

Effect of Electromagnetic Braking (EMBr) on Turbulent Flow in Continuous Casting

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INTRODUCTION

Fluid flow in the mold region of the continuous casting process is responsible for surface defects, slag entrainment, and other steel quality problems. Thus, it is very important to choose nozzle geometries and operating conditions that produce flow patterns within an operating window that avoids these problems. Operating conditions which control mold flow problems include the mold cross section, casting speed, submergence depth, mold powder, argon gas injection and electromagnetic forces. The application of a magnetic field is an attractive method to control mold flow because it is nonintrusive and can be adjusted during operation. However, the application of a magnetic field can change the flow pattern in non-obvious ways^{1,2}. Understanding how a magnetic field affects highly turbulent mold flow is both an important and challenging task.

It is difficult to take measurements in operating commercial steel casters, so experimental studies are limited³. Physical water models are problematic because water is unaffected by a magnetic field. Conducting fluids, such as tin⁴, mercury⁵ and eutectic alloys such as GaInSn^{6,7,8}, have been used to study the effect of magnetic fields on flow in continuous casters. Numerical studies of mold flow have been extensively used to understand the continuous casting process, including the effect of magnetic fields^{1,3,8-14,15-17}. Most of the studies exploring mold flow use Reynolds-averaged Navier-Stokes (RANS)^{3,10,15-18} or unsteady RANS (URANS)¹⁰ which accurately predicts the mean flow behavior. However, transient behavior and flow stability is more important to mold flow quality¹⁹, and has received relatively less attention. Only a few recent studies, using Large Eddy simulations (LES) without EMBr^{10,11} and with EMBr^{1,12-14}, have been performed to understand the transients involved in the process.

Cukierski et al.³ observed that application of local EMBr weakens the upper recirculation region and decreases the top surface velocity. Harada et al.⁵ compared the effects of local and ruler EMBr systems and claimed that both configurations increase surface velocities and dampen high velocities below the mold, and that configuring the ruler configuration below the nozzle ports has better braking efficiency and also results in better surface stability. Similar behavior was observed by Chaudhary et al.¹ in a computational model of a physical model with insulated walls. The predictions agreed well with measurements in the same system.^{6,7} However, raising the ruler magnetic field to center it across the nozzle ports resulted in severely unstable transient flow, with large scale fluctuations of the jets and great asymmetries^{1,6}. Adding conducting side walls with the same ruler configuration over the nozzle produced stable transient jet behavior^{7,8}. Li et al.⁴ also observed that the incorporation of accurate wall conductivity is necessary as it affects the braking efficiency of the magnetic field.

In the current study, mold flow with ruler EMBr fields was simulated using a high-fidelity, fine-grid LES code, CUFLOW, incorporating the influence of the conducting shell. CUFLOW is an in-house Computational Fluid Dynamics code using graphics processing unit (GPU). CUFLOW was first validated by comparing with previous measurements taken in a scaled GaInSn model⁷. It was then applied to simulate the full scale real caster with and without the ruler EMBr field. Time averaged and transient flow patterns, surface velocities, surface level profiles and surface level fluctuations were computed to investigate the effect of ruler EMBr on the details of the flow phenomena, and to investigate similarity criteria for scaleup.

GOVERNING EQUATIONS FOR LARGE EDDY SIMULATIONS

The fluid flow program developed for this work performs LES by solving the three-dimensional “filtered” continuity and Navier-Stokes (N-S) equations given in equations (1) and (2) respectively. The flow phenomena too small to be captured by the grid spacing, and thus are spatially filtered, are incorporated by the eddy viscosity ν_s which is modeled using a Sub-Grid Scale (SGS) model. In this study, both the Wall Adapting Local Eddy-Viscosity (WALE)²⁰ SGS model and the Coherent-Structure Model (CSM)²¹ were implemented and compared.

$$\frac{\partial u_j}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p^*}{\partial x_i} + \frac{\partial}{\partial x_j} \left((\nu + \nu_s) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right) + \frac{1}{\rho} F_i \quad i = 1, 2, 3 \quad (2)$$

Here, i, j , are tensor notation and repeated indices in a term indicate summation,
 u_i are the i^{th} velocity components,
 p^* is the pressure modified to include the filtered normal stresses,
 ν is the kinematic viscosity, and
 F_i are the i^{th} Lorentz-force components.

Conducting metal flowing through a magnetic field generates an electric current ($\vec{J}$) field in the domain, which produces Lorentz forces ($\vec{F}$) according to equations (3)-(5). These equations are simplified because the induced magnetic field is small enough, compared to the applied magnetic field, that it can be neglected in most MHD application including continuous casting²². Ohm's law (3) can be combined with the charge conservation law ($\nabla \cdot \vec{J} = 0$) to give the Poisson equation for electric potential (4). The Lorentz force is calculated according to equation (5).

$$\vec{J} = \sigma(-\vec{\nabla}\phi + \vec{u} \times \vec{B}_0) \quad (3)$$

$$\nabla \cdot (\sigma \nabla \phi) = \nabla \cdot (\sigma(\vec{u} \times \vec{B}_0)) \quad (4)$$

$$\vec{F}_L = \vec{J} \times \vec{B}_0 \quad (5)$$

Here, σ is the conductivity of the material,
 ϕ is the electric potential, and
 $\vec{B}_0$ is the applied magnetic field.

COMPUTATIONAL MODEL

Computational Domain, Mesh and Boundary Conditions

Two computational domains were investigated in this work: a scaled low-melting liquid-metal GaInSn physical (plastic) model with a ruler EMBR field, and the corresponding full-scale commercial continuous caster, which is 6-times larger in every dimension. Figure 1 shows the geometric details, with dimensions corresponding to the real caster domain, and the sectioned region represents the solidified steel shell on the walls of the real caster mold. The maximum field strength of the ruler EMBR is positioned across the nozzle outlet ports, centered 92-mm below the free surface of the liquid metal in the scale model (6*92 = 552mm in the real caster). The variation of the applied magnetic field within the mold for the GaInSn model and the real caster is shown in figure 2. Geometric details, process parameters and material properties for both domains are provided in Table I.

The GaInSn model has been experimentally studied with No-EMBr (case 1),⁶ EMBR (case 2) with insulated walls⁶ and EMBR with conducting walls (Case 3).⁷ Chaudhary et al.¹ validated CUFLOW with measurements for case 1 and case 2, and also studied the flow features in detail. Case 3, which has conducting brass-plate wide-face walls, was simulated in the current work to investigate the effects of wall conductivity and the results were compared with measurements.

For the real caster domain, simulations with No-EMBr (Case 4) and EMBR (Case 5) were performed. The computational domain for the real caster included both the liquid pool, shown in figure 3, and the solidifying shell, which was initialized to move in the casting direction with the casting speed. The shell thickness s at a given location below the meniscus was calculated from $s = k\sqrt{t}$, where t is the time the shell takes to travel the given distance and the constant k was chosen to match the steady-state shell profile predicted from break-out shell measurements by Iwasaki et al.²³. The scaling factor of six over the GaInSn model was chosen to have mold dimensions typical of a commercial continuous slab caster. In the absence

of EMBr, many previous studies have found²⁴, the Froude similarity criterion to match the flow pattern between a real caster and a $1/3^{\text{rd}}$ scaled water model. In a previous study with EMBr in a

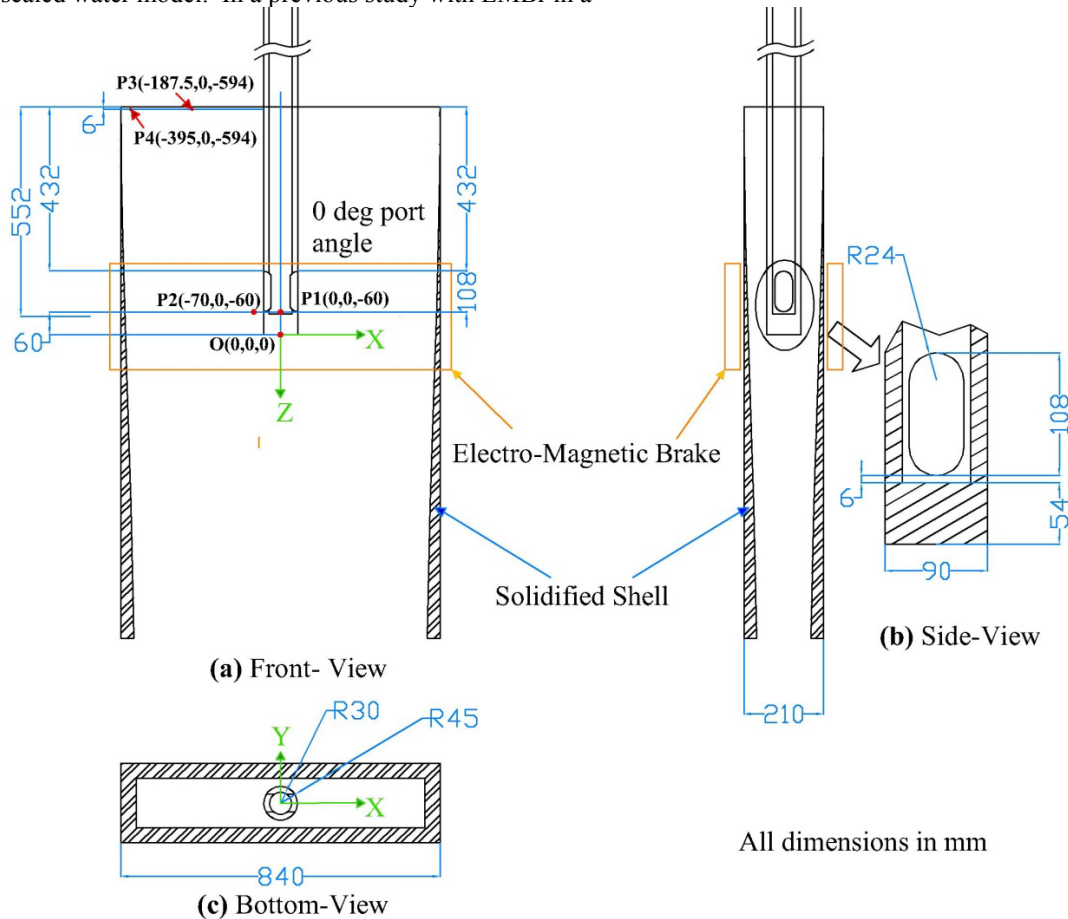


Figure 1. Geometry of the real caster with the rectangle showing the location of the applied ruler EMBr

scaled mercury model, Froude number ($Fr = U/\sqrt{gL}$) and Stuart number ($N = B_0^2 L \sigma / \rho U$) similarity criteria were simultaneously maintained by scaling the casting speed and the magnetic field strength⁵. Froude number maintains the ratio between inertial and gravitational forces, whereas Stuart number maintains the ratio between electromagnetic and inertial forces. However in the present study, only the Stuart number was matched, keeping the magnetic field strength constant at the realistic maximum of 0.31 Tesla. Maintaining Froude similarity as well would have required in the real caster a very high casting speed of 3.3 m/min, and a higher magnetic field strength of 0.44 Tesla. The accuracy of this scaleup criterion was investigated by comparing results for the scale model and the real caster with EMBr.

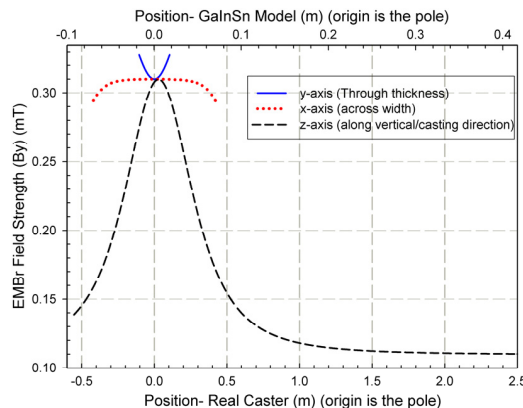


Figure 2. Applied magnetic field in the x,y and z directions for GaInSn model and real caster

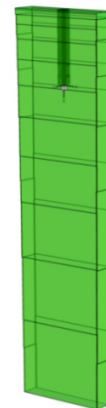


Figure 3. Isometric view of the computational domain (fluid flow region) for the real caster

The GaInSn and the real caster computational mesh consist of 7.6 million and 8.8 million brick cells respectively. The nozzles were very long, (20 diameters), so that the inlet flow control conditions had no effect. This was modeled by truncating the nozzles at the level of the liquid surface and an inlet mapping condition was applied to achieve fully developed pipe flow, as discussed previously^{10,25}. The top free surface in the mold was a free-slip boundary with zero normal velocity and zero normal derivatives of tangential velocity. Convective boundary condition (equation 6) was applied for all three velocity components at the two mold outlet ducts on the narrow faces (NF) in the scaled model¹⁰ and across the open bottom of the real caster domain. All other boundaries were solid walls and Werner-Wengle wall treatment was applied²⁶. In the real caster the boundaries, between the shell and fluid region, were initialized with fixed downward vertical velocity equal to the casting speed, which accounts for solidification as mass transfers from the fluid region to the solidified shell. The fluid flow equations were solved only in the fluid domain but the MHD equations were solved in the entire computational domain, including the brass walls for the GaInSn domain and the shell (shaded) region for the real caster domain.

$$\frac{\partial u_i}{\partial t} + U_{convective} \frac{\partial u_i}{\partial n} = 0 \quad i = 1,2,3 \quad (6)$$

Here, $U_{convective}$ is the average normal velocity across the outlet plane(s), and n is the normal direction to the outlet plane.

Table 1-Process Parameters

	GaInSn Model	Real Caster
Volume flow rate nozzle bulk inlet velocity	110 mL/s 1.4 m/s	4.8 L/s 1.7 m/s
Casting speed	1.35 m/min	1.64 m/min
Mold width (=Domain width)	140 mm	840 mm
Mold thickness (=Domain thickness)	35 mm	210 mm
Mold length	330 mm	1980mm
Domain length	330 mm	3200 mm
Nozzle port dimensions (width x height)	8 mm x 18 mm	48 mm x 108 mm
Nozzle bore diameter (inner/outer)	10 mm/ 15 mm	60 mm / 90 mm
SEN submergence depth (liquid surface to top of port)	72 mm	432 mm
Thickness of shell on the wide face and narrow face(t)	Wide faces- 0.5 mm Narrow Faces- 0 mm	$s(mm)=k\sqrt{t(s)}$; k=2.75
Wall material	Brass	Solidified steel
Fluid material	GaInSn eutectic alloy	Molten steel
Viscosity	$0.34 \times 10^{-6} \text{ m}^2/\text{s}$	$0.86 \times 10^{-6} \text{ m}^2/\text{s}$
Fluid density	6360 Kg/m ³	7000 Kg/m ³
Conductivity of liquid (σ_{liquid})	$3.2 \times 10^6 \text{ } \Omega\text{m}$	$0.714 \times 10^6 \text{ } \Omega\text{m}$
Conductivity of walls (σ_{wall})	$15 \times 10^6 \text{ } \Omega\text{m}$	$0.787 \times 10^6 \text{ } \Omega\text{m}$
Conductivity ratio(c_w)	0.130	0.130
Nozzle port angle	0 deg	0 deg
Gas injection	No	No
Reynolds number (Re, based on nozzle diameter)	41,176	118,604
Froude number (Fr, based on mold width)	1.19	0.59
Stuart number (N, based on mold width)	4.84	4.84
Cases	1. No EMBR ^{1,6} 2. EMBR with insulated walls ^{1,6} 3. EMBR with conducting walls	4. No EMBR 5. EMBR

Numerical Methods and Computational Costs

The in-house LES code, CUFLOW, used in this work employs a finite volume discretization on a structured Cartesian grid to solve the coupled N-S-MHD equations (1-5). A geometric multigrid solver is used to solve the pressure Poisson equation (PPE) and electric Poisson equation (EPE) (equation 4). The No-EMBr cases were started with zero initial velocity whereas the EMBr cases were started from the fully-developed No-EMBr flowfield.

The computations were optimized for and performed on a NVIDIA C2075 GPU with 6GB memory. The calculations with EMBr produced $\sim 55,000$ time steps ($\Delta t = 0.00005$ sec) per day for the GaInSn model and $\sim 35,000$ time steps per day for the real caster. The added computational expense due to a larger grid size and double precision accuracy in the real caster cases resulted in slower time marching. The GaInSn model was simulated for a total of 27 seconds, which took 10 days. The EMBr was applied at 10 seconds after which the flow was allowed to stabilize for 5 seconds. The means were collected, starting from this developed flow, for 12 seconds. The real caster case 4 took 10 seconds to stabilize, followed by 20 seconds of simulation, taking 10 days of total simulation time. Starting from 30 seconds into Case 4, EMBr was applied for Case 5 given 10 seconds to stabilize, and run for 15 seconds, which took 15 days total. The EMBr simulations cost were nearly double the ones without EMBr, as EMBr cases require the solution of another Poisson equation, electric Poisson equation (EPE), which is the most expensive step in the solver¹⁰.

MODEL VALIDATION WITH GaInSn EXPERIMENTAL MEASUREMENTS

Measurements of time-varying horizontal velocity V_x in the GaInSn model were collected at ~ 5 Hz using an array of ten ultrasonic Doppler velocimetry (UDV) sensors.^{6,7} The first sensor was placed at $z = -40$ mm on the midplane at the NF; the second was placed 10mm below the first, and so on⁶⁻⁸. Contour plots of time averaged horizontal velocity are given in figure 4. The top row shows results for case 2 (insulated walls), contrast with the bottom row for case 3 (conducting walls). Figure 4b and 4c show the effect of different methods of postprocessing the time-average results from CUFLOW. Figure 4b was plotted using data only along the 10 horizontal lines corresponding to the UDV sensors. Whereas, figure 4c contains data on all grid points in the midplane of the computational mesh. Figure 4b, which has the same data resolution as the plots with the experimental data, shows a good qualitative match with the measurements. However, none of these figures represent the flow completely, as they are contours of only the horizontal component of the velocity. They are plotted this way, because that is the only component available from the experiments.

The application of a ruler magnetic field is known to deflect the jet upwards¹ and similar behavior is seen for the conducting wall case 3. The time-averaged horizontal velocity shows that the jet angles for both cases are nearly the same, but the conducting wall case shows less spreading of the jet, before it impinges on the NF, as compared to the insulated wall case 2. Also, strong recirculation regions were present, just above and below the jet, (red indicates flow towards the SEN). This contrasts with the insulated wall case, in which the recirculation region is seen only above the jet.

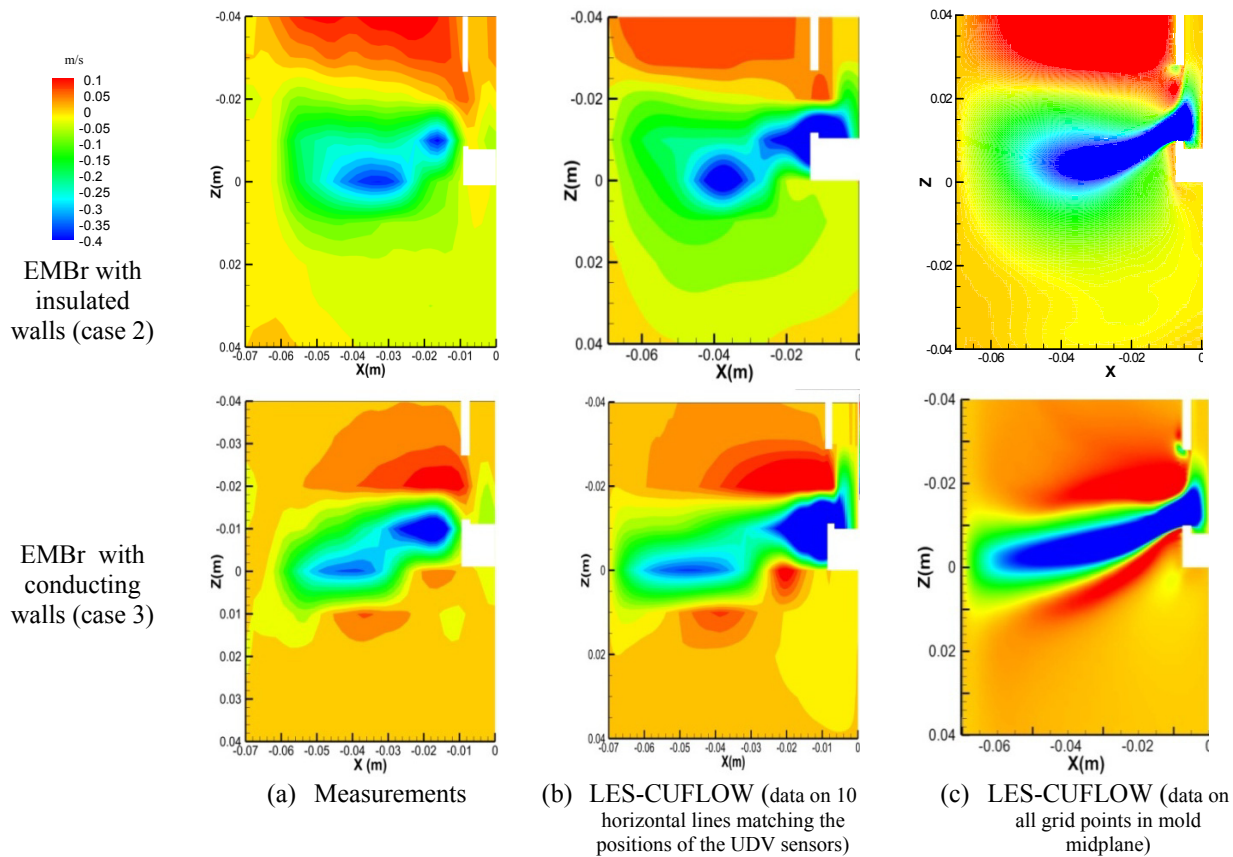


Figure 4. Contours of time-averaged horizontal velocity for case2 (top) and case3 (bottom) for the GaInSn model caster
(a) Measurements (b)(c) Calculations using LES-CUFLOW
(b)

Quantitative comparison between measurements and calculations for case 3 is made in figure 5, which shows the time averaged horizontal velocity plotted on three horizontal lines, 90 mm, 100 mm and 110 mm from the free surface (corresponding to the 4th, 5th and 6th sensors). Results computed using both the WALE SGS model and the CSM SGS model are shown. For the present case, both SGS models match each other closely, but the CSM SGS model is expected to perform better at higher Reynolds numbers where the filtered scales should be responsible for a greater fraction of the energy spectrum. Thus all further results show only the CSM SGS model results. The match between the measurements and the calculations was good except close to the SEN and NF walls, which is due to limitations of the UDV measurements. Timmel et al^{6,7} report that the UDV measurements are inaccurate near the SEN and the walls, due to the low vertical resolution and interaction with solid surfaces.

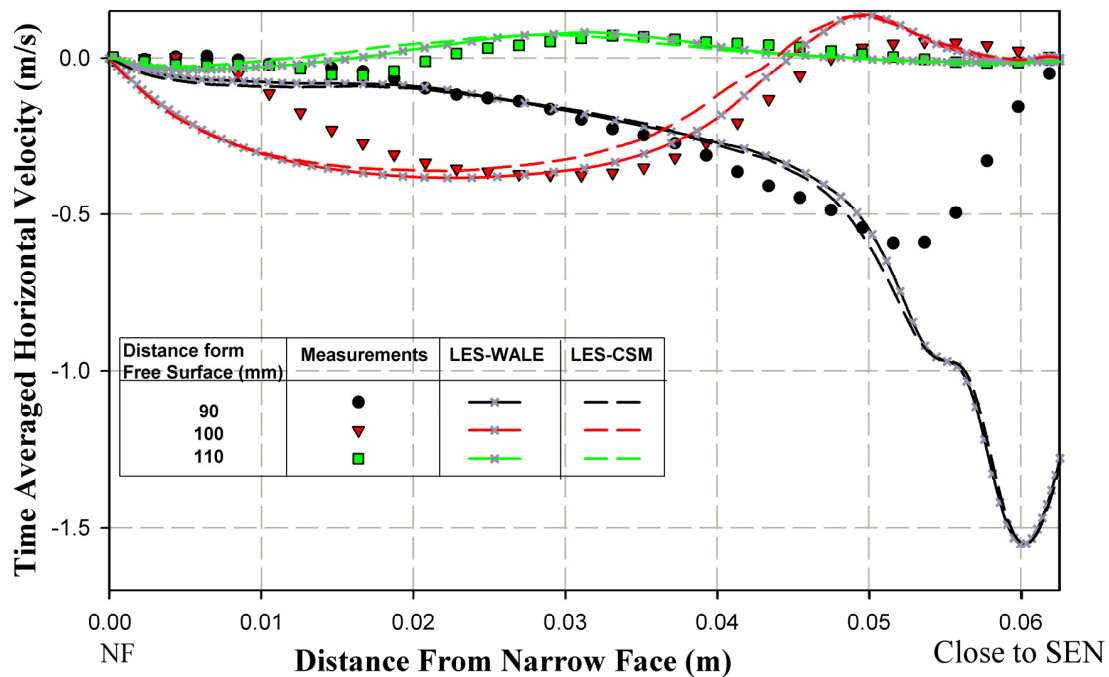


Figure 5. Comparison of time averaged horizontal velocity between measurements and LES-CUFLOW calculations using WALE SGS model and CSM SGS model for the GaInSn model caster (case 3)

The transient horizontal velocities are compared with the measurements for case 3 in figure 6b, at a point in the jet region ($x=-41\text{mm}, y=0\text{mm}, z=0\text{mm}$). For a more appropriate comparison with the transient measurements, a 0.2 second moving time average was performed on the calculated signal to match the measuring frequency of the sensor. Spatial averaging, performed in the previous study¹ to accommodate the spreading of the sensor beam, was not performed in the present study as it resulted only in a minor change. The measured and the time-averaged signals match well for the present case.

EFFECT OF WALL CONDUCTIVITY

The flow pattern for the EMBR case with insulated walls (case 2) was remarkably different from the same case with conducting walls (case 3). The transient differences are much greater. Figure 6a shows the history of horizontal velocity for case 2 at a typical point in the jet, which contrasts greatly with the history in figure 6b for case 3 at the same location. The insulated wall case has strong low-frequency fluctuations which indicate large scale wobbling of the jets. This behavior is not seen in the conducting wall case. The contrasting transient behaviors are clearly visualized in figure 7, which show contour plots of instantaneous velocity magnitude at the midplane between wide faces at three instances, separated by 1 second each, for both cases. Case 2 has both side-side and up-down wobbling of the jets, which makes the entire mold flow very unstable; whereas the jet in case 3 is relatively stable. Figure 7 also shows the time-averaged velocity magnitude contours for both cases (leftmost frames). Case 2 had an asymmetric flow pattern even after collecting the mean for ~ 28 seconds, whereas case 3 produced a symmetric mean velocity magnitude plot after collecting the mean (time-averaging) for only 12 seconds. The enhanced stability of the transient mold flow in case 3 is enabled by the alternative path provided to the induced current through the conducting wall. Most of the current is generated in the jet region and closes locally through the conducting wall, forming short loops where the magnetic field is strongest. This prevents the current from wandering through the flow, where it generates strong transient forces responsible for the unstable flow with insulated walls.

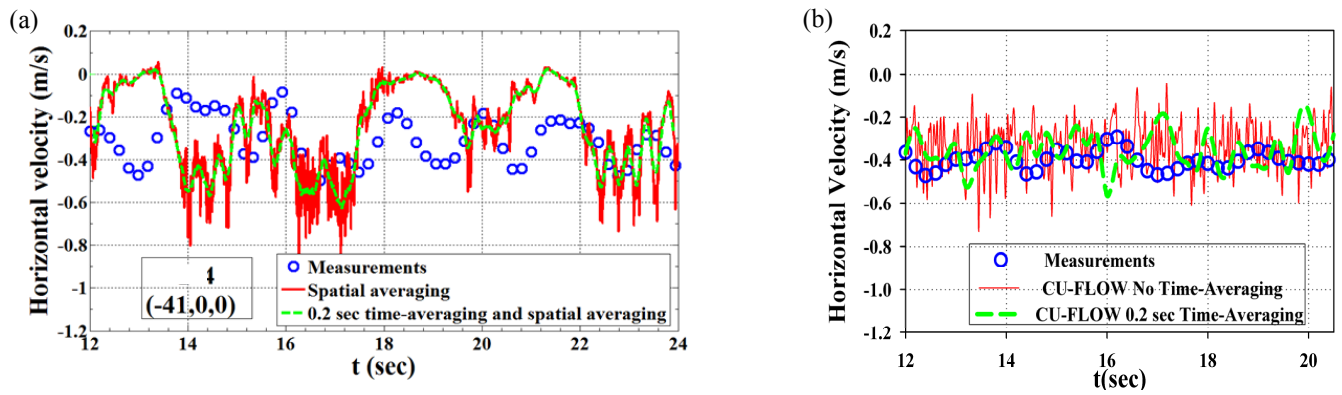


Figure 6. Transient horizontal velocity comparing LES-CUFLOW predictions and measurements in GaInSn model at $x=-41\text{mm}$, $y=0$, $z=0$ (a) EMBR with insulated walls and (b) EMBR with conducting walls

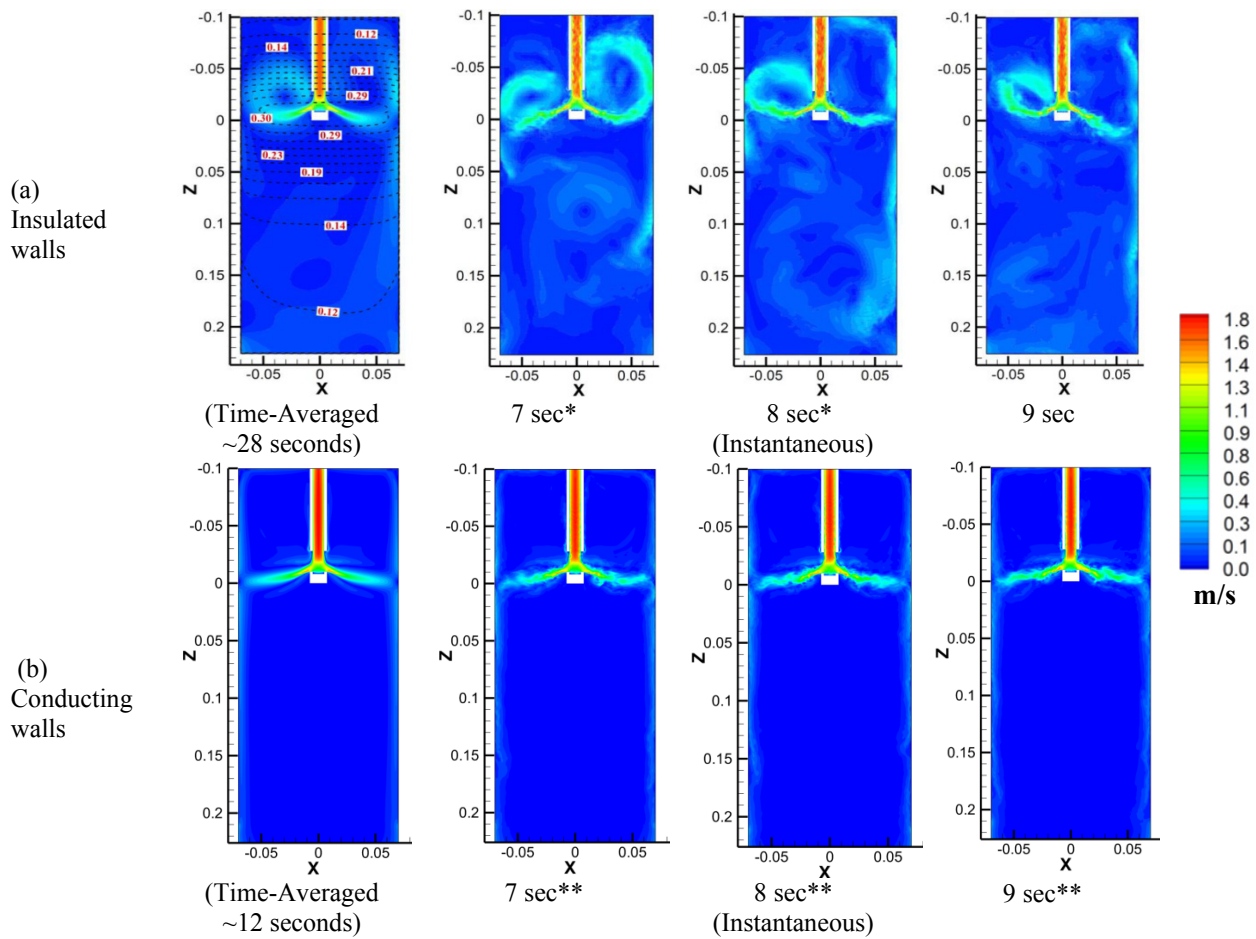


Figure 7. Time-averaged and instantaneous velocity magnitude (a) EMBR with insulated walls (b) EMBR with conducting walls

(* Time from start of simulation, **Time after switching on EMBR)

Flow across the top surface is of critical importance to steel quality. Various defects form if the surface flow is either too fast or too slow. Figure 8a shows the time-averaged horizontal surface velocity at 1mm below the free surface across the mold width, for cases 1, 2 and 3. In general, the surface velocity in this GaInSn model is low due to the deep submergence depth. The No-EMBr case has the lowest surface velocity, which could make it susceptible to meniscus freezing¹. The EMBR case with conducting walls has the highest surface velocities, and is symmetric on both sides.

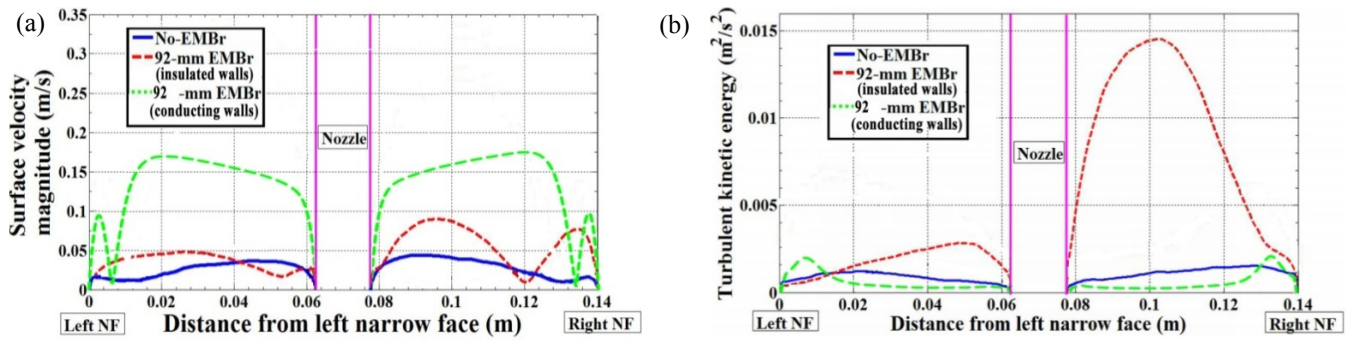


Figure 8. (a) Time-averaged horizontal (x) velocity and (b) Turbulent kinetic energy along the surface centreline in GaInSn model

The flow with conducting walls EMBR also has the beneficial effect of lowering the turbulent kinetic energy at the surface, as shown in figure 8b. The extremely high and asymmetric turbulent kinetic energy at the surface for the insulated wall case suggests large-scale level fluctuations and associated quality problems. Thus the effect of the shell conductivity should be considered in order to accurately study the mold flow under the influence of applied magnetic fields, especially when considering transient phenomena.

EFFECT OF EMBR ON TRANSIENT RESULTS

Real Caster Flow

Having validated the CUFLOW model, it was applied to simulate transient flow in a realistic full-scale commercial caster. For both No-EMBr case 4 and EMBR case 5, figure 9 shows instantaneous contours of velocity magnitude at two different times, separated by one second. With No-EMBr, the transient flow field is dominated by small-scale fluctuations. The application of EMBR damps most of the small-scale fluctuations and deflects the jets upwards. These deflected jets were reasonably stable and long scale fluctuations were not much worse than with No-EMBr. The flow below the jet region quickly aligns to the casting direction and the lower roll was restricted to a small, elongated recirculation loop just below the jet.

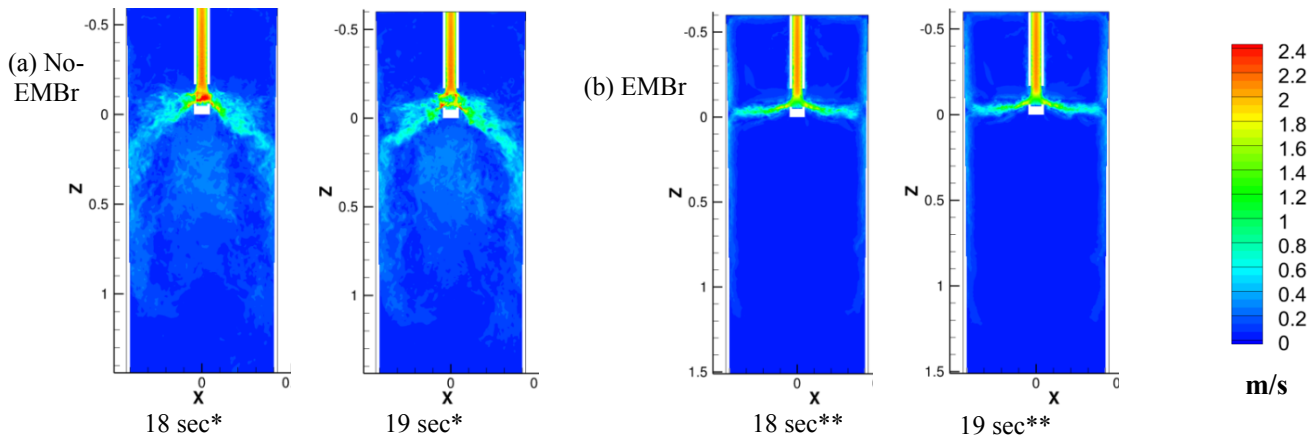


Figure 9. Instantaneous velocity magnitude in the real caster (a) No-EMBr (b) EMBR
(* Time from start of simulation, **Time after switching on EMBR)

The applied magnetic field preferentially damps the transient flow fluctuations parallel to its direction the most²². Figure 10 shows the time history of two fluctuating velocity components (y in the thickness direction and z in the casting direction) at two points P1 (center of SEN bottom) and P2 (near port exit) as shown in figure 1, for cases 4 and 5. The high variation in V_z' and V_y' at P1 with No-EMBr indicates the presence of swirling flow in the nozzle bottom. The frequency of the alternating direction of the swirl can be approximated, from the time history of V_y' in figure 10a, to be about 1.5Hz. With EMBR, the low velocity fluctuations at P1 indicate very little swirl in the nozzle which results in a smoother jet with less high-frequency turbulent fluctuations. The time history at P2 shows highly anisotropic suppression of turbulence, as the thickness-direction V_y' component is damped more by the magnetic field.

Level Fluctuations and Effect of Scaling

The steel surface level and its fluctuations are of critical importance to the steel quality as the slag layer effectiveness is greatly affected by it. The surface level can be approximated by Pressure method which gives an estimate of the liquid surface variation ($\Delta z = (p - p_{mean})/\rho_{steel}g$) using potential energy balance¹¹. The average pressure (p_{mean}) in the current study was calculated on the horizontal line along the top surface on midplane and g was taken as 9.81 m/s^2 .

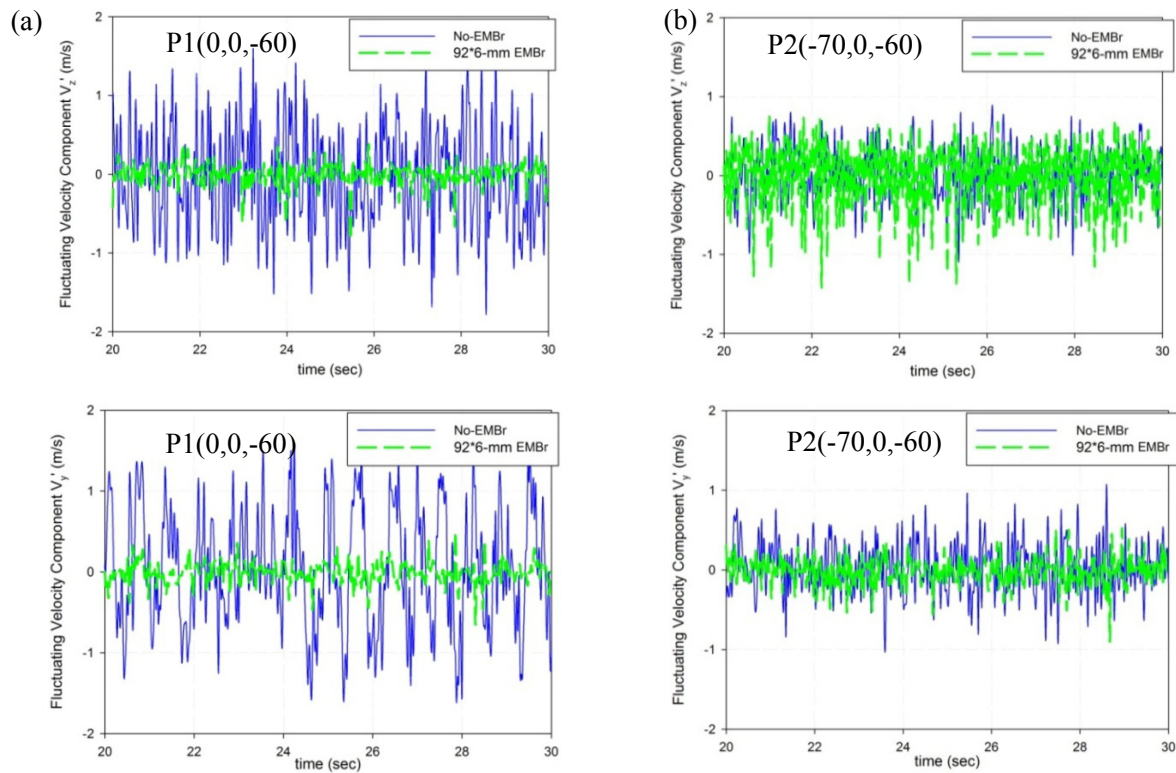


Figure 10. Time variation of components of the fluctuating velocity plotted at (a) P1 (b) P2 for real caster with and without EMBR

Figure 11 shows three typical instantaneous surface level profiles for the real caster cases, with a 0.5 seconds moving time average, at three instances separated by 5 seconds each for both real caster cases. With No-EMBr, the surface level remains almost horizontal with higher level ($\sim 0.5 \text{ mm}$) close to the NF and SEN. The level variation in the EMBR case was greater, due to the increase in momentum close to the NF ($\sim 2.7 \text{ mm}$) and SEN ($\sim 1.7 \text{ mm}$).

Time variation of the level fluctuation was plotted, at P3 and P4, and is shown in figure 12. P3 is at the midpoint between the NF and the SEN; and P4 is close to the NF as shown in figure 1. The No-EMBr case at both locations is found to be stable with only small scale fluctuations. The EMBR case at P3 has small fluctuations with oscillation amplitude of $\sim 0.5 \text{ mm}$; whereas at P4 there was a periodic oscillation with amplitude of $\sim 3 \text{ mm}$ and frequency of $\sim 0.2 \text{ Hz}$. The length scaling factor ($=6$) was used to scale the level fluctuations in case 3 at scaled P3 and P4 locations in the GaInSn domain and are shown in figure 12 to facilitate comparison with the real caster (case 5). The scaling predicts much higher frequency and amplitude in surface level fluctuations in the real caster as compared with the calculated results for case 5. The Froude number for the GaInSn model is much higher compared to the real caster (values given in Table I). This confirms that surface level behaviors, where gravitational forces balance inertial forces, do not scale if the Froude numbers are not matched.

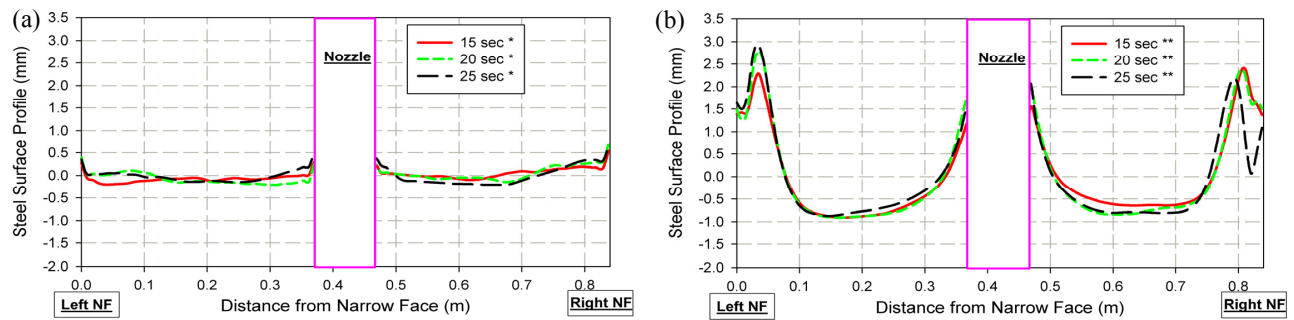


Figure 11. Instantaneous mold surface level prediction at three instances for real caster (a) No-EMBr (b) EMBR (* Time from start of simulation, **Time after switching on EMBR)

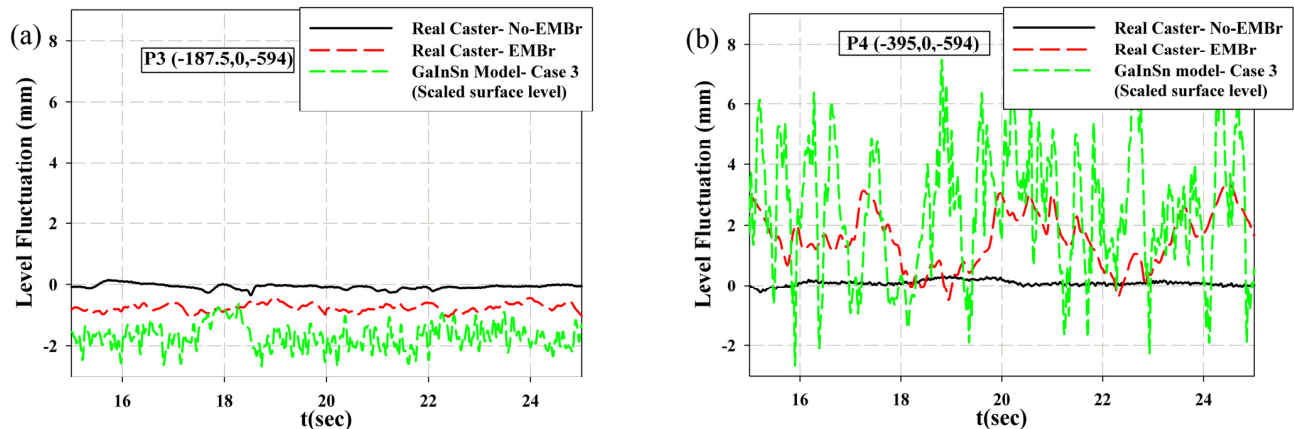


Figure 12. Mold surface level histories for real caster cases and GaInSn model case 3 with scaled surface level (a) midway between SEN and NF at P3 (-187.5,0,-594) and (b) near NF at P4 (-395,0,-594)

TIME AVERAGED RESULTS

Real Caster Flow

Figure 13 shows the contour of time-averaged velocity magnitude in the mold region with streamlines for the No-EMBr and EMBR cases. Time averaging over a long time shows the double roll flow pattern present with a weaker upper roll. The mean mold flow pattern for the EMBR case is expected to be the same as the GaInSn model EMBR case with conducting walls because Stuart number similarity was used to scale the process parameters. Application of the EMBR deflects the jets upwards resulting in an increased impinging velocity at higher positions on the NFs. The deflected jets strengthen the upper roll and create a similar stable flow pattern to the EMBR with conducting walls case for the GaInSn model. The two small recirculation regions, immediately above and below the jets as seen in the case 3, were also observed in the real caster with EMBR case. In addition to this small recirculation region in case 5, there were two other recirculation loops in the upper mold region. The jet rising along the NF and the stream rising along the SEN wall form two loops with opposite recirculation. The time averaged surface velocity at 6mm from free surface for the real caster cases is shown in figure 14. The surface velocities for the EMBR were much higher (max=0.25 m/s) than the No-EMBr case (max=0.07 m/s).

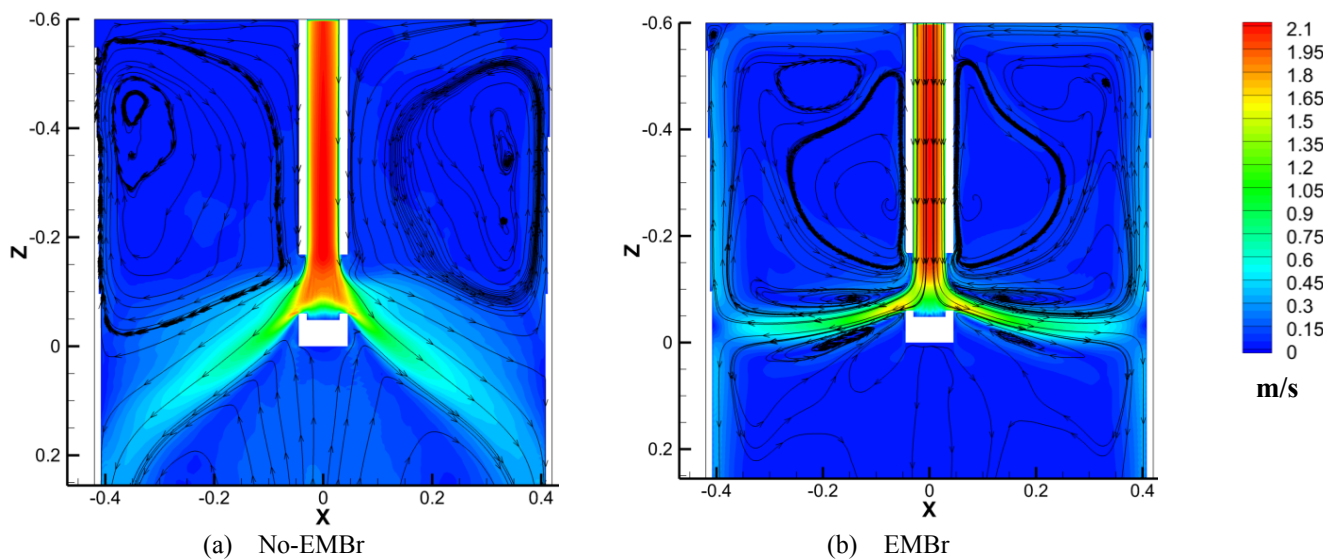


Figure 13. Time-averaged velocity magnitude contours and streamlines at mold midplane for real caster (a) No-EMBr (b) EMBr

Effect of Scaling

The flow fields for case 3 and case 5 were found to be very similar. To further study the validity of using Stuart number similarity for scaling EMBr, velocities in the GaInSn model were scaled by the ratio of the average nozzle inlet velocity between the real caster and the GaInSn model ($1.7/1.4=1.21$, Table I). The resulting scaled surface velocities are compared with real-caster values in figure 14 and matches reasonably well. The higher surface velocity in the real caster is due to the tapered solidifying shell. It has been shown in a previous study that the tapered shell and the consequent reduction in cross-section area deflects more fluid upward into the upper recirculation region, leading to the increased surface velocity²⁴.

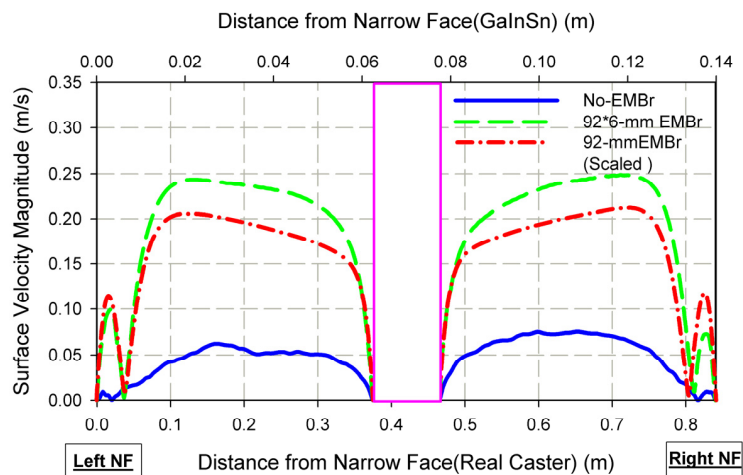
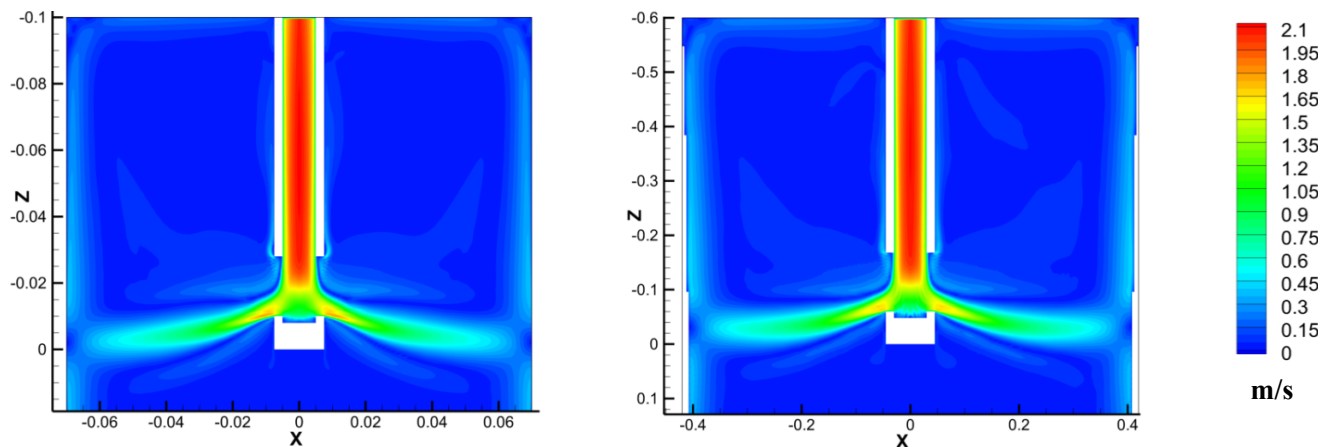


Figure 14. Time-averaged horizontal velocity at the surface plotted against distance from NF for real caster and GaInSn model conducting wall case with scaled velocity

The match between the scaled velocities for case 3 and the real-caster velocities for case 5 is shown more completely in figure 15. Both the flow patterns and velocity magnitudes match very well over the entire mold.



(a) GaInSn Model EMBR with conducting walls
(Scaled Velocity Magnitude)

(b) Real Caster EMBR

Figure 15. Time-averaged velocity magnitude contour on midplane between wide faces for (a) GaInSn model conducting wall case with scaled velocity magnitude (b) Real caster

SUMMARY AND CONCLUSIONS

A Large Eddy-Simulation code, CUFLOW, was improved to simulate fluid flow in a full-scale commercial steel caster including the effects of ruler EMBR with a realistic conducting steel shell. The model was successfully validated with measurements made in a GaInSn physical model⁷ and then was applied to explore the flow behaviors in greater detail. The corresponding full sized caster was studied at conditions similar to industrial operations; however the submergence depth was deep to match the GaInSn model in order to assess the model scaling criterion using the Stuart number.

Large scale jet wobble and transient asymmetric flow in the mold, which was found with insulated walls, did not occur with a realistic conducting shell for otherwise identical conditions. With conducting walls, the flow was stable and quickly achieved a symmetrical flow pattern, which featured three counter-rotating loops in the upper region and top surface flow towards the SEN. Thus, it is essential to include the effect of the conducting shell when studying transient mold flow with a magnetic field.

Relative to no EMBR, the ruler magnetic brake across the nozzle deflects the jets upwards, from $\sim 30^\circ$ down to only $\sim 10^\circ$ down. This strengthens the flow in the upper region and increases the top surface velocity from NF to SEN, from 0.07 m/s to 0.25 m/s in the real caster. The weak upper recirculation region without EMBR becomes more complex, with three distinct recirculation loops, which features upward flows along both the NF and the SEN. The momentum from these flows raises the surface level near both the NF and SEN, and generates more level fluctuations in these two regions. The lower recirculation region becomes a very small elongated loop just below the jet (which matches the small loop just above the jet). Flow below this small recirculation loop aligns quickly to the casting direction. The lower velocities should be beneficial for lessening the penetration and entrapment of bubbles and inclusions.

The Stuart number similarity criterion enables a close match of both the time-averaged mold flow pattern (qualitative) and velocities (quantitative) between the 1/6-scale model and the real caster. However, the scaled surface level profile and its time fluctuations were both larger in the scale model, as expected. Thus, it is better to maintain both Froude number and Stuart number similarity conditions.

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