Suppression of the Vortex in Ladle by Static Magnetic Field

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The vortex formation in draining the melt in ladle can be suppressed by the reduction of the tangential flow velocity of the melt. Two magnetic devices were designed in order to reduce the tangential flow velocity and tested with wood metal melt. One consists of 4 permanent magnets (PM device) and the other consists of an electromagnet (EM device). Magnetic flux density around each device was calculated and compared with the measured one. Induced body force in the melt was calculated with both of the calculated magnetic flux density and velocity profile. The dimensionless vortex formation height, where the vortex formation height is divided by orifice inner diameter, decreased from 1.7 down to 0.85 in both cases of the PM device and the EM device as the static magnetic field increased up to 0.17 T.

KEY WORD: vortex suppression; static magnetic field; ladle; steel-making process; vortex formation height.

1. Introduction

In general, steel-making process is composed of the following steps, BOF–ladle–RH–tundish–continuous casting mold. When iron melt drains from ladle to tundish through the bottom nozzle, whirlpool forms on the surface of the melt and the shape of free surface becomes convex downward in the final stage. This phenomenon is called as vortex. If this vortex forms during emptying the ladle undesired slag floating on the steel melt can be entrained from the beginning of drain into the tundish through its core even though melt height is still high. The vortex formation in the ladle increases the amount of harmful inclusions and decreases the quality of steel in the end. Therefore, it is very important in steel making process to suppress the vortex formation in the ladle in order to improve the steel quality as well as the productivity.

This vortex phenomenon has been studied by many researchers. Lugt1) has published a textbook on vortex flows. The Chang2) has reported the literature review on draining vorticities up to 1976. The effect of Earth’s Coriolis force can be neglected in normal technical flow conditions3–5) except the fluid settled completely for a long time. There is always some convection in a tangential direction in emptying ladle under practical circumstances. As increasing the tangential flow velocity in ladle, the height of vortex formation increases. This can be simply explained by the principle of conservation of angular momentum and Bernoulli’s law6) From the principle of conservation of angular momentum \((\rho r^2 \omega = c)\), the angular velocity, \(\omega\), is inversely proportional to \(r^2\) and the centrifugal force \((\rho r^2 \omega = c^2/r^2)\) is also inversely proportional to \(r^2\), where \(\rho\) is the density and \(r\) is the radius from the center of the rotation. As approaching the nozzle, \(r\) becomes small and the angular velocity increases rapidly by a factor of \(1/r^2\) and the centrifugal force also becomes very large by a factor of \(1/r^3\). Therefore, vortex can develop and undesired slag floating on the melt can sink down through the bottom nozzle.

Other factors also affect the vortex formation. If the nozzle eccentricity increases, the height of the vortex formation decreases.7) As the drain velocity increases, vortex formation height increases, but beyond a certain drain velocity the tendency is reversed.8,9) As increasing the viscosity ratio of melt to slag \((\eta_{\text{melt}}/\eta_{\text{slag}})\) and the density ratio of slag to melt \((\rho_{\text{slag}}/\rho_{\text{melt}})\), the vortex formation height increases.9,10)

There are several methods to prevent slag carry-over: use of a syphon tapping hole for converters,1) use of slag-cut balls or pots,12) casting with increased bath depth in the tundish,13) installation of a circular ring around the stopper rod,14) electromagnetic counter-stirring of the vortex,15) gas injection close to the nozzle16,17) or into the nozzle,18) electromagnetic stirring with two linear induction motors,19) and use of static magnetic field in horizontal direction with permanent magnets or in vertical direction with a solenoid.20) Obstacles near the nozzle with fireproof material or the combination of the slag detector and the sliding gate is being used now in real industry.

Among above earlier studies, all methods excepting the case with magnetic field need a direct contact with melt. Therefore, these methods can be another source of inclusion. And the earlier methods with magnetic field were restricted within only experimental work not considering an application to the real situation. In this study, two static magnetic devices were designed and tested with wood metal melt, which can be applied to the industrial ladle. One was a device with permanent magnets (PM device) and the other was a device with electromagnet (EM device). The velocity component of the melt perpendicular to the static magnetic field is decelerated due to the body force induced in the melt. This principle is also applied to...
The static magnetic field was applied through the bottom and the side of a ladle to reduce the tangential velocity with these magnetic devices. The principle of this method is explained in Fig. 1. An induced current occurs when a conductive material moves under static magnetic field as follows:

$$J = \sigma V \times B$$ .................................. (1)

where $J$ is current density, $\sigma$ is electrical conductivity, $V$ is the velocity, $B$ is magnetic flux density.

Body force is always induced in the opposite direction to the melt flow, $V$ as follows:

$$F = J \times B$$ .................................. (2)

where $F$ is the induced force per unit volume. Therefore, the tangential velocity can be suppressed by means of static magnetic field. In this article, magnetic flux density around each device was calculated and compared with the measured one. And the magnitude of the Induced body force was calculated using both the static magnetic field calculated with ANSYS and the fluid velocity obtained by mathematical model under some assumptions.

2. Experiments

The experimental setup shown in Fig. 2 consists of a stainless steel ladle, a mechanical stirrer, a load cell and a PM or an EM device. The inner diameter of the ladle was 264 mm, which was designed to be able to replace the bottom nozzle with different diameters, 9.8 or 12.3 mm. The eccentricity of the nozzle, $e=a/r_2$, shown in Fig. 2, was 0.65 where $a$ is a distance between the center of the ladle and the nozzle and $r_2$ is the radius of the ladle.

After filling the ladle with Wood metal melt up to 80 mm depth, the melt was rotated with a mechanical stirrer for 120 sec at 70 rpm in counter clockwise direction to make a constant initial condition. The composition of the Wood metal was Bi–25Pb–12.5Sn–12.5Cd (in wt%) and its melting point was about 72°C. The melt discharge started by removing the stopper after a waiting time of 90 sec. The static magnetic field was applied with a PM device or an EM device from the end of mechanical stirring to the end of discharge. The vortex formation time was measured by the weight measurement method. The ladle was placed on the Al plate which placed on a fulcrum on one side and on a load cell on the other side. The total weight was measured with a load cell during emptying the ladle and the signal was converted into the melt height. Figure 3(a) shows an example of melt height versus drainage time curve, in which two curves are plotted. The one is the drainage curve.
without magnetic field \((B=0 \text{T})\) and the other is that with magnetic field \((B=0.19 \text{T})\). The magnetic flux density was measured at the positions of \(P_s\) and \(P_b\) plotted in Fig. 6 and averaged. The slope of weight versus drainage time curve didn’t change until air-entraining vortex forms. When an air core of the vortex passes through the bottom nozzle, the tapping rate decreases abruptly due to the decrease of the flow area through the nozzle. Therefore, the slope of the drainage curve changes abruptly at this moment. This point was defined as a vortex formation point in this article. In the case of \(B=0.19 \text{T}\), vortex forms at about 18 sec in Fig. 3(a). The point can be obtained precisely by converting the melt height, \(h\), versus drainage time curve to the differential of the melt height with time, \(dh/dt\) vs. drainage time curve as shown in Fig. 3(b). Measured vortex formation height \((H_v)\) was divided by nozzle inner diameter \((d)\) to get the dimensionless vortex formation height \((H_v/d)\). Each experiment was done twice to investigate the reproducibility. For example, a drainage curve with a nozzle diameter of 12.3 mm was shown in Fig. 4. In this figure, the dashed line \((\text{EM12.3-10A-01})\) and the dotted line \((\text{EM12.3-10A-02})\) having the same experimental condition but done separately show a good reproducibility.

It is important to know the distribution and direction of the induced magnetic force in melt in order to suppress the tangential flow of melt by static magnetic field. The magnetic flux density and the velocity are necessary to calculate the induced magnetic force. The magnetic flux density near each magnetic device was calculated by ANSYS and it was compared with experimental result. In addition to the magnetic flux density, the velocity of melt in ladle was also calculated under some assumptions. Finally, the induced force in melt was calculated using both the magnetic flux density and the velocity.

The effect of static magnetic field on the vortex suppression was investigated with two magnetic devices, a PM device and an EM device. The vortex formation height in emptying ladle was monitored as increasing the static magnetic field.

### 2.1. Calculation and Experiment with a PM Device

An PM device was designed to apply a static magnetic field normal to a tangential velocity in the melt through the ladle. The PM device and its application position to the ladle were shown in Fig. 5. Static magnetic field was applied by four Nd–Fe–B magnets and mild steel yoke. A steel plate of a thickness of 0.5 mm was used as a shielding material to reduce the magnetic field strength. The size of the steel plate was the same as the pole surface of the magnet. The three-dimensional magnetic flux density around the PM device was calculated by ANSYS. The coercive force and the residual induction of the permanent magnet were 852 kA/m and 1.13 T, respectively. The magnetic flux density around the PM device was measured and compared with the calculated one. The PM device was simpler and smaller than the EM device because the former doesn’t need to power supply.

### 2.2. Calculation and Experiment with an EM Device

The EM device and its application position to the ladle are shown in Fig. 6. The EM device consists of a mild steel core, two pieces of copper coils and D.C. power supply. The core was made of mild steel that can highly concentrate the magnetic field into its interior due to its high magnetic permeability. The number of turns of coil 1 and coil 2 were 171 and 684, respectively. The strength of the magnetic flux density was measured at the positions of \(P_s\) and \(P_b\) plotted in Fig. 6 and averaged. The slope of weight versus drainage time curve didn’t change until air-entraining vortex forms. When an air core of the vortex passes through the bottom nozzle, the tapping rate decreases abruptly due to the decrease of the flow area through the nozzle. Therefore, the slope of the drainage curve changes abruptly at this moment. This point was defined as a vortex formation point in this article.
density was controlled by the D.C. power source that can supply max. 72 A and 32 V. In this experiment, direct current was applied to the coil from 0 up to 10 A. The electromagnet had two poles, the one was placed near the bottom of the ladle with a gap of 5 mm and the other was located by the side of the ladle with a gap of 5 mm.

The 3-dimensional magnetic flux density around the EM device in case of the input current of 10 A was calculated with ANSYS. In this calculation, three materials (air, copper coil and mild steel core) were used. The relative permeability, \( \mu_r \), of air and copper was 1. The nonlinear relative permeability of the mild steel was considered. Total ampere-turns of the electromagnet were about 85 500 ampere-turns. Only a half section of the total domain was calculated because of the plane symmetry of the calculation model. Magnetic flux density around the EM device was also measured with a Gaussmeter and a Hall probe and compared with the calculation result.

3. Results and Discussions

3.1. Calculation and Comparison of Magnetic Flux Density

The three dimensional magnetic flux density around the EM device and the PM device were calculated and their contour plots of \( B_{\text{sum}} = (B_x^2 + B_y^2 + B_z^2)^{1/2} \) at the symmetric plane of \( y=0 \) were plotted in Fig. 7. The area beyond 0.005 T is wider in case of the EM device than the PM device.

The most effective direction of the magnetic field is normal to the tangential flow velocity of the melt, that is, \( B_x \) component at the ladle side and \( B_z \) component at the ladle bottom. The direction of the magnetic field near the poles of the magnet was nearly perpendicular to the ladle wall as expected.

In the case of the EM device with a current of 10A, the measured \( B_x \) at a distance of 5 mm from the N-pole was about 0.26 T and the measured \( B_z \) at a distance of 5 mm from the S-pole surface was about 0.15 T. The \( B_x \) and the \( B_z \) of the PM device were also measured with and without the shield of a steel plate of 0.5 mm thickness. The \( B_x \) of the PM device without shielding was about 0.29 T and the \( B_z \) was about 0.2 T at a distance of 5 mm from each pole. After shielding, the magnitude of B decreased to about 75% of that without shielding at a distance of 5 mm, but the difference was very small over the distance of 20 mm. The measured \( B_x \) of the EM device and the PM device was plotted together and was compared with the calculation results in Fig. 8. The magnitude of \( B_x \) of the EM device is smaller than the PM device up to the distance within 15 mm from the N pole but becomes larger beyond the distance. This is due to size effect of each device. That is, as the size of the EM device is bigger than the PM device, the B of the EM device is larger extending a long distance. The calculated B
3.2. Calculation of the Melt Velocity in Ladle

The velocity profile immediately after the end of the mechanical stirring was calculated from the momentum equation in cylindrical coordinates with several assumptions. By considering the stirring condition plotted in Fig. 2, it is assumed that radial velocity, \( v_r \), and axial velocity, \( v_z \), are zero and tangential velocity, \( v_\theta \), is only a function of radius, \( r \), as Eq. (4).

\[
v_r=v_z=0, \quad v_\theta=f(r) \quad \text{and} \quad P=P_0=1 \text{ atm at } z=z_0 \quad (4)
\]

where \( v_r \), \( v_\theta \) and \( v_z \) are velocity components in cylindrical coordinates, \( P \) is a pressure, \( z \) is the melt height from the bottom of ladle and \( z_0 \) is the melt height at the position of the stirrer tip.

At steady state, momentum equations of cylindrical coordinate with above assumptions can be written as

- \( r \)-component: \[
\rho \frac{v_\theta^2}{r} = \frac{\partial P}{\partial r} \quad (5)
\]

and

- \( \theta \)-component: \[
0 = \eta \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial}{\partial r} (rv_\theta) \right) \quad (6)
\]

where \( \rho \) is density, \( P \) is pressure and \( \eta \) is viscosity of the melt.

The integration of the Eq. (6) can be written as

\[
v_\theta = \frac{1}{2} C_1 r + \frac{C_2}{r} \quad (7)
\]

where \( C_1 \) and \( C_2 \) are integration constants.

First, the velocity distribution between \( r=0 \) and \( r=r_1 \) is considered. At \( r=0 \), \( v_\theta \) must have finite value, so \( C_2 \) in Eq. (7) is zero. The stirrer tip is placed at a distance of \( r_1 \) from the center of ladle and rotates with angular velocity, \( \omega \), so the \( v_\theta \) at the stirrer tip position becomes \( r_1 \omega \). Therefore, the \( v_\theta \) between \( r=0 \) and \( r=r_1 \) is as follows:

\[
v_\theta = r \omega \quad (8)
\]

The velocity distribution between the tip of the stirrer, \( r = r_1 \) and the ladle wall, \( r = r_2 \) is different. The \( v_\theta \) at \( r = r_1 \) and at \( r = r_2 \) can be written as

\[
v_\theta = \frac{1}{2} C_1 r + \frac{C_2}{r_1} = r_1 \omega, \quad \text{at } r = r_1 \quad (9)
\]

and

\[
v_\theta = \frac{1}{2} C_1 r + \frac{C_2}{r_2} = 0, \quad \text{at } r = r_2 \quad (10)
\]

From the Eqs. (7), (9) and (10), the \( v_\theta \) between \( r = r_1 \) and \( r = r_2 \) is as following:

\[
v_\theta = r_1^2 \omega \left( \frac{r_2^2-r_1^2}{r} \right) \quad (11)
\]

The calculated melt velocity at 70 rpm is shown as a vector plot in Fig. 9(a). The initial rotating direction was counter clockwise. The maximum velocity at 70 rpm was about 0.37 m/sec at the tip of the stirrer and decreased with increasing the distance from the stirrer as shown in Fig. 9(b).

3.3. Calculation of the Magnetic Force Induced in Melt

Induced current in the melt was calculated by Eq. (1) using both the magnetic flux density and the velocity that were calculated in advance. The induced force was calculated by Eq. (2) using the induced current and the magnetic flux density. The maximum magnitude of the induced force in the melt is opposite to the initial stirring direction (Figs. 10(c) and 10(d)). As increasing the height, the strength of the induced force decreases due to the decrease of the magnetic flux density. The maximum magnitude of the induced force in the melt at \( z = 11.7 \text{ mm} \) was about 703 N/m³.

Induced current obtained by magnetic flux density and velocity through Eq. (1) must satisfy equation of continuity (\( \text{div} \mathbf{J} = 0 \)) and appropriate boundary conditions for induced current. But in this calculation these were not considered just to get a qualitative comparison. Therefore, there are some calculation errors such as the exaggeration of the magnitude of the induced current.
3.4. Suppression Experiment of Vortex by Magnetic Field

Vortex suppression experiments were conducted with two magnetic devices. The strength of magnetic field of the EM device was controlled with input currents from 0 to 10A and the one of the PM device was varied with and without a steel plate for shielding. Vortex formation heights were measured and plotted with the variation of the magnetic flux density for two nozzles with different diameters in Fig. 11(a), and the dimensionless vortex formation heights were plotted in Fig. 11(b). The magnetic flux density in Fig. 11 was the average value measured at the points of $P_s$ and $P_b$ in Fig. 5 or Fig. 6 near the electromagnet or the permanent magnets without melt. For the larger nozzle with 12.3 mm diameter, the vortex formation heights are also larger. But the dimensionless heights are similar for the two nozzle diameters. If we compare these two devices, the EM device is somewhat effective to suppress the vortex formation but there is no significant difference. This can be explained by the difference of the penetration depth of the magnetic field of each device, which is shown in Fig. 7.

As increasing the static magnetic field, the vortex formation height decreased. This decrease in vortex formation height is due to the deceleration of the tangential melt flow by the induced force in the melt. The dimensionless vortex

![Image](a)
![Image](b)

**Fig. 9.** Velocity profile of the melt in the ladle immediately after stirring with 70 rpm: (a) vector plot of velocity, (b) velocity profile in radial direction.

![Image](a)
![Image](b)
![Image](c)
![Image](d)

**Fig. 10.** Magnetic flux density and induced force at the end of initial stirring in the case of EM device: (a) and (b) are vector plot of the magnetic flux density ($B_x + B_y$ in T) at $z = 11.3$ mm and $z = 21.7$ mm plane respectively, and (c) and (d) are vector plot of induced force ($F_x + F_y$ in N/m$^3$) at $z = 11.3$ mm and $z = 21.7$ mm plane respectively. Melt rotates counterclockwise and the direction of the induced force is clockwise.

![Image](a)
![Image](b)

**Fig. 11.** Comparison of the vortex formation height of PM device with that of the EM device: (a) vortex height with the variation of the $B$, (b) dimensionless vortex height with the variation of $B$. The symbols of solid circle and open circle show the vortex heights of only stirring of 12.3 mm nozzle and 9.8 mm nozzle, respectively.
The vortex formation height of the EM device decreases remarkably from about 1.7 to about 0.85 in average by the application of the static magnetic field up to 0.17 T, which seems to be the limit of the suppression. The half of the total suppression is achieved already at a field of about 0.05 T. And the dimensionless vortex formation height of the PM device was also decreased from about 1.7 to about 0.85 in average by the application of the static magnetic field up to 0.19 T.

Even though a slight reduction in the height of vortex in steel making process, more melt can be poured and can expect less inclusion in the ingot. Eventually the suppression of the vortex formation can increase the quality of steel as well as the productivity in continuous casting process.

4. Summary

The vortex formation in emptying ladle with a bottom nozzle can be suppressed by decreasing the tangential flow velocity of melt with two magnetic devices, which were designed to generate static magnetic field perpendicular to the tangential flow through the side and the bottom of ladle. The magnetic flux densities of the PM device and the EM device were calculated and compared with the measured one. The velocity profile of melt was also calculated with the momentum equation under several assumptions. The induced force in melt was also calculated with both the magnetic flux density and the velocity. The comparison of the vortex formation heights of the EM device with that of the PM device shows a similar tendency. As the magnetic field increases, the vortex formation height decreases. The dimensionless vortex formation height decreased from about 1.7 without magnetic field to about 0.85 with magnetic field in both devices. Even with a small magnetic field of 0.05 T, the vortex formation can be suppressed significantly. Therefore, it is thought that an entrainment of slags into the continuous casting mold can be reduced by the suppression of the vortex in ladle with static magnetic devices.

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