Effect of Argon Injection in Meniscus Flow and Turbulence Intensity Distribution in Continuous Slab Casting Mold Under the Influence of Double Ruler Magnetic Field

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In the present investigation, an experimentally validated coupled two phase Magnetohydrodynamics (MHD) flow and turbulence model has been developed to analyse the combined implications of Argon injection and double ruler electromagnetic breaking (EMBr) in continuous casting flow control (FC) mold of the Tata Steel plant. The numerical model essentially solves transient Euler–Euler two-phase model, turbulence, and MHD Maxwell equations for prescribed experimentally plant measurement of magnetic field boundary conditions data at various Argon flow rates, casting speeds, and submerged entry nozzle (SEN) depths. The numerical model primarily validated with the plant experimental measurement data and found to be in good agreement. The computational results demonstrate that the application of magnetic field suppresses turbulence and meniscus velocity decrement. However, increasing Argon flow rate is found to magnify meniscus velocity and turbulence intensity at the mold. The Argon gas injected from the ports clusters nearer to the SEN and a local chunk of it gradually escapes from the meniscus by short-circuiting its path. Effect of EMBr is not found to be prominent at the higher Argon gas flow rate values. Maximum meniscus level disturbance is noticed at an Argon flow rate of 10 L/min.

KEY WORDS: argon flow; EMBr; mold; casting; steelmaking; two phase flow.

1. Introduction

In most of the modern integrated steel plants, argon gas is usually employed in the continuous casting process to prevent nozzle clogging, encourage mixing, and encouraging floatation of non-metallic inclusion particles from the molten steel by altering the flow field. The injected argon gas into the molten steel enters into the continuous casting mold through the SEN. Thereafter, the argon gas disintegrates into swarm of bubbles with different diameters due to intense shear forces exerted by molten steel. In general, bubbles with larger in diameter have the tendency to escape from the liquid steel surface through the mold flux powder layer, whereas, smaller diameter bubbles track the primary stream of molten steel flowing deep into the mold cavity. In contrast, these small bubbles and non-metallic inclusions sticking to the surface of these bubbles can be entrapped by solidified shell. This, eventually results in defects in the final cast product, namely, “pencil pipe” blisters, slivers, etc. The complexity and instability imparted by the injected argon gas on the transient flow pattern may be further circumvented by the application of electromagnetic forces during continuous casting. One of such celebrated practice is the Electromagnetic brake (EMBr), where a static magnetic field on the mold region of a steel continuous caster is applied to control meniscus flow and turbulence intensity distribution. The influence of superimposed magnetic field in the continuous casting flow control (FC) mold functionally dampens the local turbulent fluctuations and therefore facilitates substantial capabilities to improve the quality of the steel and to enhance the productivity of the process. Physically, the EMBr’s employ twin magnets at each wide faces of the mold, which generates rectangular regions of magnetic field distributions near the SEN ports. The EMBr follows the principle of employing a static magnetic field aligned perpendicular to the main flow direction. Owing to the interactions between the induced magnetic flux and the electrically conductive molten steel inside the mold cavity, a Lorentz force is generated in the opposite direction of fluid motion. This, in turn, imparts a retarding influence in slowing down the jet velocity emanating from the submerged entry nozzle ports. The resulting consequence yields in damping strong velocity fluctuations inside the mold cavity. In reality, the superimposed EMBr fields involve double-ruler fields, cylindrical-shaped fields, and wide “ruler-shaped” magnetic field over the entire mold width. In addition, for electromagnetic stirring (EMS) applications, alternating current (AC) fields are occasionally used. There have been few cases, where a level accelerator (EMLA) by employing “multimode EMS” and an electromagnetic level stabilizer (EMLS) for decelerating flow is used.

Therefore, in an aim to improve the quality of the final steel products, it is of paramount importance to obtain an in-depth knowledge of the fluid dynamic characteristics under the combined influences of the two-phase molten steel–argon gas hydrodynamics along with the electromagnetic field induced magnetohydrodynamics in the continuous casting process. In the recent past, there have been few numerical
and experimental studies, where researchers tried to explore the influence of gas on time-averaged flow in the nozzle and mold. Few studies are reported on the on the consequence of gas on transient fluid dynamic behaviour. Liu et al.\textsuperscript{10} simulated two-phase flow of argon gas and molten steel in slab continuous casting mold using Euler–Euler Large Eddy Simulation (EELLES) scheme. Steady $k$–$\epsilon$ turbulence computational results of Bai and Thomas\textsuperscript{31} revealed that increasing argon gas volume fraction or bubble diameter bends the jet angle more upward and also increases turbulence. Apart from investigating argon flow on hydrodynamic scenario, studies on effect of magnetic field on flow behaviour at mold are also carried out. Qian and Wu\textsuperscript{12} reported LES computational results on the influence of EMBr, submerged entry nozzle (SEN) depth, and port angle on the flow dynamics in the continuous slab casting. Kageyama and Evans\textsuperscript{13} carried out a coupled LES-electromagnetic field with a mold free surface model to analyze the effect of electromagnetic forces on the turbulent flow kinetics at the mold. Miki and Takeuchi\textsuperscript{14} reported flow stability and turbulent fluctuations under the influence of a double raker magnetic field. A recent study by Chaudhary \textit{et al.}\textsuperscript{15} reported the effect of EMBr on unsteady turbulent flow in continuous slab casting using LES computations. LES computations in a continuous slab casting mounted with double-ruler electromagnetic field is reported recently by Singh \textit{et al.}\textsuperscript{16}

Therefore, from the foregoing discussions it is clear that despite a number of studies on the effect of argon flow and magnetic field on the hydrodynamics of slab caster mold in the literature, investigation on the combined consequences of argon gas and magnetic field has largely been ignored. Although very few studies with similar objectives have been reported, a systematic study addressing this extremely significant issue is yet to be found in the literature. The current investigation deals with the development of combined MHD two-phase flow and turbulence model with the variation in SEN depths. Studies have been performed for various argon flow rates and SEN depths. In accordance with the plant’s requirement, additional studies have been carried out to further tuning up of the existing current settings for the identification of operating windows of Argon flow rates.

2. Mathematical Modelling

2.1. Computational Geometry of the Model Slab Caster

To develop a two-phase MHD model for the slab caster of LD2 plant at Tata Steel India, exact mold geometry and plant operating condition data have been adopted. Towards this, for a fixed section size of 1300 mm $\times$ 218 mm, three specified plant operating SEN depths have been considered in the present investigation. The relevant SEN depths are varied as 160 mm, 200 mm, and 240 mm, respectively. Where, the SEN depth is defined as the downward distance from the meniscus till the top edge of the outlet port. Table I summarizes the details of SEN geometry analyzed by CFD calculations. In each case, results have been generated for the Argon gas flow rate in the range 6 L/min–10 L/min (litres per Minute) and casting speed range 1 m/min–1.6 m/min respectively. It is important to mention here that since unsteady computations have been carried out in the current investigation, a mold length of 5 000 mm has been chosen to accommodate two recirculation vortices being shedded from the primary recirculation zone.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter</td>
<td>75 mm</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>125 mm</td>
</tr>
<tr>
<td>Outlet port shape</td>
<td>Rectangular</td>
</tr>
<tr>
<td>Outlet port size</td>
<td>100 mm $\times$ 55 mm</td>
</tr>
<tr>
<td>Outlet port angle</td>
<td>15$^{\circ}$ downward</td>
</tr>
<tr>
<td>Outlet port chamfer radius</td>
<td>15 mm</td>
</tr>
</tbody>
</table>

### 2.2. Governing Equations for Two-phase Magnetohydrodynamic Flows and Boundary Conditions

In this study, the Euler–Euler two-phase model has been employed to simulate the Argon gas injection behaviour in shear liquid. Gas and liquid phases have been considered as Newtonian, incompressible, and unsteady. The other assumptions that go with the present study are: the magnetic Reynolds number (defined as the ratio between magnetic advection to the magnetic diffusion, $Re_m$) is less than one, which is true for liquid steel, the electric potential is coupled with Maxwell stress.\textsuperscript{17} The magnetohydrodynamic induced Lorentz force is acting perpendicular to the flow direction; and as compared to turbulent boundary layer, the Hartmann layer is negligible. It may be mentioned here that when an electrically conducting material moves through a magnetic field, an electric current is induced. This induced electric current interacts with the magnetic field and produces a force ($J \times B_0$) on the flow field, called the Lorentz force. This Lorentz force breaks the flow and therefore opposes the very mechanism that created it. The Euler–Euler two-phase MHD model treating both the liquid and gas phases as continua solves two sets of conservation equations governing mass and momentum, which are written for $q$ phase as:\textsuperscript{17–19}

\begin{equation}
\frac{\partial}{\partial t} \left( \alpha_q \rho_q \right) + \nabla \cdot \left( \alpha_q \rho_q \mathbf{u}_q \right) = 0 \quad \text{......(1a)}
\end{equation}

\begin{equation}
\frac{\partial}{\partial t} \left( \alpha_q \rho_q \mathbf{u}_q \right) + \nabla \cdot \left( \alpha_q \rho_q \mathbf{u}_q \mathbf{u}_q \right) = -\alpha_q \nabla p + \nabla \cdot \left[ \alpha_q \tau_{\text{eff}} + \alpha_q \tau_{\text{L}} + \alpha_q \rho_g g + \mathbf{M}_{\text{ef}} + \mathbf{F}_L \right] \quad \text{......(1b)}
\end{equation}

Here, $\alpha_q$ represents volume fractions of $q$ phase, $\rho_q$ is the density, $\mathbf{u}_q$ is the velocity vector of the $q$ phase, respectively. Furthermore, $p$ is the pressure, and $\mathbf{F}_L$ is the Lorentz force vector. The stress term of $q$ phase is described as:\textsuperscript{19}

\begin{equation}
\tau_{\text{eff}} = -\mu_{\text{eff} q} \left( \nabla \mathbf{u}_q + \nabla \mathbf{u}_q^T \right) - \frac{2}{3} \left( \nabla \cdot \mathbf{u}_q \right) \nabla \cdot \mathbf{u}_q \quad \text{......(2a)}
\end{equation}

In Eq. (2a), $\mu_{\text{eff} q}$ is the effective viscosity. Note that the effective viscosity of the liquid phase is composed of three contributions: the molecular viscosity, the turbulence viscosity, and an extra term due to bubble induced turbulence. The calculation of the effective gas viscosity is based on the effective liquid viscosity as: $\mu_{\text{eff} q} = \frac{\rho_q}{\rho_l} \mu_{\text{eff} l}$. In the present investigation, the model proposed by Sato and Sekiguchi has been employed to account of the turbulence induced by the movement of the bubbles, and is expressed as: $\mu_{\text{lift} q} = \rho_q \alpha_q \mathbf{d}_l C_{\text{BTur}} \left( \mathbf{u}_q - \mathbf{u}_l \right)$. Here the model constant $C_{\text{BTur}}=0.6$\textsuperscript{19}

The momentum exchange term, $\bar{M}_{\text{ef} q}$, defined in Eq. (1b), delineating the interface forces is expressed as follows:\textsuperscript{19}

\begin{equation}
\bar{M}_{\text{ef} q} = \bar{M}_{\text{ef} q} + \bar{M}_{\text{drag} q} + \bar{M}_{\text{virtualMass} q} \quad \text{......(2b)}
\end{equation}

Here the terms, $\bar{M}_{\text{lift} q}$, $\bar{M}_{\text{drag} q}$, $\bar{M}_{\text{virtualMass} q}$, are the forces due to lift, drag, and virtual mass force, respectively. The mathematical expressions for the lift, drag, and virtual mass forces are given as follows:\textsuperscript{19}
Following Drew and Layhe, the model constant for lift force is chosen as \( C_{lift} = 0.5 \).\(^{19}\) The model constant for drag force, \( C_D \), is dependent upon the particle Reynolds number, \( \text{Re}_{p} = \rho_d u_i / \mu \), and is given by:

\[
C_D = \left( \frac{24}{\text{Re}_{p}} \right)^{1+\left(0.15 \frac{\text{Re}_{p}}{0.667} \right)}
\]

However, following universal drag law, for sufficiently high values of the Reynolds number, the drag coefficient becomes independent of Reynolds number and is given as: \( C_D = 0.44 \). In the present study, considering the bubble to be spherical, the model constant for virtual mass force is chosen as \( C_{VMass} = 0.5 \). Here, \( D/D \) is the material derivative.

Turbulence: Standard \( k-\varepsilon \)\(^{20}\)

Turbulence kinetic energy:

\[
\frac{\partial (\rho \alpha \varepsilon)}{\partial t} + \nabla \cdot (\rho \alpha \varepsilon \mathbf{u}) = \nabla \cdot \left[ \frac{\mu}{\alpha} \nabla \varepsilon \right] + G - \rho \alpha \varepsilon
\] ..............................(4a)

Turbulence dissipation rate:

\[
\frac{\partial (\rho \alpha \varepsilon^2)}{\partial t} + \nabla \cdot (\rho \alpha \varepsilon^2 \mathbf{u}) = \nabla \cdot \left[ \frac{\mu}{\alpha} \nabla \varepsilon^2 \right] + \frac{\varepsilon}{k} \left( C_G - C_1 \rho \varepsilon \right)
\] ...............................(4b)

Where \( \Gamma_k \) and \( \Gamma_{\varepsilon} \) are the diffusion coefficients for the turbulent kinetic energy and its dissipation rate, respectively, and are given by:

\[
\Gamma_k = \frac{\mu_{\text{eff}}}{\sigma_k}, \quad \Gamma_{\varepsilon} = \frac{\mu_{\text{eff}}}{\sigma_{\varepsilon}}
\] ..............................(5a)

Where \( \mu_{\text{eff}} \) is the effective viscosity and is given by \( \mu_{\text{eff}} = \mu_1 + \mu_2 \)

The tensor expression for the generation term \( G \) is given as

\[
G = \mu \left( \frac{\partial \mathbf{u}_i}{\partial x_j} + \frac{\partial \mathbf{u}_j}{\partial x_i} - \frac{2}{3} \frac{\partial \mathbf{u}_k}{\partial x_k} \right)
\] ..............................(5b)

Values for \( C_{\mu}, C_{1}, C_{2}, \sigma_1, \sigma_2, \) and \( \sigma_\alpha \) are 0.09, 1.44, 1.92, 1.0, 0.9, and 1.3, respectively.\(^{20}\) Furthermore, it is also recognized that \( \alpha_1 + \alpha_2 = 1 \). It is to be mentioned here that gas bubble size and volume fraction are very important input parameters which control bubble behaviour in the flow simulation. As a result of both heating by the liquid steel and pressure variation, both of these parameters change significantly after injection into the liquid steel in the SEN. In the present investigation, assuming Argon gas is injected at standard conditions (temperature 30 °C and pressure 1 atm), the modified effective gas volume fraction \( \alpha_{\text{eff}} \) at the mold inlet plane has been calculated by applying the following equation as:\(^{19}\)

\[
\alpha_{\text{eff}} = \frac{\lambda q_i}{\lambda q_i + q_t}
\] ..............................(6)

In Eq. (6), \( q_t \) is the inlet Argon gas flow rate at standard conditions, \( q_i \) is the inlet liquid steel flow rate, and \( \lambda \) is the gas volume expansion coefficient due to changes in temperature and pressure. The value of \( \lambda \) is assumed to be a value of \( \lambda = 5 \).\(^{18}\)

Since magnetic Reynolds number \( (Re_m) \) is less than unity for liquid metals, the induced magnetic field due to the induced electric current can be neglected. After neglecting the induced magnetic field, the electric potential method can be used to determine the induced current and the Lorentz force by the following set of Maxwell’s equations.\(^{4,15,16}\)

Lorentz force: ..............................(7a)

\[
\mathbf{F}_L = \mathbf{J} \times \mathbf{B}_0
\]

Ohm’s law: ...............................(7b)

\[
\mathbf{J} = \sigma \left( \mathbf{E} + \mathbf{u} \times \mathbf{B}_0 \right) = \sigma \left( -\nabla \phi + \mathbf{u} \times \mathbf{B}_0 \right)
\]

Charge conservation: ...............................(7c)

\[
\nabla \cdot \mathbf{J} = 0 \quad \text{..................(7c)}
\]

where \( \mathbf{E} \) is the induced electric field.

By inserting current from Eq. (7b) into the conservation of charge Eq. (7c), a Poisson equation for electric potential can be derived as:\(^{14}\)

\[
\nabla^2 \phi = \nabla \cdot \left( \mathbf{u} \times \mathbf{B}_0 \right) \quad \text{..................(8)}
\]

As per the boundary conditions are concerned, at the mold inlet the mean velocity is assumed to be uniform though its cross section and is specified with a velocity value confirming to a typical casting speed, the other two perpendicular velocities are assumed to be zero. The turbulent kinetic energy and its dissipation rate are assumed to be uniform and also calculated in terms of turbulence intensity by fixing as 5%. Boundary conditions for momentum transfer at all solid surfaces including the narrow and wide faces are specified with no slip boundary conditions. At the meniscus, degassing boundary condition has been employed. Such boundary conditions are usually employed in two-phase Eulerian model. Similar boundary conditions are established for turbulent kinetic energy and its dissipation rate. Near any solid surface, a standard wall function for velocity distribution was applied. At outlets pressure outlet boundary condition was adopted. The boundary condition for electric potential \( \phi \) at all surfaces is Newman with zero flux. For Eulerian two-phase flows, the volume fractions at the inlet have been calculated based on the Argon gas flow rates. Accordingly, the steel inlet velocity is modified by the following relationship: \( \mathbf{U}_{inlet} = \mathbf{U}_{inlet, based \ on \ casting \ speed} \left(1 - \alpha_\text{eff} \right) \), whereas for gas phase it is calculated after incorporating volume expansion due to temperature. The density and dynamic viscosity of the molten steel are taken as 7 200 kg/m\(^3\) and 0.00648 kg/m.s, respectively. \( \sigma \) is the electrical conductivity value of the liquid steel. The electrical conductivity of the liquid steel is used as 714 000 1/Ω m and Magnetic Permeability is set to 1.257 × 10\(^{-6}\) H/m.\(^{21}\) At a particular casting speed, the mathematical simulations of the process consist of employing a constant flow rate of incoming steel from the SEN (treated as with insulating walls). The transient simulations are carried out with the combined flow, turbulence, and MHD Maxwell equations. It is important to note here that assumption of solidifying steel shell to govern the electric current loop in the mold may be relevant to analyze the electromagnetic breaking phenomena in continuous casting mold.\(^{15}\) However, in the present work, such consideration have been ignored by noting the fact that the non-conducting mold walls provide a return path for the induced electric current generated in the liquid steel.\(^{4}\)

2.3. Numerical Methodology, Grid Independence Test, and Model Validation

The model slab caster geometry and grid have been generated by employing commercial software Gambit, whereas finite volume based computational fluid dynamics (CFD) software, ANSYS Fluent, has been used to solve governing

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two-phase MHD equations. In the present research, a complete Hexahedral mesh has been generated with a quality of 0.85 (bad quality value = 0; ideal quality value = 1). Figure 1 displays typical grid used for the numerical simulations. To capture near-wall turbulence, the grid is refined very fine around the walls. Based on the variation of the time averaged meniscus velocity, a grid independence study has been carried out to choose optimum grid points. Typical to a section size of 1 300 mm × 218 mm and SEN depth of 160 mm, computations are performed at a casting speed of 1.25 m/min. The results of grid independence study for four different mesh sizes, namely, 0.6 million, 1.1 million, 1.5 million, and 2.2 million, have been shown in Fig. 2. It is found from Fig. 2 that the grid independence situation has been achieved for 1.5 million cells, which is computationally economical for the present numerical investigation. The Semi Implicit Method for the Pressure Linked Equations (SIMPLE) algorithm has been used to solve coupled momentum, turbulence, and MHD Maxwell equations. Moreover, for the convective terms, a second order upwinding scheme has been adopted. To capture small scale structures and fitting turbulence upwinding scheme has been adopted. For preventing numerical oscillations, the time step value during transient computations has been determined from the Courant-Friedrichs-Lewy (CFL) condition.

In order to validate the current mathematical model results with the plant experimental data, nail board experiments have been carried out at the continuous caster of Tata Steel LD2 plant. Nail board dipping experimental tests have been conducted with a two rows of ten 10 mm diameter, 220 mm long, stainless steel nails attached to a wooden board. During each plant experiment, the submergence depth of nail has been maintained as 110 mm, whereas, the submergence time of nail being 6 secs. For an argon flow rate of 6 L/min and at a casting speed of 1.25 m/min, the plant experimental measurement data of meniscus velocity variation at the mold mid-plane has been compared with the time averaged data of present two-phase mathematical model. The comparison result is shown in Fig. 3, and can be found to be in good agreement with the experimental data.

3. Effect of Bubble Size on Gas Volume Fraction Distribution

Figures 4(a)–4(c) show the effect of bubble size on the gas volume fraction distribution inside the mold. This is obtained from the present numerical simulation with water as the operating media. For all cases (water–Argon system), the water flow rate is 19 L/min and the gas flow rate is 6 L/min. The bubble size (d_b) is considered as 1, 2, and 5 mm, respectively. A comparison between Figs. 4(a)–4(c) clearly shows that smaller bubbles exhibited a more dispersed pattern and have a tendency to penetrate further across the mold. Subjected to stronger buoyancy forces, large bubbles show a less dispersed pattern and quickly float towards the water surface. The predicted gas volume fraction distribution inside the mold obtained from the current Euler-Euler model has been used to validate against the measured bubble distribution obtained from the water model experiment from literature. The correspondence with the experimental water modelling results is found to be in satisfactory agreement. Therefore, in the subsequent analysis, without resorting for bubble size distribution, an average bubble size of 1 mm being considered throughout the whole simulation studies. This may eventually corroborate the actual conditions of Argon flow rate at the plant.

4. Current Settings and Gauss-meter Magnetic Field Plant Measurement Data

In general, typical characteristics of existing current setting for different casting speeds follows percentage of maximum current pass through upper and lower coils. However,
the maximum current passing through the coils is fixed by the supplier as 700 A. Therefore, the strength of the induced magnetic field generated is limited to maximum current as specified by the supplier. Here, it is important to mention that the iron core position of EMBr, which was analyzed by CFD calculations, is as follows: the thickness and centre position (from the meniscus) of the upper core are 100 mm and 200 mm, respectively; whereas, for lower core it is 100 mm and 700 mm, respectively. The distance from the core end to the surface of the mold copper plate is 109 mm. In order to evaluate maximum accuracy in measurement, many locations have been covered along the mold. For this purpose, in a single experiment, all total 450 data locations are measured at plant. The measurement is done for 100 A, 350 A, and 600 A of current settings both at upper and lower coils. Figures 5(a)–5(c) show the experimental results on the contours of the magnetic field (Tesla map) at the mold mid plane for current settings 100 A (Fig. 5(a)), 350 A (Fig. 5(b)) and 600 A (Fig. 5(c)), respectively. It can found from Fig. 5 that there is a change in sign of magnetic field once it crosses the location downward from the meniscus at 500 mm. This phenomena is quite palpable since there are two ruler type EMBr brake have been mounted. The magnetic field induced at the lower brake interacts with the magnetic field of the upper brake at the zone of neutrality, where its strength comes down to zero value. Moreover, as can be observed from Fig. 5 that the positive field always corresponds to that for the upper brake, whereas, it takes negative sign for the lower brake. It should be worth mentioning here that the magnetic field strength will come down to zero value once one may go far downward (more than 900 mm) direction from meniscus.

4.1. Electromagnetic Field Distribution

The primary contribution from the electromagnetic field emerges from the fact that for MHD flows the primary source of turbulence is governed by the velocity fluctuations with the first derivative of electric potential. Notably, the correlation of axial velocity fluctuations is a function of the horizontal derivative of electric potential, i.e., both are perpendicular to applied magnetic field. Therefore, the functional distribution of electric potential across the mold cross section is a key parameter in delineating typical characteristics of electromagnetohydrodynamics. In the present investigation, the measured magnetic field experimental data (as shown in Fig. 5) have been used while modelling the continuous casting mold. Corresponding to those initial magnetic field distributions, the representative contours of electric potential (\( \phi \)) at the mold mid plane are shown in Figs. 6(a)–6(b) for two different values of SEN depths of 160 mm (Fig. 6(a)) and 240 mm (Fig. 6(b)), respectively. The results are shown for sample Upper coil: 600 A; Lower coil: 600 A currents respectively. It is revealed from electric potential contours in Fig. 6 that throughout the whole domain the electric potential lines follow a cyclic rotation. This characteristics distribution in electric potential generates an additional inertial force to that of fluid kinetics. This, in turn, imparts an impede motion to that of hydrodynamic inertia by conserving constant global energy. It is also observed that along the port areas a cyclic loop of electric potential is also evident. A typical double ruler brake type configuration is observed from the electric potential plots. This is very typical to the TATA Steel caster EMBr and has been widely used at all such flow control steel making processes. It is important to mention here that the field saturation limit is about 70% of the applied current. This is actually measured from the plant data during one of the plant trials. Therefore, in the subsequent discussions on other casting speed values, the same field distribution with minute alternations (about 10%) of their peak amplitude value will be used.
5. Results and Discussions

The aim of the present investigation is to analyse the combined influence of superimposed static magnetic field and Argon gas flow on unsteady turbulent hydrodynamic characteristics of the slab caster mold at various casting speeds and SEN depths. All computational results have been generated for both EMBr OFF and ON situations. Towards this, the ranges of casting speed have been considered from 1 m/min to 1.8 m/min, in the steps of 0.1. Iterations in each time loops for time marching simulations are continued till global error in spatial domain reached to a limiting value, i.e., less than $10^{-4}$, whereas, in time domain, computations have been performed till the system has reached a dynamically steady state situation (where hydrodynamic parameters varies asymptotically during successive time steps). The results are obtained after 400 seconds of simulation time. In the present work, a 15° downward nozzle port angle has been fixed.

5.1. Unsteady Two-phase Fluid Flow and Turbulence Field

In the present investigation, the unsteady two-phase flow and turbulence fields have been visualized in-terms of instantaneous contours of velocity, and turbulence KE (kinetic energy) respectively. For a casting speed of 1.5 m/min, Figs. 7(a)–7(b) show the instantaneous contours of velocity (Fig. 7(a)) and turbulence KE (Fig. 7(b)) at the mold mid plane during EMBr OFF and EMBr ON situations at the three representative Argon flow rates of 6 L/min, 8 L/min, and 10 L/min, respectively. The SEN depth is considered as 240 mm. From the velocity contours in Fig. 7(a), a typical ‘double-roll’ type flow pattern in the mold is noticed. The streaming liquid steel strand from the SEN ports displays a strong flow directed across the top surface, from the narrow face toward the SEN, and the lower rolls penetrates deep into the strand. On the other hand, it is seen that flow in the liquid cavity of a continuous casting mold is greatly affected by the Argon gas injection. With increasing Argon flow rates, disturbance at the upper side of the mold increases considerably. As depicted in the Fig. 7(a), part of fluid moved up toward the top surface after leaving the SEN port, another part of fluid continue as a jet impinge at a slightly higher location on the narrow wall. More small scale structures are seen at the 10 L/min flow rate. In this context, it is appropriate to mention here that after entering the mold with the liquid steel jet, most Argon gas is concentrated at the vicinity of the SEN and float upward through the upper recirculation zone and escape from the top surface sequentially. Meanwhile, few volume fraction of the Argon gas may penetrate further across the upper recirculation zone and migrated to the middle of wide face.24) A characteristic behaviour can be obtained from Fig. 7(a) that EMBr produces more surface directed flow. In addition, thinning of velocity boundary layer is also observed in the flow physics. Dramatic reduction in velocity fluctuations is also evident in the EMBr cases.25) In contrast, the large scale disturbances in the mold are primarily governed by the Argon gas injections in comparison to that of the effect of EMBr. It can be seen that for gas flow rates of 8 L/min and 10 L/min, the EMBr effect in suppressing the magnitude of the overall flow instability is marginal. Therefore, it may be concluded that one should restrict Argon flow rates beyond 6 L/min. Furthermore, it is also seen that effect of EMBr is more prominent in reducing overall disturbances below the port areas. Absence of small scales structures are seen at those areas and the flow become calm and smoother. It is found from Fig. 7(b) that increasing Argon gas flow rates increases turbulence inside the mold. The effect is much higher at the 10 L/min Argon gas flow rates. The global turbulence kinetic energy contours show higher in magnitude as the Argon gas flow rate is increased. Important to point here that meniscus level turbulence is noticed at 10 L/min Argon gas flow rate. The effect of EMBr is seen as suppressing the turbulence magnitude. Influence of superimposed magnetic field on turbulence in the mold cavity is further recognized with the generation of large scale vortical structures whose axes are aligned with the magnetic field plane. During the subsequent process, as a result of accumulation of high decaying eddies, these vortical structures constrict and tend to move in the direction of upper- and lower-recirculation regions similar to that of laminar unsteady flows. This, eventually shifts the flow paradigm towards quasi 2-D turbulence. This is characteristically known as magneto-turbulence for the present situation of highly recirculating flow at the mold cavity. For such large scale dominations, the magnetic and viscous dissipation of turbulence decreases. However, EMBr effect becomes peripheral as the gas flow rate is increased. One can clearly observe that at the lower part of the SEN, the turbulent dissipation of kinetic energy is of maximum in magnitude, while lower value of the core of the fluid jet is located elsewhere. At the bottom most part of the SEN, turbulent swirling jet is also evident. Physically, the swirling jet is composed of smaller scale eddies and can contribute in turbulent dissipation of Argon bubbles. Here also, it is noticed that turbulence magnitude is higher after 6 L/min gas flow rates. Furthermore, the dissipation of spatial intermittent structure to form coherent turbulence structure is much higher at 8 L/min and 10 L/min gas flow rates. Therefore, to restrict overall mold turbulence within the safe limit, it is advisable not to go beyond 6 L/min gas flow rates.
5.2. Gas Flow Dynamics

Figures 8(a)–8(b) show the instantaneous combined velocity vectors and gas volume fractions for EMBr OFF and ON conditions at the mold mid plane for casting speeds of 1.3 m/min and 1.5 m/min, respectively. The results are shown for an Argon flow rates of 6 L/min and 10 L/min, respectively. The overall distribution of the gas volume fraction show intermittent trajectory with various positioning of their positions coinciding with the velocity vectors (as detailed in black colour). As also noticed, there is a crowding of the gas volume fraction after exiting from the ports. An interesting observation from Figs. 8(a)–8(b) reveals the fact that Argon flow rate causes the formation of secondary recirculation zone nearer to the corner region of the mold. Effect of EMBr show formation of complex flow structures below the port region, whereas the upper part of the mold, more surface directed flow structure and thereby formation of primary double roll kind of flow structure is noticed. It is seen that increasing Argon flow rate causes crowding of velocity vectors nearer to the meniscus and at the narrow face of the mold. The effect is more at the higher casting speed. This is due to the reason that Argon flow rate enhances the flow velocity of the liquid steel at the mold; this in turn increases the magnitude of the velocity vectors. Proceeding further, the global comparisons of gas volume fraction distribution for various SEN depths are shown as an iso-surface plot. At a casting speed of 1.5 m/min and 6 L/min Argon flow rates, the sample results are shown during EMBr OFF condition in Fig. 9. From the iso-surface trajectory, as shown in Fig. 9, it is found that increase in SEN depths increases lateral spread of the gas volume fraction distribution. The maximum spread is seen at 240 mm SEN depth. The reason behind these phenomena is due to the effect of enhanced SEN depth. This causes the Argon gas to penetrate deep in the mold and thereby travel large distances. The final effect shows in terms of larger spatial spread.23 On the other hand, at shallower SEN depths, the gas could not able to penetrate deep and therefore escape easily from the meniscus by travelling a shorter distance. At the meniscus, this leads to higher and comparably more localized bubble density. As a result, the bubbles, when coming out impart more energy to the surface causing higher mold level fluctuations (MLF).

5.3. Meniscus Behaviour at Two–phase Flow and EMBr

A complete picture on the meniscus behaviour for different Argon flow rates with EMBr OFF and ON conditions can be obtained from the combined velocity vectors and gas volume fraction at the meniscus. Figures 10(a)–10(b) show the instantaneous coupled velocity vectors and gas volume fraction contours at the meniscus for different gas flow rates for EMBr OFF and ON conditions at casting speeds of 1.3 m/min (Fig. 10(a)), 1.5 m/min (Fig. 10(b)). The results are shown for a fixed value of SEN depth 160 mm. The meniscus behaviour, as evident from Fig. 10, is highly sensitive with the gas flow rates. It is seen that, higher gas flow rates cause intermittent distribution of the velocity vector and the gas volume fractions. The effect is much more aggravated at the higher casting speed (Fig. 10(b)). The gas escape locations, as seen from the Fig. 10, show formation of source point topology of the velocity vectors in the meniscus. The source points shifts at different locations as the casting speed and gas volume fraction is increased. The overall distribution in the gas volume fraction for all casting speeds show maximum crowding nearer to the port areas. The effect of EMBr show much calmer meniscus when the gas volume fraction is low (6 L/min). A near symmetric distribution in the gas volume fraction is observed during EMBr ON conditions, whereas is becomes asymmetric in the absence of EMBr. However, its effect becomes marginal and thereby causing heavy meniscus disturbance when the gas volume fraction is increased (at 10 L/min). Notably, as a consequence of swirling phenomena arising out of high jet impacting velocity, a small recirculation zone is observed nearer to the SEN area. Therefore, it may be worthy to conclude here that apart from the influence of Argon flow rates, influence of superimposed magnetic field cause global suppression of both the small and large scale fluctuations at the meniscus.24 Although, towards the safe applicability of EMBr for stable meniscus, one may have to limit the maximum Argon gas flow rate being injected to the mold.

5.4. Effect of Two–phase MHD on Jet Stabilization Hitting at Narrow Wall

Jet stabilizing, in other words, lateral diffusion of jet emanating from the ports is one of the prime factor in gen-
erating turbulent large scale structures and thereby intensity distribution in the mold. Lower the jet spread hinders global turbulent energy cascading and thereby production of small scale structures. In order to capture the effect of MHD on jet spreading at the narrow wall of the mold, Figs. 11(a)–11(b) display the wall shear stress contours at the mold narrow wall during EMBr OFF and ON conditions for different SEN depth and Argon gas flow rates. It can be noticed from Fig. 11 that there is a lateral spread of the jet hitting at the narrow wall at EMBr OFF condition, whereas more focused jet with minimal spread is noticed during EMBr ON condition. Therefore, it may be established here that the effect of magnetic field causes reduction in the formation of fine scale turbulent structures; this in effect lowers turbulent intensity in the mold. In addition to these and as also can be observed from Fig. 11 that EMBr affects in reductions of wall shear stress of the mold and thereby imparts better mold life. Similar phenomena are also seen at other ranges of operating casting speeds also. The effect of increasing Argon flow rates show similar trend to that of EMBr OFF and ON conditions. Higher SEN depths shift the jet hitting location downward. A slightly lower value of jet spread is seen at 10 L/min Argon flow rate and 200 mm SEN depth during EMBr ON condition. However, at all cases the jet hitting effect is much less at SEN depth of 200 mm.

5.5. Effect on Time-averaged Two-phase Velocity Variation at the Meniscus Mid Plane

The combined effects of Argon flow rates, casting speed, and magnetic field in mid plane velocity variation is quantitatively analyzed with the time-averaged variations of meniscus- mid plane velocity. For a section size of 1 300 mm, Figs. 12(a)–12(b) display the variation of time-averaged velocity at the meniscus mid-plane for EMBr OFF and ON conditions and various Argon flow rates for casting speeds of (a) 1.3 m/min, and (b) 1.5 m/min. (Online version in color.) The maximum percentage enhancement in time-averaged meniscus velocity for 8 L/min Argon flow rate is 40%, whereas, for 10 L/min Argon flow rate, it is about 80% compared to the situation for 6 L/min Argon flow rates. Hence, this result is also in agreement with our previous observation that increasing Argon flow rate beyond 6 L/min will encourage meniscus instabilities for the complete range of operating casting speeds at the LD2 plant of Tata Steel. It may be mentioned here that enhancement in meniscus velocity is an implicit function of the growing magnitude of turbulence intensity in the flow. This is attributed to an average 40% enhancement in the maximum turbulence intensity with Argon flow conditions, which, as obtained from the current numerical results. On the other hand, the effect of EMBr is always seen to reduce the meniscus velocity magnitude. The velocity variation is somewhat stretched with the application of EMBr field and do not follow an ideal parabolic shape. The reduction in velocity with EMBr is less as the Argon flow rate is increased. Increasing casting speed shows enhancement in the meniscus velocity magnitude. A typical situation at all Argon flow rates seen to be an augmenting parameter in overall enhancement of the time averaged meniscus velocities at all casting speeds. From an application perspective, it may be reiterated here that the surface flow speed is a direct function of the steel quality. The mechanism of shear-layer instability added up with the influence of increasing magnitude of the meniscus velocity finally results in slag entrainment. In contrast, lower value of surface velocity is prone to meniscus freezing. Hence, it is necessary to select the safe operating window on the combined higher and lower threshold of EMBr settings and Argon flow rates for circumventing those effects. The optimum range of mold top surface velocity distribution and consequently the hydrodynamics are explicitly reported.
in the literature as 0.26 m/s to 0.43 m/s. However, from the plant to plant the appropriate optimum value varies and is subjected to the degree of superheat and other various online plant operating conditions. Furthermore, from a physical stand point, suppression of meniscus velocity with EMBr can be explained by the fact that in the flow domain the magnetic field generates a Lorentz force (per unit volume) of magnitude $j \times B$. This turns out to be an encumbering influence to the resultant hydrodynamic transport. As, the strength of the magnetic field induced suppression is directly proportional to the flow strength ($u$) and the square of the magnetic field $\sim B^2$.

5.6. Effect on Time-averaged Two-phase Velocity Variation along the Port Plane

Further characterization of the mold plane velocity distribution due to the effect of EMBr, Argon flow rates and casting speed are analysed with the variations in time-averaged velocity magnitude along the port plane (at 0.295 m below the meniscus). At a representative SEN depth of 240 mm, Figs. 13(a)–13(b) shows the time-averaged velocity variation along the port plane for various casting speeds and Argon flow rates. From Figs. 13(a)–13(b), one can clearly make out the effect of Argon flow rates. It is seen that for all cases, velocity enhancement is higher as the Argon flow is increased. Similar effect is seen as the casting speed is increased. This has an importance in enhancing the meniscus velocity magnitude, since; the mean velocity of the liquid steel stemming from the SEN is also increased. Alternatively, it is seen that compared to that for EMBr OFF conditions, the magnitude of the time-averaged velocity dampened when EMBr is switched ON with increasing Argon flow rate from 6 to 10 L/min. Overall the velocity variation displays a sudden jump in its magnitude along the port areas. This is attributed to the effect of liquid steel jet emanating from the ports, this, in turn, results in sudden jump in the velocity magnitude. The global trend in velocity distribution shows a symmetric profile. Away from the port areas (where the velocity distribution attains its peak magnitude), the time averaged velocity further decays down to its minimum value towards the narrow mold face. Further, it is imperative to note that with increasing downward velocity beneath the jet area, the jet penetration depth increases. This leads to the casting inclusions being arrested into the solidified shell. Here, a general conclusion can be made from Figs. 2, 3, 12, and 13, that the direction of flow at the meniscus of mold is reversed between the SOUTH SIDE and the NORTH SIDE. (The flow from the narrow face of mold toward the nozzle is positive).

5.7. Effect on Time-averaged Two-phase Velocity Variation along the Casting Direction

We, finally, conclude our discussions with the time-averaged velocity variation along the casting direction (downward direction from the meniscus), two representative locations are chosen at the mold mid plane at $x = \pm 0.325$ m. In an aim to cover the jet area, the downward directional length below the meniscus is taken till $z = -1$ m. For a SEN depth of 240 mm, Figs. 14(a)–14(b) shows the time-averaged velocity variation along the downward direction from the meniscus till $z = -1$ m and at locations $x = -0.325$ m (South side of the mold) and $x = 0.325$ m (North side of the mold), for various casting speeds and Argon flow rates. It is clear from Fig. 14 that there is a local peak in the velocity distribution nearer to the meniscus. This phenomenon is due to the effect of Argon flow rates. The Argon gas injected from the ports clusters nearer to the SEN and a local chunk of it gradually escapes from the meniscus by short-circuiting its path. This causes local enchantment in the velocity distribution nearer to the meniscus. On similar lines, it is seen that increasing Argon flow rate and casting speeds cause gradual augmentation in the time-averaged velocity, whereas, effect of EMBr always imparts a suppressing influence on the velocity magnitude. The overall velocity variation is symmetric in nature and from the port region it dampens grossly. As a result of shearing action of the mold level velocity towards the SEN, the time-averaged velocity variation is found to be slightly higher towards the meniscus direction.

6. Summary and Conclusions

In the present investigation, a three dimensional Euler–Euler two-phase poly dispersed bubbly flow with Magnetohydrodynamic flow model has been developed by pairing two phase fluid flow and Maxwell equations for slab caster at Tata Steel LD2 plant. An extra contribution in the effective viscosity for the turbulence induced by bubbles was taken into account. The model evaluates global flow dynamics under the effect of externally applied magnetic field, Argon gas flow rates, SEN depths, for different casting speeds. The simulation result exhibits the following conclusions:

(1) Increase in Argon flow rate is found to enhance meniscus velocity and turbulence intensity at the mold. More small scale structures are seen at the 10 L/min flow rate.
(2) EMBr produces more surface directed flow and thinning of velocity boundary layer. Influence of EMBr is not found to be effective at the higher Argon gas flow rates.
(3) Increasing Argon flow rate and casting speeds influence crowding of velocity vectors nearer to the meniscus and at the narrow face of the mold. Maximum meniscus level disturbance is noticed at 10 L/min Argon flow rates.
(4) Increase SEN depth is found to reduce meniscus
level velocity and turbulence intensity at the mold. Lowest meniscus level velocity is noticed at SEN depth = 240 mm. Argon flow is found to interact with the primary liquid steel and cause formation of secondary recirculation bubble.

(5) Along the casting direction, increasing Argon flow rate and casting speeds show gradual augmentation in the time-averaged velocity, whereas, effect of EMBr is found to suppress the velocity magnitude.

(6) The operating window for the existing current setting must be fixed with maximum Argon flow rate of 6 L/min.

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