Modeling of Melt Flow in Continuous Casting Facilities

A. Kapusta, B. Mikhailovich, Sh. Lesin and M. Khavkin

Abstract

In the presented paper we describe the results of experimental study of liquid metal flow in a low-temperature model of continuous casting facility equipped with two electromagnetic stirrers (EMS). Characteristics of turbulent melt flows in such facilities are computed on the basis of a semi-empirical model of "external" friction taking into account the experimental angular velocities distribution along the liquid core of the ingot in the gap between the inductors

Experimental results are compared with the results of computations using the proposed mathematical model.

Introduction

At present, most facilities of steel continuous casting into billets of circular or rectangular cross-section are equipped with electromagnetic stirrers.

As a rule, stirrers are arranged in the mold (or under the mold) and on the strand, in the lower part of the continuous ingot liquid core.

The spatial distribution of the rotating velocity component of the melt turbulent flow in relatively short vessels placed into a rotating magnetic field (RMF) excited by inductors with the pole length on the order of the vessel length has been extensively studied both theoretically and experimentally [1]. In contrast, angular velocity distribution in long (\( \delta_z = Z_0 / R_0 >> 1 \)) vessels simulating the liquid core of a continuous ingot in the presence of one (upper) or two (upper and lower) inductors, whose active forcing zone is small in comparison with the vessel length, has been insufficiently explored.

1. Experiment

To fill this gap, we have constructed a low-temperature laboratory facility (using InGaSn alloy as a simulating medium), which simulates the liquid core of continuous ingots of circular and square cross-sections on the scale 1:3 (Fig.1) with respect to the liquid core of a continuous round steel ingot 210 mm in diameter or a square ingot 210 x 210 mm.

In the first set of experiments we used a conical vessel 1 of circular cross-section simulating a half-length of the liquid core. In its upper and lower parts, two-phase explicit-pole inductors 2, 3 generating RMF in the melt were placed. The inductors simulate electromagnetic stirrers used in industrial plants. The active zone
length of each inductor amounted to ~ 0.1 of the vessel length. The vessels were made of nonmagnetic steel 304 with the wall thickness ~ 2 mm and the taper of 1.26°.

Three-phase alternating voltage with the frequency of 8 Hz was applied to the inductors windings from a controllable power source.

At the power $N = 600$ W, the mean integral value $\langle B \rangle$ of the RMF magnetic induction in the inductor bore was ~ 36 mT, whereas at $N = 370$ W, $\langle B \rangle \sim 28.3$ mT.

Mean velocities of the turbulent flow were measured using a propeller installed in the quasi-solid flow core and a digital tachometer Line Seiki E90-103. Local velocity values were measured by a two-electrode conductive probe with a permanent magnet connected to a low-noise preamplifier AMETEK 5113 using National Instruments PCI 6052E A/D (Fig. 2). The signals were processed by a virtual measuring system developed on the basis of LabVIEW 7.0 package, allowing us to process experimental data and perform spectral analysis of dynamic flow characteristics.

2. Mathematical model

The distributions of the dimensionless angular velocity $\bar{\Omega} = \Omega / \bar{\omega}$ (where $\bar{\omega}$ is the angular velocity of RMF rotation) along the channel for two values of the Hartmann number under the action of the upper inductor and under a simultaneous action of both upper and lower inductors are shown in Fig. 3.

Since the Reynolds number $Re = \frac{\langle \Omega \rangle < R_0 >^2}{\nu}$ of the rotating flow in a vessel at $N = 600$ W is ~ 38,000 and at $N = 370$ W ~ 30,000, the flow possesses a developed turbulent structure, and a faster decrease in the angular rotation velocity of the fluid along the vessel than in a laminar flow was anticipated a priori. Velocity profiles presented in Fig. 3 (figures 1, 2 denote the number of inductors; letters a, b correspond to power supply output 370W and 600W, respectively) cannot be explained from a purely dissipative (either laminar or turbulent) point of view. However, these profiles can be reasonably explained using the "external" friction model that we have developed [2]. Within the framework of this model, a quasi-
solid turbulent rotating flow excited by the upper inductor can be described by the following dimensionless equation:

\[
\frac{d^2 \Omega}{dz^2} + \delta^2 \Delta \lambda \Omega + \delta^2 Ha^2 (1 - \Omega) \theta(z) = 0, \tag{1}
\]

where \( \delta_z = Z_0 / R_0 >; \ Ha = B_0 R_0 \sqrt{\sigma / \eta}; \ \theta(z) = \begin{cases} 1 & Z_i \leq Z \leq 1 \\ 0 & 0 \leq Z < Z_i \end{cases}; \) \( R \) and \( r \) are the bigger and smaller radii of the conical vessel; \( \Delta \lambda = \lambda_g - \lambda_d \) is the "external" friction coefficient; \( \lambda_g, \lambda_d \) are the generative and dissipative parts of \( \Delta \lambda \). In the general case, \( \lambda_d = C_\varepsilon \cdot \text{Re}^{1-\varepsilon}, \) where \( C_\varepsilon = 0.0184 e^{11.82 \varepsilon}, \) \( \varepsilon \) being an empirically determined structural constant.

The boundary conditions are

\[
\Omega|_{z=0} = 0 \quad \text{and} \quad \frac{\partial \Omega}{\partial n}|_\Gamma = 0, \tag{2}
\]

where \( \Gamma \) is a free surface.

To explain the experimental curves (Fig. 3), we resort to (1). Since in the active zone (inside the inductor) \( \Omega \approx \text{const}, \) we obtain \( \Omega = 0 \) and

\[
\Delta \lambda = -\frac{Ha^2 (1 - \Omega)}{\Omega}. \tag{3}
\]

Since in a short vessel \( \lambda_d = \frac{Ha^2 (1 - \Omega)}{\Omega}, \)

\[
\lambda_g = 0. \tag{4}
\]

Beyond the active zone \( (Z < Z_i), \)

\[
\Omega'' + \delta^2 \Delta \lambda \Omega = 0. \tag{5}
\]

The analysis of experimental data gives

\[
\Delta \lambda \sim 10^{-3} \div 10^{-4} \quad \text{and} \quad \delta^2 \Delta \lambda < 1. \tag{6}
\]

Then, expanding the solution (5) in the powers of a small parameter \( \delta^2 \Delta \lambda, \) we obtain, to the zero approximation, an equation \( \Omega'' = 0, \) whose solution has the following form:

\[
\Omega_0 = C_1 z + C_2, \tag{7}
\]

which ensures a good approximation of the observed piece-wise quasi-linear velocity profile.

It follows from the condition (6) that beyond the active zone \( \lambda_g \approx \lambda_d, \) i.e. the turbulent dissipation of the energy flow is compensated by the generative process of turbulence energy transfer along the spectrum into a large-scale structure. As demonstrated in [3], such transfer can be realized by inertial waves.
Conclusions

Using the "external" friction model, we explain the behavior of the mean velocity of a rotating electroconducting fluid flow generated in a conical channel by rotating magnetic field inductors. Peculiar features of the mean velocity profile of a rotating flow are well explained from the standpoint of this model by the presence of a generative component in the "external" friction coefficient.

The model can be applied for calculating dynamic modes of stirring the liquid core of continuous ingots of circular and square cross-sections.

References

Authors
Prof. Kapusta, Arkady Dr. Lesin, Shaul
Dr. Mikhailovich, Boris Eng. Khavkin, Michael
Center for MHD Studies Energetics Technologies Ltd., Omer, Israel
Ben-Gurion University of the Negev Omer Industrial Park, P.O.B. 3026, 84965 Omer, Israel
P.O.B. 653, 84105 Beer-Sheva, Israel E-mail: borismic@bgu.ac.il