EFFECTS OF ELECTROMAGNETIC BRAKING ON THE FLUID FLOW INSIDE A THIN SLAB CONTINUOUS CASTING MOLD THROUGH NUMERICAL SIMULATIONS

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Abstract

In the present work, a magnetic field and the behavior of electrically conducting fluid flow under the influence of the magnetic field are numerically simulated using commercial software packages ANSYS Mechanical and ANSYS FLUENT, respectively. The reliability of the numerical models is verified using a comparison with results from experiments of physical models. Good agreement is found between the predictions and experimental results. Finally, the verified models are used to analyze molten steel flow inside a thin-slab continuous casting mold. The difference between flow fields with and without electromagnetic brakes (EMBr) is discussed. The results show that EMBr greatly affects the flow field. The velocity of the fluid flow decreases and swirls at the lower half of the mold are suppressed, leading to a more uniform flow in the mold.

Keywords: Continuous Casting, Thin Slab, Electromagnetic Braking

1. INTRODUCTION

Thin-slab continuous casting is a type of near-net-shape casting that can provide a short rolling process [1, 2]. A schematic of part of the thin-slab continuous casting process is shown in **Fig. 1**. Fluid flow in copper molds is of great interest because it is related to many important phenomena. Inadequate fluid flow might cause breakouts, liquid slag layer entrapment [3, 4], and the entrapment of inclusions and bubbles [5]. If the steel flow velocity near the top surface is excessive, transient fluctuations and waves at the top surface level may form, disrupting solidification and confusing the level control system, and therefore causing surface defects [6]. Therefore, it is necessary to understand and control the fluid flow inside the mold for continuous casting.

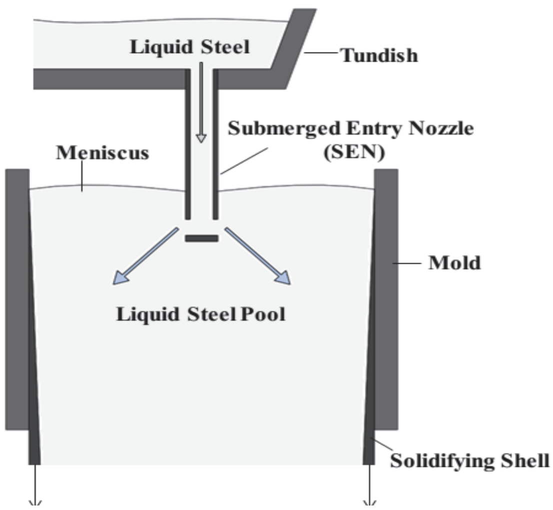


Fig. 1 Schematic of continuous casting process

Fluid flow can be controlled by applying an electromagnetic field. Electromagnetic fields can be classified as electromagnetic stirrers (EMS) or electromagnetic brakes (EMBr) based on their effects. A properly designed electromagnetic field can stir, accelerate, or brake fluid flow.

In this study, commercial software packages ANSYS Mechanical and ANSYS FLUENT are used to simulate the electromagnetic field and three-dimensional (3-D) flow in a thin-slab continuous casting mold, respectively. The simulation results are compared with experimental results to validate the reliability of the simulation. The validated computational models are used to investigate the fluid flow inside the mold cavity under the influence of an electromagnetic field.

2. NUMERICAL MODELS

To calculate the electromagnetic and flow fields inside the mold, commercial software packages ANSYS Mechanical and ANSYS FLUENT were used, respectively. First, the electromagnetic field applied to the fluid generated by copper coils and iron cores was calculated using ANSYS Mechanical. The solution data of the magnetic field was then exported and transformed into a format for use in ANSYS FLUENT. The magnetic field data was then loaded for the flow region using the magnetohydrodynamics (MHD) module in ANSYS FLUENT to calculate the coupled solution of all other fields.

3. VALIDATION OF NUMERICAL MODEL

In order to verify the numerical models, the models were used to simulate several simplified physical models constructed by other researchers [7,8,9]. The simulation results were compared to the reported measured results to verify the reliability of the numerical simulation.

3.1. Verification of Magnetic field

Fig. 2 shows a schematic diagram of an inductor used in magnetic field experiments [7, 8]. The inductor consists of a pure iron core and coils. **Fig. 3(a)** shows the measured magnetic field distribution of the cross section at x = 0 of the inductor [7]. **Fig. 3(b)** shows the magnetic field distribution computed using the proposed models at the same cross section. The two magnetic field distributions are similar. **Fig. 4** shows the distribution of the induced magnetic density in the z direction at x = 0 and y = 0 along the z direction. The measured results [7] and simulation results match pretty well, verifying that the magnetic fields calculated using the proposed models are reliable.

3.2. Verification of Flow Field Coupled with Electromagnetic Force

A previous study used mercury and a commercial linear inductor to conduct an MHD experiment [9]. **Fig. 5** shows a schematic diagram of the experiment. The linear inductor is placed under a shallow bath of mercury to drive the fluid flow. The nitric acid above the mercury prevents the mercury from oxidizing. **Fig. 6(a)** shows the flow pattern of the mercury obtained by photographing the path of glass beads floating on the surface of the mercury. A major swirl occupies most of the space in the container, with a minor swirl near one of the corners [9]. **Fig. 6(b)** shows the velocity field computed in the present work. The pattern is similar to that observed in the experiment. Therefore, the reliability of the models for calculating fluid flow coupled with an electromagnetic force is verified.

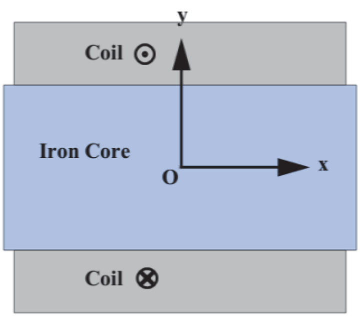
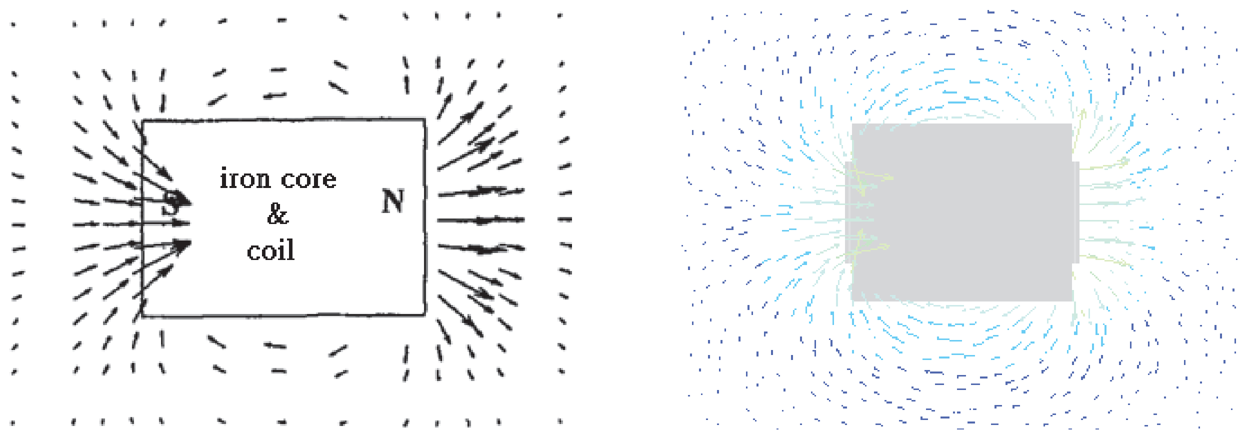


Fig. 2 Schematic of inductor [8]



(a) (b)

Fig. 3 Magnetic field distribution obtained from (a) experiment [7] and (b) simulation using proposed models

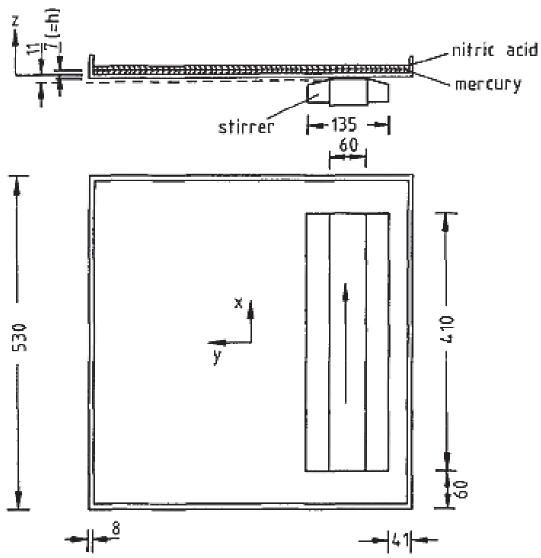
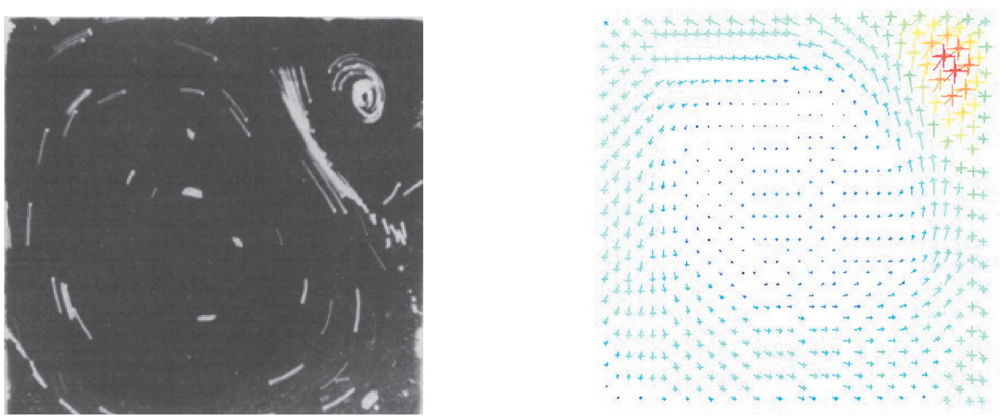


Fig. 5 Schematic drawing of MHD experiment [9]



(a) (b)

Fig. 6 Flow pattern of mercury under effect of magnetic field from (a) measurements [9] and (b) simulation using proposed models

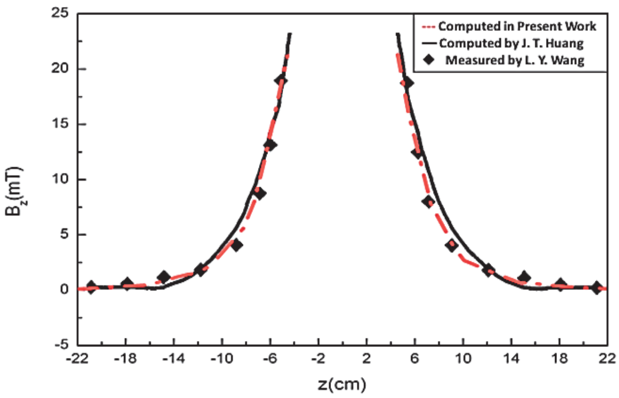


Fig. 4 Distribution of induced magnetic density in z direction at x = 0 and y = 0

4. SIMULATION OF THIN-SLAB CONTINUOUS CASTING WITH APPLIED MAGNETIC FIELD

The flow pattern and the magnitude of the velocity in the region of the thin-slab continuous casting mold under the effect of an electromagnetic field were analyzed using the proposed numerical models. **Fig. 7** shows a schematic diagram of the funnel-shaped mold and the position where the magnetic field is applied. The detailed parameters for continuous casting are listed in **Table 1**. The physical properties of the steel used for calculations are listed in **Table 2**. The simulation results of the flow field inside the continuous casting mold without and with a magnetic field are discussed below.

4.1. Without EMBr

Fig. 8 shows the velocity field of the molten steel inside the mold at the half thickness of the thin slab (y = 0). When the molten steel reaches the end of the submerged entry nozzle, it divides into two streams, which flow to the narrow face of the mold at each side. When the streams reach the mold wall at the narrow side, they divide into two flows again. One flow goes up to the meniscus and forms a swirl at the upper half of the mold, and the other one goes down and forms another swirl at the bottom half of the mold.

The swirl formed at the upper half of the mold causes the fluctuation of the meniscus, and may thus affect the surface quality of the thin slab. The swirls formed at the bottom half of the mold are related to the entrapment of inclusions and impurities. If the flow goes downward too deep and too fast, it is difficult for the inclusions and impurities to float up to the meniscus, and thus more of them become entrapped in the solidification layer.

4.2. With EMBr

Fig. 9 shows the velocity field of the molten steel inside the mold at the half thickness of the thin slab (y = 0) with EMBr applied. The maximum intensity of the magnetic density is 0.3 T. As shown in the figure, after EMBr is applied to the mold, the flow field greatly changes. The two swirls at the bottom half of the mold weaken and almost disappear. The electromagnetic force suppresses the downwards velocity of the molten steel. The flow at the bottom half of the mold is more uniform compared to the result without EMBr. Two swirls at the upper half of the mold are slightly accelerated, which may make the meniscus fluctuate more intensely.

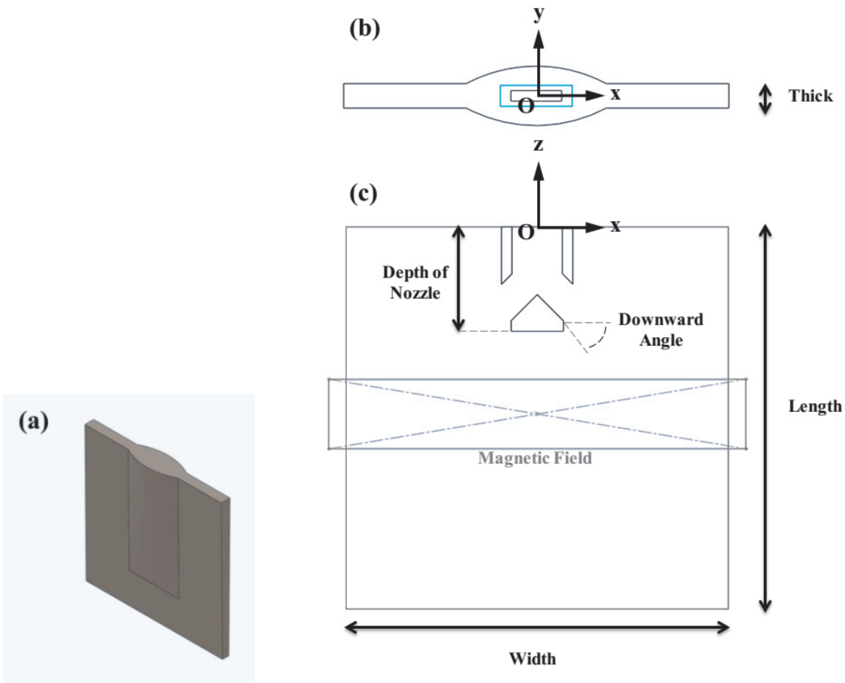


Fig. 7 (a) Schematic of funnel-shaped mold. (b) Top view and (c) cross section of mold at y = 0

Table 1 Parameters for continuous casting

Parameter	Value
Mold length	1100 mm
Mold width	1100 mm
Mold thickness	60 mm
Depth of nozzle	300 mm
Downward angle	45°
Casting speed	4 m/min

Table 2 Physical properties of steel

Physical Property	Value
Density	7020 kg·m-3
Viscosity	0.0062 kg·m-1·s-1
Electrical conductivity	714000 ohm-1·m-1

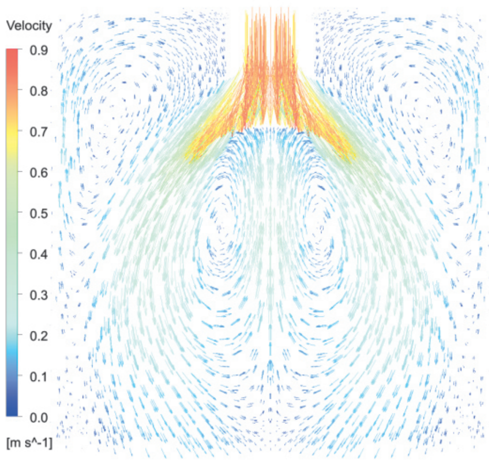


Fig. 8 Velocity field of molten steel at y = 0

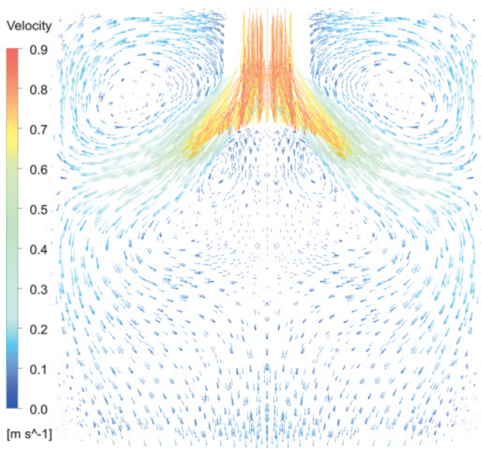


Fig. 9 Velocity field of molten steel under effect of EMBr at y = 0

CONCLUSION

The behavior of an electrically conductive fluid under the effect of a magnetic field was predicted using numerical simulation. The proposed numerical models were verified with results from physical experiments. The computed and experimental results show good agreement. The flow field of molten steel inside the copper mold was simulated to determine the effect of EMBr. EMBr was found to greatly change the flow field. The downward velocity of the flow is suppressed. Two swirls at the bottom half of the mold disappear. The flow is more uniform compared to the result without EMBr. However, EMBr might accelerate the swirls at the upper half of the mold, which may lead to the fluctuation of the meniscus. Therefore, EMBr has both posivite and negative effects.

ACKNOWLEDGEMENTS

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