Effect of Electromagnetic Stirring on Continuous Casting of a Steel Billet using 2D Magnetohydrodynamic Analysis

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Abstract

The molten liquid in the mold of continuous casting is churned using electromagnetic field to produce homogeneous and defect-free billets. In this investigation a two-dimensional computational model to simulate the effect of electromagnetic stirring on continuous casting of steel billets is developed using magnetohydrodynamic (MHD) module present in ANSYS-FLUENT 18.1 software. A solidified shell of the billet is formed in the vertical water-cooled copper mold in the primary stage of cooling. The primary stage cooling is investigated in this work with and without employing electromagnetic stirring. A moving electromagnetic field of intensity 0.1 T and frequency 10 Hz is applied in horizontal and vertical directions separately for electromagnetic stirring. The electromagnetic stirrer is of length 100 mm and it is placed at various locations of the vertical mold of 1 m height. The stirrer is placed at locations 100, 300, 500 and 700 mm from the meniscus. The velocity field and porosity of the solidifying liquid within the mold are computed and compared with and without electromagnetic stirrer. A dense mushy zone is formed at the center of the mold and recirculation loops are formed near the electromagnetic stirrer.

Introduction

Continuous casting is a pivotal process in steelmaking as the liquid steel is shaped into blooms and billets without rolling. This casting process pertains pouring of steel from a tundish which is a large vessel to hold the molten liquid into a vertical water-cooled copper mold so that it solidifies and pulled continuously (Figure 1).

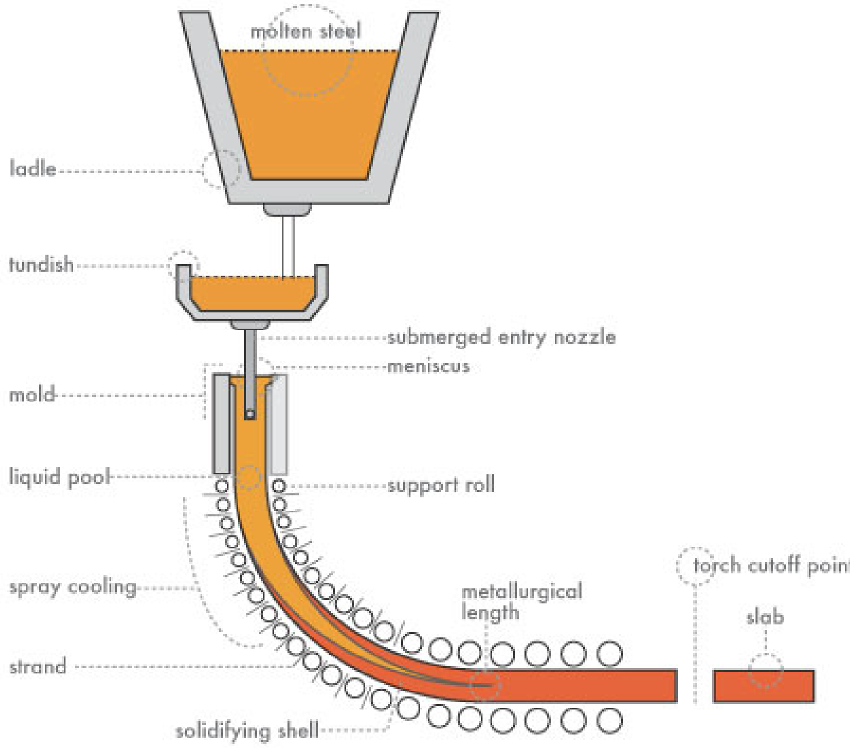

Figure 1. Continuous casting process

The cooling of molten steel in the mold is the primary cooling zone, where a solidified shell is formed near the walls of the mold. This solid shell should have adequate thickness at the exit of mold to withstand the ferrostatic pressure of liquid metal present inside it. The quality of the strand also gets impaired by the presence of nonmetallic inclusions and segregation of solute elements. The minimization of such irregularities can be achieved by altering the flow of fluid inside the mold. The liquid steel is stirred inside to generate heat transfer and helps breaking down the columnar dendritic solidification.

The stirring effect can be introduced by introducing external electromagnetic field inside the mold. When a magnetic field is applied to a liquid or solid conductor, eddy currents are induced. This produces an electromagnetic force called Lorentz force, which is generally rotary in nature. The strong rotation of liquid steel inside the mold caused by the electromagnetic stirring improves the surface quality by reducing the surface defects and ensures sub-surface cleanness. Stirring in the specific region of the mold is generally used to change the flow pattern and achieve the regeneration of liquid characters and also to form equiaxed grain structure.

The effect of stirring phenomenon in continuous casting on its metallurgical effectiveness for improving the quality of steel billets and slabs has been developed for many years. Many experimental and numerical investigations have been carried out to explore the effect of electromagnetic stirrer (EMS) on continuous casting of steel. Mramor et al. developed an advanced meshless method to investigate the effect of electromagnetic stirring and observed that the EMS stirs the flow by the application of an alternating magnetic field which improves the quality of the strand, reduction of defects at the surface and subsurface, boosts the solidification and reduces breakouts at the exit of the mold. Maurya and Jha developed a coupled three-dimensional flow and solidification model to study the effect of position of electromagnetic stirrer and reported that vertical recirculation zones are formed above and below the EMS and as the position of the EMS was lowered the length and diameter of vortices diminishes. A numerical investigation of Ren et al. studied the interaction of the flow and impinging jet coming from a submerged entry nozzle (SEN) in the caster, due to the rotational movement made by the mold EMS, it shows that the electromagnetic force seemed to circinate at the position EMS in the round bloom and a dominating swirl motion along azimuthal direction of the horizontal plane is observed. Javurek et al. compared numerical solutions of flow and temperature of continuous casting subjected to electromagnetic stirring with semi-empirical solutions available in literature and concluded that the numerical solutions overpredicted the velocities. Yu and Zhu used a combined 3-D finite element-finite volume magnetohydrodynamic (MHD) model to study continuous casting process under the influence of rotating electromagnetic force led to the formation of two pairs of recirculation zones. It is also observed that the stirring effect makes inclusions to float on the top of the mold. The relation between the stirring current and rotational velocity of the molten metal have been analyzed by Yang et al. It is concluded that the rotational velocity increases with increase in the current intensity and the number of the vortices formed is also relative. Cho et al. carried nail board dipping experimental test and compared with large eddy current simulations coupled with Lagrangian discrete phase method to study the surface velocity and level fluctuations in continuous casting process by employing electromagnetic field. It is reported that electromagnetic braking increased surface level stability. A transient 3D model of a slab-type continuous casting with electromagnetic braking and stirring near the meniscus separately is investigated by Takatani. It is reported that the electromagnetic stirrer near the meniscus removes bubbles and inclusions as the flow velocity is low but turbulence is high. Otake et al. investigated the effects of double-axis electromagnetic stirrer on continuous casting process which is comprised of a rotating and a vertical electromagnetic stirrer using unsteady hydrodynamic analysis and found that there is a balance between rotational and vertical electromagnetic stirrer of optimum intensity that is to be maintained to stabilize the free surface. Sivak et al. suggested that an optimum linear velocity by the action of the stator of electromagnetic stirrer is required and reported that a maximum linear velocity range of 0.5-1.0 m/s provide for an efficient stirring. Barna et al. observed that optimum velocities near the solidifying shell are favored to improve the solidification by the conversion of columnar dendritic to equiaxed grain structure.

Based on review of literature the effect of direction and position of the electromagnetic stirrer on the quality of continuous casting needs to be explored. Therefore, a two-dimensional transient magnetohydrodynamic model of continuous casting of steel using ANSYS-FLUENT software is developed to analyze the effect of direction and position of the electromagnetic stirrer on the flow and solidification characteristics with and without electromagnetic stirrer in this investigation.

Numerical Modeling

A model is prepared to best represent the cast of the continuously casting process, which is simple enough to numerically evaluate the effect of EMS on the process.

The following assumptions are made in this work:

- The continuous casting strand is considered as straight and vertical for numerical computation.
- The liquid steel is considered to be a homogeneous incompressible Newtonian fluid.
- A 2D model is analyzed for the sake memory requirements and solution time.
- The material properties such as density, viscosity, thermal conductivity, heat transfer coefficient, specific heat and latent heat are assumed as constant and are independent of temperature.

The governing theories for flow of the fluid, its phase interaction and ensuing solidification after its filling of the mold for this problem are discussed below.

Multiphase modeling

The liquid steel is treated as an interpenetrating continua where the volume of primary phase (air) is not penetrated by secondary phase (steel). The tracking of each phase is calculated using volume fraction (α)

which is evaluated explicitly with the following expression:

$\frac{\alpha_q^{n+1}\rho_q^{n+1}-\alpha_q^n\rho_q^n}{\Delta\tau}V+\sum_f\left(\rho_q U_f^n\alpha_{q,f}^n\right)=\left[\sum_{p=1}^n\left(\dot{m}_{\text{pq}}-\dot{m}_{\text{qp}}\right)+S_{\alpha_q}\right]V$	(1)

Where, $n+1$ is the new or current time step, n is the previous time step, $\alpha_{q,f}^n$ is face value of the volume fraction of$q$ computed from before, V is volume of cell, U_f is normal velocity of volume flux through the face.

Turbulence modelling

A standard kinetic energy (k) and dissipation rate (e) (k-e) model is used to control the flow behaviour by solving the unknowns of Navier-Stokes (RANS) equations through Reynolds-averaging. The transportation of kinetic energy across the domain is equated as:

$\frac{\partial\overrightarrow{B}}{\partial t}+\left(\overrightarrow{U}.\nabla\right)\overrightarrow{B}=\frac{1}{\mu\sigma}\nabla^2\overrightarrow{B}+\left(\overrightarrow{B}.\nabla\right)\overrightarrow{U}$	(6)

The transportation of dissipation rate across the domain is given as:

Where, U_i is the velocity component, μ_t is the turbulent viscosity, G_k is the generation turbulent kinetic energy due to mean velocity gradients, G_b is the generation of turbulent kinetic energy due to buoyancy, Y_m denotes the influence of the fluctuating dilation in compressible turbulence to total dissipation rate,$C_{1\varepsilon}$, $C_{2\varepsilon}$ and$C_{3\varepsilon}$ are the constants, σ_k andσ_ε are the Prandtl numbers of k and e respectivelyS_k and S_ε are user defined source terms for k and e respectively.

Solidification modeling

An enthalpy-porosity technique is used to track the liquid-solid transition with a parameter called liquid fraction, which it indicates the fraction of each cell of the domain which is in liquid form. The liquid fraction for is equal to porosity of a cell, which is determined using following conditions:

$\beta=0$ if $T<T_{\text{solidus}}$ (solid)

$\beta=1$ if $T>T_{\text{liquidus}}$ (liquid)

$\beta=\frac{T-T_{\text{solidus}}}{T_{\text{liquidus}}-T_{\text{solidus}}}$if $T_{\text{solidus}}<T<T_{\text{liquidus}}$ (mushy zone)

The mushy zone is the region where it is neither completely liquid nor completely solid. The enthalpy justifies the solidification with the release or absorption of latent heat (ΔH) and sensible heat (h).

$H=h+\Delta H$	(4)
$H=\beta L$	(5)

Where, L is the latent heat of the material, which is given in the Table 1.

Magnetohydrodynamic modeling

The magnetic field induction is achieved from Ohm's law and Maxwell's equations to induce Lorentz force for stirring inside the domain. The derived equation as:

Where, $\overrightarrow{B}$ is the induced magnetic field, μ is magnetic permeability and σ is the electrical conductivity.

The Lorentz force is calculated from the following as:

$$F_{\mathrm{emag}} = \sigma\,(E + U \times B) \times \mu_0\,(H + M) \quad (7)$$

Where, σ is the electrical conductivity, E is electrical field, B is magnetic induction, μ is the magnetic permeability, H is magnetic induction, M is magnetization vector.

Design

The concast mold is of square cross-section of 220 mm side and 1000 mm high. The liquid steel is poured into the mold from the top through a nozzle which is at its center and of diameter 46 mm. The speed of continuous casting is 1.8 m/min. To minimize the cost of computation a vertical section (Figure 2) at the center of the mold is analyzed. In the computational model the nozzle at the top boundary is taken as inlet, and bottom boundary of the mold is taken as outlet. The two vertical sides of the mold are taken as walls subjected to convection of water circulation to cool the mold. The toplet of the mold is assumed to be perfectly insulated. The inlet velocity of the liquid metal is calculated using the following equation:

$$v_i = \frac{v_c \times A_o}{A_i} \quad (8)$$

Where, v_i is the inlet velocity, v_c is the casting speed,A_o is area of the cross-section of the mold (outlet), $A_i$is the area of the nozzle (inlet).

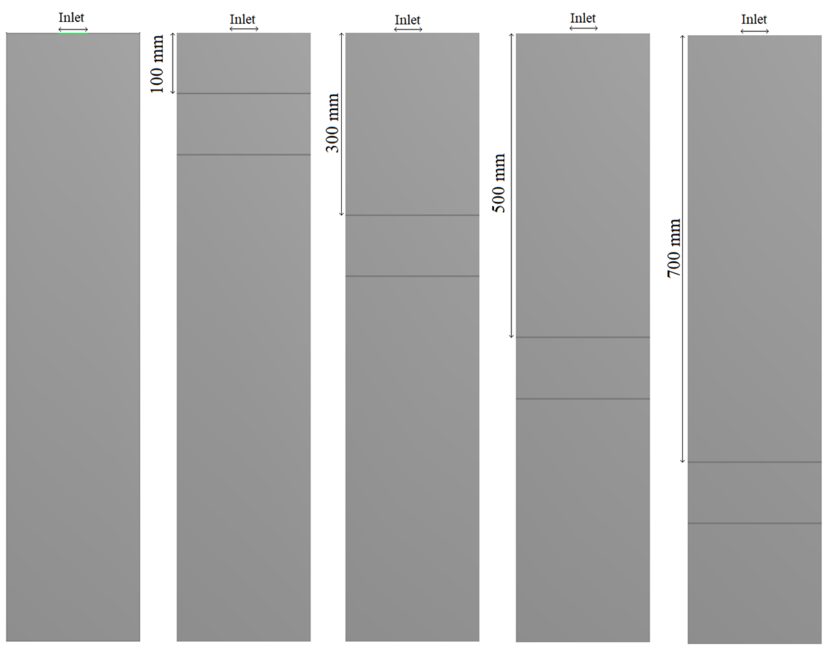

Figure 2. Mold design and the position of electromagnetic stirrer

The various process parameters and material properties are given the table below.

Table 1 Material properties of steel considered

Material properties	**Values**
Density (kg/m^3)	7200
Specific heat (J/kg K)	750
Thermal conductivity (W/m K)	41
Viscosity (kg/m s)	0.0067
Molecular weight (g/mol)	55.585
Latent heat (J/kg)	2.72×10^5
Solidus temperature (K)	1792
Liquidus temperature (K)	1805
Heat transfer coefficient (MW/m^{2}K)	1.2
Electrical conductivity ((Ωm)$^{-1}$)	7.14×10^5
Magnetic permeability (H/m)	1.257×10^{-6}
Casting speed (m/s)	0.03
Ambient temperature (K)	300

Initially simulations of heat transfer and fluid flow for the casting process is performed without electromagnetic stirrer. Then MHD module in ANSYS FLUENT is activated and a sinusoidal magnetic flux density 0.1 T and frequency 10 Hz is applied at the location of stirrer. This stirrer is having a length 100 mm in vertical direction and it is placed at various vertical locations of the mold. It is placed at 100, 300, 500 and 700 mm from the level of meniscus Figure 2. The electromagnetic field is applied separately in horizontal and vertical directions and is called H-EMS and V-EMS respectively for the rest of the paper.

After the boundary conditions and magnetic field are applied to the domain inside the mold, it is simulated with initial room temperature 300 K. As the simulation is transient an initial time step size of 0.0001 s and 20 iterations for each time step are used to find the converged time dependent solution. Then the time step size is gradually increased to 0.001 s. The optimum grid size is found from convergence test. The transient simulation is assumed to reach steady state at the end of 200 s of flow time. The time taken for this simulation up to steady state for each case on an 8 GB RAM and 2.30 GHz processor is about 7 days.

Results and discussion

As the simulations are carried out using numerical methods a convergence study is carried out to ascertain the accuracy of the solution using four different meshes. The number of grid elements in each of these meshes are 679, 1005, 1494 and 2212 corresponding to uniform grid sizes 18, 15, 12 and 10 mm respectively. The simulations are carried out without application of EMS. The temperature at 800 mm below the meniscus and 20 mm from the left wall is taken as the parameter to check grid convergence. A plot (Figure 3) is drawn with these temperatures against grid sizes for all these meshes and it is almost flat in x-direction. Hence, it can be concluded that grid convergence has been achieved with grid size 10 mm and this has been used in all subsequent simulations.

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Figure 3. Grid convergence

Further simulations are carried out by placing EMS as per the specified positions to obtain the histories of velocity and liquid fraction of the liquid metal solidifying in the mold.

The contours of magnitude of velocity along the length of the mold without EMS and with different positions H- EMS and V-EMS are shown in Figure 6 and Figure 7 respectively. The vectors indicate that the fluid flow velocity is maximum at the location of EMS, in its respective directions of application. The fluid is dispersed to form recirculation loops above and below at the position of EMS at centre of the mold due to the stirring effect. As the position of the EMS is lowered the thickness of loops increases but is more confined to the center of the mold. It is observed that the recirculation loops formed are more defined for all the positions of the V-EMS. The decrease of thickness of the loops and its confinement to the center because of lowering of EMS position is not as significant as H-EMS. The maximum values of velocity magnitude for H-EMS and V-EMS are given in the Table 2.

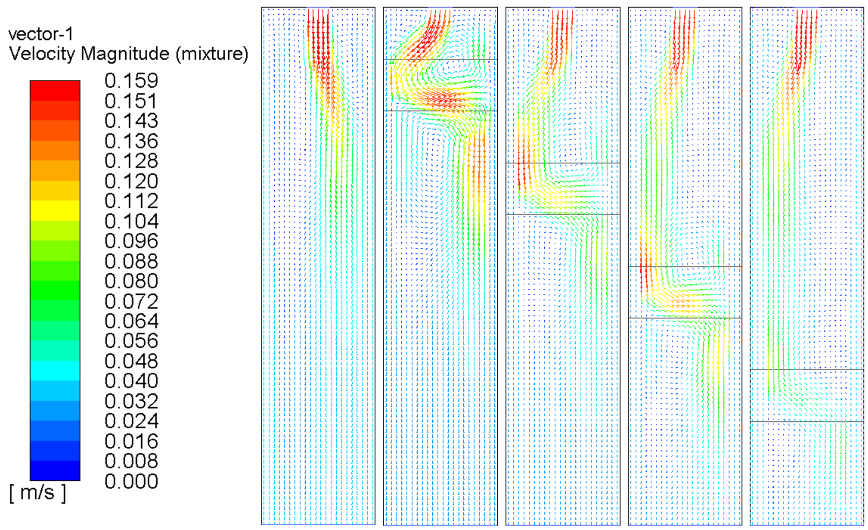

Figure 6. Comparison of velocity magnitude vectors for horizontal magnetic flux

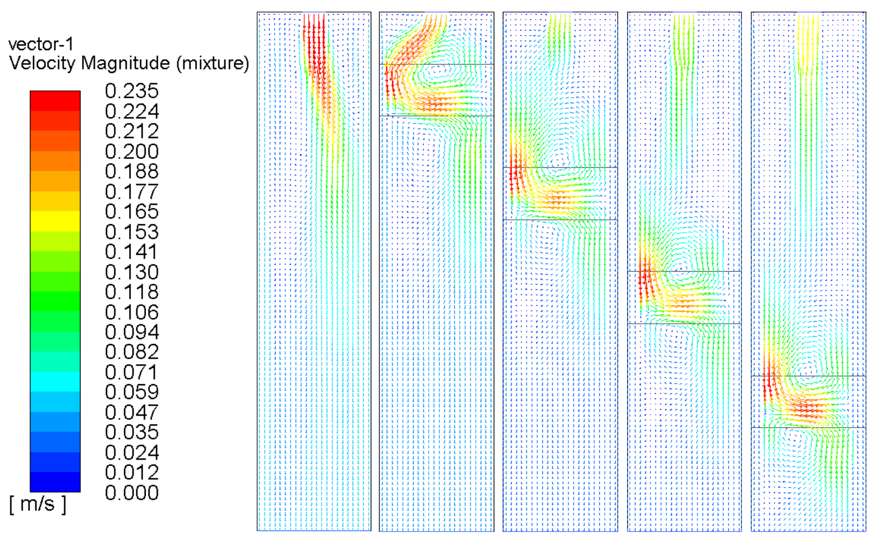

Figure 7. Comparison of velocity magnitude vectors for vertical magnetic flux

Table 2 Maximum values of velocity magnitude obtained in each case

Position of EMS	**Maximum velocity magnitude in** H-EMS	**Maximum velocity magnitude in** V-EMS

Position of EMS	**Maximum velocity magnitude in**	**Maximum velocity magnitude in**
100 mm	0.147 m/s	0.181 m/s
300 mm	0.155 m/s	0.224 m/s
500 mm	0.152 m/s	0.235 m/s
700 mm	0.144 m/s	0.206 m/s

The contours of liquid fraction with EMS at various positions and the direction of H-EMS and V-EMS are shown in Figure 8 and Figure 9. The liquid fraction varies as discussed in sub-section 2.3, it can be observed that the thickness of the solid shell has increased progressively towards the exit of the mold because of the continuous convection on the walls of the mold. The rotatory action activated by the Lorentz force inside the mold at the location of EMS aids in heat dissipation of the liquid steel. As the heat gets dissipated along the mold liquid pool starts to solidify and forms the mushy zone. The mushy zone starts only below the location of H-EMS, but for V-EMS it is also formed above the position of the EMS due to the change in the direction of the magnetic flux density.

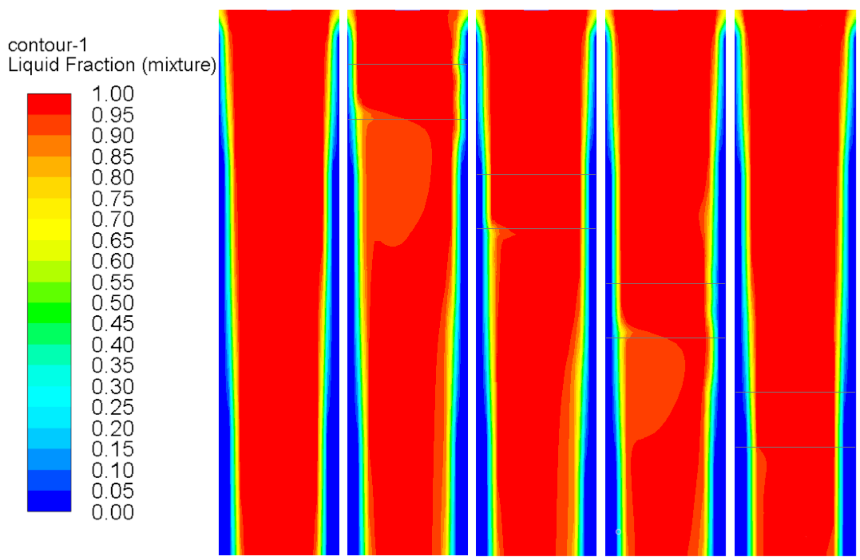

Figure 8. Contours of liquid fraction for horizontal EMS

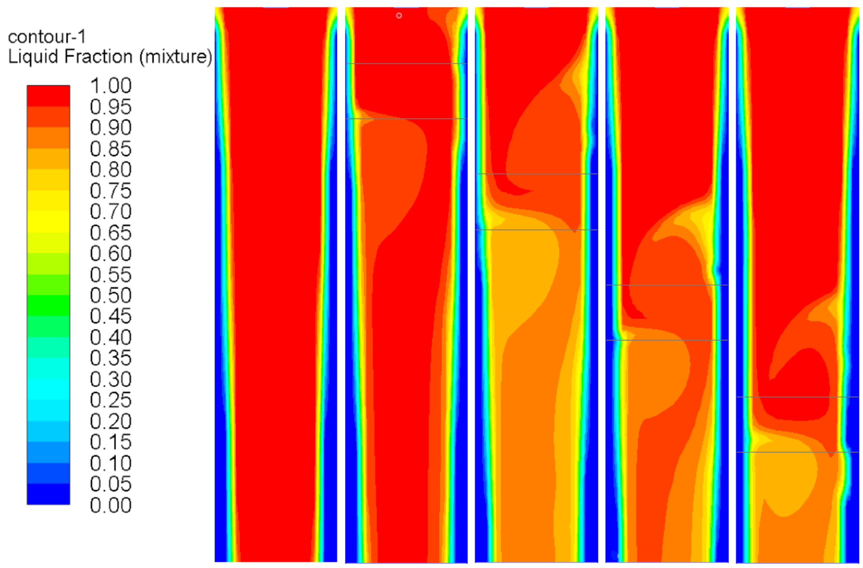

Figure 9. Contours of liquid fraction of vertical EMS

Liquid fraction or porosity is plotted against distance along a line parallel to the toplet at the center of the mold. Majority of center portion of the mold at this level is completely liquid when there is no EMS acting. The liquid fraction at this region varies from 0.96- 0.99 (mushy zone) with the H-EMS at 100 and 300 mm level. However, the metal at this region is completely liquid with H-EMS at 500 and 700 mm (Figure 10).

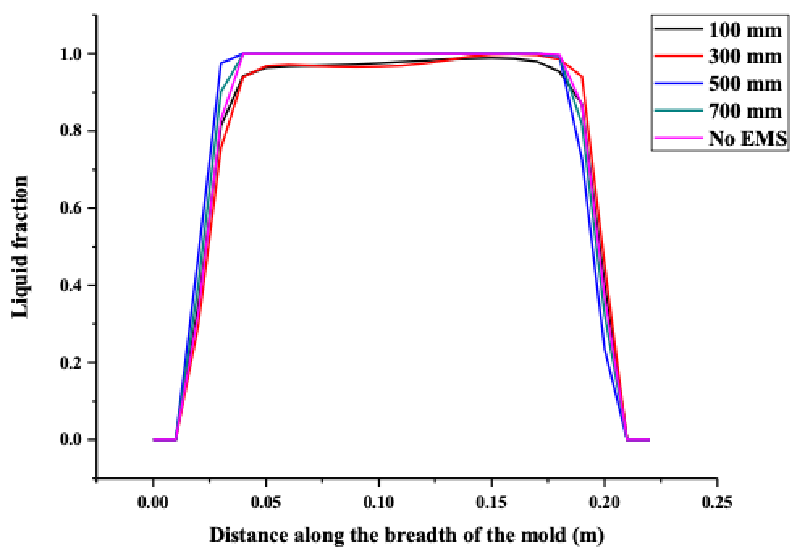

Figure 10. Liquid fraction at the centre of the mold for H-EMS

The liquid fraction of metal at the same region varies from 0.83 to 0.96 for the positions of V-EMS at 100, 300 and 500 mm and when the position is at 700 mm the metal in this region is completely liquid. A mushy zone is formed in general at this region with V-EMS (Figure 11).

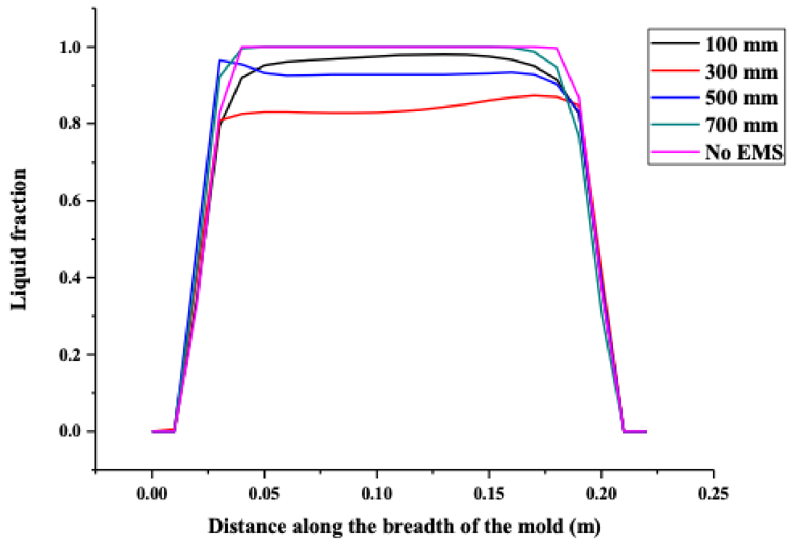

Figure 11. Liquid fraction at the centre of the mold for V-EMS

Conclusions

A two-dimensional transient magnetohydrodynamic model of continuous casting of steel using ANSYS-FLUENT software is developed and an electromagnetic stirrer is placed on the mold at different positions. The electromagnetic field is applied horizontal and vertical directions separately, the effects are simulated at each position of the EMS and are compared with no EMS results and the following conclusions are made:

1. The application of EMS causes churning which enables the liquid steel to interact with the solidified shell and enhances heat transfer inside of the mold.
2. The churning effect reduces as the position of the EMS is lowered for both the directions of magnetic field and it is more pronounced in V-EMS
3. The recirculation loops are formed at the centre of the mold in each case of EMS above and below of its position and are more well-defined with V-EMS.
4. The velocity accelerates due to the stirring effect. As the position of EMS is lowered with respect to the meniscus, the velocity acceleration decreases and its effect on the walls also decreases.
5. The mushy zone formed is visibly denser with the V-EMS and it is completely non-existent when no EMS was applied.
6. It can be concluded from all these observations that the change in position of the EMS effects the solidification and velocities of fluid flow.
7. The change of direction of stirring has a significant impact on the formation of mushy zone.

The author declares no potential conflict of interest.

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