approximation and turbulent effect is approximated using SST K-\(\varepsilon\) model of turbulence.
- Material was considered homogeneous and isotropic.
- Transport of complex geometry inclusions through the liquid, entrapment of gas bubbles, mould flux and the inclusion onto solidifying steel shell and the top surface has not considered.
- Effect of Argon flow, mould oscillation, strand deformation (bulging) etc. has not considered.
- Multiphase fluid flow in the mould region and secondary cooling zone is avoided.

2.2 Fluid Flow

2.2.1 General Consideration

Fluid flow inside the mould is turbulent flow in liquid core. The turbulent flow is modelled by SST K-\(\varepsilon\) model from various pervious acceptable works\(^{16-18}\). The governing equations for fluid flow are following\(^6\):

Continuity Equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0 \quad \text{......................(1)}
\]

Momentum Equation:

\[
\frac{\partial (\rho u_j)}{\partial t} + \rho u_j \frac{\partial u_j}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_j}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{\partial P}{\partial x_i} - \rho \beta_i \left( T_{ref} - T \right) \quad \text{......(2)}
\]

Energy Equation:

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

2.3 Mushy Region Consideration

The mushy region considers as a region in which liquid and solid phases coexist and temperature of this region lies between liquidus and solidus temperature. The turbulence of the fluid is reducing in the mushy region due to the columnar dendrites but turbulence is increased by thermal buoyancy\(^7\). Therefore, flow in the mushy region remains unclear.

In mould as liquid jet strike the wall, there form a chilled zone near the wall; around centre of the mould there exist the equiaxed crystal zone and in the middle part between chilled zone and equiaxed zone there exist a columnar dendrites. It means that mushy zone is either composes of columnar
dendrites or equiaxed crystals and both these zone block the fluid flow in mushy zone. In columnar
dendrites, mushy zone some of the dendrites are cut due to the fluid flow and move with it and some
remain attached to the solid shell. To capture the above phenomena a microscopic model is required
for accurate simulation but due to unavailability of sources of have exact model of mushy region it is
consider as a porous media whose porosity depend upon the liquid fraction which is keep on changing
with solidification and for the porous media, Kozeny- Carman equation is applicable which is:
\[
\frac{\Delta P}{L} = \frac{180 \mu (1 - \beta)^2}{\phi^2 \bar{D}_p \beta^3} \nu \quad \text{........................ (4)}
\]

It is assumed that \(\Delta P/L\) is constant for the particular plane, \(\phi^2, D_p^2\) is constant throughout the porous
media, then the velocity \(\nu\) is proportional to
\[
\nu \propto \frac{\beta^3}{\left[1 - (0.001 + \beta)\right]^2} \quad \text{........................ (5)}
\]
\[
\nu = k \frac{\beta^3}{\left[1 - (0.001 + \beta)\right]^2} \quad \text{........................ (6)}
\]

Therefore, in mushy region velocity should vary according to above formula that depends on the
porosity which is nothing but the liquid fraction. The small value of 0.001 is added in the denominator
to avoid divisible by zero.

3. Modelling Conditions

A three dimensional fluid flow and heat transfer model for continuous slab caster was developed and
solve on the CFD commercial software FLUENT. Figure 1 give description of slab caster which was
discretised in structured mesh of 2.7 million cells shown in figure 2. The inlet velocity calculated to
maintain the casting speed of 0.8 m/min. At the narrow wall and wide wall of the mould heat flux
profile is attracted to extract heat from the mould. For the narrow face and wide wall mixed boundary
condition with thermal conductivity equals to 750 W/m²K and 620 W/m²K is used. The mesh was
refine around the mushy region for a particular plane, created to study thermal driven buoyancy flow.

| 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)            | 0.8                     |
| Density (kg/m³)                  | 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                    |
It is difficult to determine the mould heat flux due to the gap between the mould and shell. A local heat flux can be obtained by measuring the mould water volume and water temperature between inlet and outlet. Savage-Prichard in 1954 has reported the following relation for heat flux in the mould by assuming heat flux in the mould does not vary along the width of the mould:

\[ q = 2.67 - 0.33 \sqrt{\frac{z}{u}} \] ........................ (7)

The values of heat transfer below the mould from strand surface to the environment are calculated by three heat transfer modes: conduction, convection, and radiation. Therefore, it is difficult to combine heat transfer coefficient and for this trial and error, method has been adopted by knowing the spray cooling water volume obtain from plant data and heat transfer coefficient is used to calculate the surface temperature and compared with the measured temperature.

4. Result and Discussion
4.1 Verification of Calculated Result

Figure 3 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.
4.2. Comparison between Thermal Driven Buoyancy Force and Inertia Force by Jet Impinging

In present study, $Gr/Re^2$ (called as Richardson number) is studied to determine the importance of buoyancy driven flow and forced flow from SEN impinging jet, given by $^8$:

$$\text{Richardson Number} = \frac{Gr}{Re^2} = \frac{gLc\beta'\Delta Tc}{u_c^2} = \frac{\text{BUOYANCY FORCE}}{\text{INERTIAL FORCE}} \quad ............ (8)$$

In continuous casting the solidification is mainly from upstream to downwards along longitudinal direction and from narrow face towards centre of the mould along lateral direction, so thermal driven buoyancy force occur 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 three plane were created perpendicular to the casting direction (or perpendicular to $z$- axis) at 800 mm, 2000 mm, and 3000 mm from meniscus. Due to symmetry any one half of the plane is consider. These plane consist of 3 zones; liquid zone whose liquid fraction is 1, means it contain only liquid steel. Next to, it is mushy zone whose liquid fraction varies from 1 to 0 and next to mushy zone is solid zone whose liquid fraction is 0. The solid zone is not considered in the study.

When $Gr/Re^2$ ratio tend to zero the inertial force is predominant over buoyancy force and it is opposite when ratio is greater than unity. Having this in mind, for plane at 800mm from meniscus $Gr/Re^2$ ratio variation shown in Figure 4 for liquid region.

![Figure 4: Richardson Number and Solid Fraction at 800 mm from Meniscus in Liquid Region](image)
Along the plane in lateral direction for liquid zone, the $\text{Gr}/\text{Re}^2$ ratio is more than unity from centre of the plane ($\text{Gr}/\text{Re}^2 = 9.56, u_c=0.0623 \text{ m/s, } \Delta T_c= 24.33 \text{ K}$) towards narrow wall and reached to the peak value ($\text{Gr}/\text{Re}^2 = 303.617, u_c=0.010588 \text{ m/s, } \Delta T_c= 22.01 \text{ K}$) shown in Figure 4. Which means thermal driven buoyancy is dominant over inertia force. After it Richardson number start decreasing and reached to the value of 1.01 ($u_c=0.169262 \text{ m/s, } \Delta T_c= 19.79 \text{ K}$) at the end of liquid zone which is just above the unity. Therefore at the end of liquid zone both thermal buoyancy and inertia force is important.

This behaviour can be explained with Figure 5. At the centre of the plane, the lower recirculation increases the velocity due to which the Richardson number is little less but high enough to show dominancy of thermal buoyancy. At the mid of liquid zone (denoted by A) recirculation of fluid has less effect and velocity of steel almost come to its dead point and that cause the Richardson number to reach peak value.

![Figure 5: Velocity Vectors at Mid Plane and Plane at 800mm from the Meniscus](image)

Near the end of the liquid zone, the jet of fluid flow from SEN still has some effect which cause velocity to increases and bring the Richardson number to unity.

Considering the mushy region of the same plane, equation 6 get solved. The variation of velocity with liquid fraction in mushy zone shown in Figure 6.

![Figure 6: Velocity in Mushy Region for plane created at 800 mm](image)
As 7%, liquid changes to solid the velocity drop from 0.2 m/s at end of liquid region to 3.62 \times 10^{-5} \text{ m/s} in mushy region and velocity keep on decreasing as move toward mushy region due to which the Richardson number attain very high value shown in Figure 7.

![Figure 7: Richardson Number and Solid Fraction at 800 mm from Meniscus in mushy Region.](image)

It shows that with decreasing in velocity the Richardson number increases and it is keep on increasing in mushy region. Therefore, in mushy region, the inertia force is infinitesimal and thermal driven buoyancy force is responsible for the motion of the fluid. When ratio of buoyancy force is plotted along the mushy region, the Figure 8 shows that it is increasing from beginning of mushy region towards the end of it and there is almost 35% increasing in the ratio.

![Figure 8: Buoyancy Force Ratio along Mushy Region.](image)

Concerning on the direction of the buoyancy force it is predicted that in mushy zone the temperature of fluid is less compared to liquid zone so the density of fluid in mushy region is high which causes fluid to move in downward direction under action of gravity because of which fluid get some momentum and ultimately increased in fluid velocity. Therefore, we can say that the buoyancy force delaying the decay of the velocity. In liquid region, density of fluid is less and it is moving in upward but inertia force is moving in downward so this two forces are opposite in the direction. Therefore, thermal buoyancy speeds up the decay of the velocity. However, in centre of plane due to
recirculation the fluid moving in upward direction so thermal buoyancy increasing the velocity in liquid region and supporting the inertia.

Moving away from the meniscus around 3000 mm outside the mould and study the effect of the thermal driven buoyancy force.

**Figure 9:** Richardson Number and Solid Fraction at 3000 mm from Meniscus in Liquid Region.

As we move outside the mould the variation of Richardson number in liquid region shown in Figure 9. At the centre of the plane the Gr/Re² ratio (Gr/Re² = 3020.28, uc=0.00356 m/s, ΔTc= 25 K) is very high and it is decreasing towards end of the liquid region (Gr/Re² = 36.5153, uc=0.03228 m/s, ΔTc= 24.92 K). However, Richardson number decreasing towards the end of the liquid region but effect of thermal driven buoyancy force is remarkable.

From Figure 10 it can be seen that at the centre the velocity of fluid comes to its dead point due to which the Richardson number at the centre of the plane is high.

**Figure 10:** Velocity Vectors at Mid Plane and Plane at 3000mm from the Meniscus

The fluid from the end of the liquid region gets recirculation and reaches to its dead point at the centre of the plane due to which the Richardson number at the centre of the plane is high compare to end of the liquid region.
For mushy region equation 6 is applicable and velocity variation in mushy region shown in Figure 11.

![Figure 11: Velocity in Mushy Region for plane created at 3000 mm](image)

Figure 11 shows same pattern of variation in velocity as that of plane at 800 mm i.e. as 1% liquid change to solid the velocity changes from 0.03 m/s in liquid region to 0.00687 m/s and it is keep on decreasing towards the narrow wall. The variation of $Gr/Re^2$ ratio in mushy region at 3000 mm plane shown in Figure 12.

![Figure 12: Richardson Number and Solid Fraction at 3000 mm from Meniscus in Mushy Region.](image)

The Richardson number increasing drastically in mushy zone with little higher magnitude compares to the plane at 800 mm. It means that away from the meniscus thermal buoyancy is important in both liquid region and mushy region.

A line is drawn along the axis of jet to analyze the effect of buoyancy force. Figure 13 shows $Gr/Re^2$ ratio for liquid region, $Gr/Re^2$ ratio ($Gr/Re^2 =0.17$, $u_c=0.29$ m/s, $\Delta T_c = 10$ K) is well below 1 for liquid region. It means that along the jet the inertia force is predominant over thermal buoyancy force.
In mushy region along the jet the velocity suddenly decreases from 0.29 m/s to 0.0001 m/s and keep on decreasing along the mushy region shown in Figure 14. Due to which the Richardson number increasing from start of mushy region towards the end it shown in Figure 15. So it can be say that along jet also thermal buoyancy plays an important role.

Figure 13: Richardson Number and Solid Fraction along the Jet in Liquid Region

Figure 14: Velocity in Mushy Region along the Jet
Figure 15: Richardson Number and Solid Fraction along the Jet in Mushy Region

Figure 16 shows the thermal buoyancy force ratio along the mushy region and it is increasing from start towards the end of the mushy region and it can be observed that there is almost 45% increase in buoyancy force which is in the statement of Sual garcia-hernandez et al.

4.3. Local Convection Strength Cause by Thermal Buoyancy Flow

Thermal Rayleigh number $Ra_T$ used to predict the local convection strength of thermal buoyancy flow in mould and sub mould region and it is given by:

$$Ra_T = Gr \cdot Pr$$

Where,

$$Gr = \frac{gL^3 \Delta \rho}{\theta^2 \rho}$$

$$Pr = \frac{\theta}{\alpha}$$
The Prandtl number of steel is around 0.127. Therefore Rayleigh number $R\alpha_T$ is:

$$R\alpha_T = 3.33 \times 10^{12} \frac{\Delta \rho}{\rho}$$

The density difference between liquid steel and solid steel is around 1-3 %, so the $R\alpha_T$ is of the order $10^{10} - 10^{11}$ which is within the turbulence range. Therefore, thermal buoyancy creating a local turbulent convection in mould and sub mould region and it is necessary to adopt a general turbulent model equation to describe local turbulence by buoyancy force.

5. Conclusion
In this study, the effect of thermal driven buoyancy flow is studied on the solidification process of continuous slab caster. Its effect is discussed using non-dimensional analysis. It was found that the strength of thermal driven buoyancy flow in mould and sub mould region was depend upon the characteristic flow velocity, temperature difference and porosity of mushy region. The importance of thermal buoyancy changes with solidification. In jet region the $Gr/Re^2$ ratio is below 1. Thermal buoyancy effect is negligible compare to forced flow. In other zone where forced flow is weak the $Gr/Re^2$ ratio is above 1 which shows the dominance of thermal buoyancy force over forced flow. In mushy zone, it is necessary to consider the porosity and its effect on fluid flow. The $Gr/Re^2$ ratio in mushy zone is very high, which demonstrate the importance of thermal driven buoyancy flow in mushy region. The buoyancy force ratio is increase around 40% in mushy zone and for jet region it is slightly increased which around 43%. The Rayleigh Number is well within the turbulence zone induced by thermal driven buoyancy flow. Therefore buoyancy force play very important role on the fluid flow behaviour, consequently they must be considered otherwise it will lead to certain grade of inaccuracy in the obtain result.

Nomenclature

- g: Acceleration due to gravity (m/s$^2$)
- $u_{ij}$: Velocity of steel flow along three dimensional coordinate
- H: Total enthalpy of material (J/Kg)
- $\Delta H$: 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 $^2$)
- $T$: Temperature (K)
- $u$: Velocity in mushy region
- z: Cast length or distance below the meniscus (m)
- u: Casting speed (m/s)
- Gr: Grashof Number
- Re: Reynolds Number
- $\rho$: Density of solid and liquid (Kg/m$^3$)
- $\beta$: Liquid volume fraction
- $\alpha$: Thermal diffusivity (m$^2$/s)

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