Control of Teeming Rate of Steel by Rotary Type Electromagnetic Stirrer

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In continuous casting of steel, control of the teeming rate of steel from the tundish to the mold is carried out by changing the cross-sectional area of the flow channel by means of a stopper or slide gate. However, nozzle clogging or air suction occasionally occur in the controlled section, and this interferes with the degree of control of the teeming rate of steel or deteriorates the cleanliness of the steel.

To improve this conventional method, some methods using a linear motor-type electromagnetic stirrer were proposed or tested, though, these methods are not yet practicable because of the difficulty of using a linear motor-type stirrer for control of the teeming rate of steel. In contrast, a rotary type stirrer is considered to be more suitable to the control of the teeming rate of molten steel, because a higher intensity of stirring can be obtained through shorter affected zone by the rotary-type stirrer than by a linear motor-stirrer.

On the basis of this idea, an electromagnetic valve using rotary-type stirrer was devised, and a series of experiments using low melting-temperature metal and molten steel were carried out to investigate the characteristics of the control and to improve the design of the electromagnetic valve. By increasing the rotational speed, the flow rate was reduced to about half of that of non-stirring when the depth of the molten steel in the tundish is 500 mm. The response of control was quick enough to apply it to steel or another high melting-temperature metal teeming as a non-contact control method.

KEY WORDS: electromagnetic stirring; continuous casting; rotary type stirrer; teeming of steel; tundish nozzle; electromagnetic valve.

1. Introduction

In continuous casting of steel, control of the teeming rate of steel from the tundish to the mold is carried out by changing the cross-sectional area of the flow channel by means of a stopper or a slide gate. However, some problems remain with these control methods such as clogging of the nozzle by alumina deposits or air suction through the gap of the sliding refractories. Because of these occurrences, the control of the teeming rate of steel is hindered, or inclusions in the steel increase. Although these methods are continually improved, these problems of control in the conventional methods seem to be difficult to solve.

Some other methods using electromagnetic force have been proposed and tested. By these methods an electromagnetic pump or a linear motor-type stirrer are used. However, these methods are not yet practicable because they offer insufficient strength or they cause clogging in the long, thin refractory channel. It is felt that these difficult problems might be solved by using rotary-type stirrer instead of linear motor-type stirrer, because a more intense stirring flow in the shorter affected zone is obtained by a rotary-type stirrer than by a linear motor-type stirrer.

Therefore, a new electromagnetic valve (EMV) with a rotary-type stirrer was devised for the control of the teeming rate of steel, and a series of experiments were carried out to investigate the effectiveness of the EMV. The experiments were started from a model experiment using low-temperature metal. These were followed by tests of molten steel, and then finally the experimental EMV was scaled up to practical size. This report details the development of the EMV through a series of experiments with special attention to the effectiveness of teeming control by the EMV.

2. Basic Idea

To decrease the flow rate from the tundish, an electromagnetic valve using a rotary-type stirrer shown in Fig. 1 was devised. The electromagnetic valve is composed of a disk-like refractory vessel and a rotary-type stirrer. In the refractory vessel, there are an upper eccentric bore and a lower centered bore. The upper eccentric bore is connected to the tundish nozzle and the center bore is connected to the nozzle submerged into the mold.

By means of rotation, the pressure on the liquid near the periphery increases, with the result that, in an open vessel, a parabolic liquid surface is formed in conformity with the pressure distribution. In contrast, in a closed vessel, the increased pressure acts on the upper layer of liquid through the eccentric bore. As a result, the apparent head in the tundish is reduced in accordance with the increase of pressure in the vessel. Thus, the flow rate can be controlled by adjusting the rotating velocity of the liquid in the vessel.
With this controlling method, it is not necessary to adjust the width of the flow channel mechanically. Therefore, nozzle clogging is prevented. The suction of air is also prevented as long as the refractory vessel is connected tightly to the bottom of the tundish.

3. Model Experiment

3.1. Experimental Method

An experimental apparatus, shown in Fig. 2, was made to investigate the characteristics of flow control with the EMV. Wood’s metal (Melting point: 47°C) was used in this experiment. The vessel was made of stainless steel to decrease the attenuation of magnetic flux, and hot water (60°C) was circulated in the vessel to keep the Wood’s metal liquid. As the rotary-type stirrer, a three-phase two-pole induction motor (7.5 kW) was used after removing the rotor. Under the EMV, a pot was set on the load cell, and the flow rate was measured by the weight change of the teemed metal. The diameter of the eccentric bore is 20 mm, and the diameter of nozzle is 14 mm.

3.2. Experimental Results

In this experiment, 35 kg Wood’s metal was used. In Fig. 3, the evolution over time of the weight of the teemed Wood’s metal is shown, as the stirring strength is changed. With the increase in stirring strength, the weight change of the Wood’s metal becomes less dramatic, and the effect of the EMV is recognizable. Fig. 4 shows the change in the teeming stream caused by the EMV. In the non-stirred case, the teeming stream is straight, though it is distorted to an umbrella-like shape by the centrifugal force of the rotation.

The gradients of the curves in Fig. 3 show the flow rate, and the flow rate at 10 kg teeming was adopted as representative, because of the stable weight changes obtained around 10 kg teeming. In Fig. 5, the flow rate after teeming 10 kg wood metal is shown in rela-
tion to the stirring strength. There is almost no change in teeming rate between 0 and 10 V, though the teeming rate is reduced rapidly with the increase of stirring strength over 20 V. The flow rate at 50 V is reduced to about half of that at 0 V.

In order to use this EMV for the control of teeming, a quick response in the flow rate is also required. In Fig. 6, the changes of flow rate are shown when the stirring was started suddenly on the intensities of 30 and 40 V. In the figure, the switching-on points are shown by arrows. The change of flow rate was obtained just after the switching on, therefore, the response brought about by the EMV is considered to be quick enough for practical use. On the other hand, delays in the flow rate change were observed when the stirring force was quickly reduced. Since the delays are due to the inertia of rotation, it was felt that a short reverse rotation before reducing the stirring force would be effective in shortening the delay.

When the molten metal is rotated with the angular velocity \( \omega \) in the cylindrical vessel, the metal rises along the wall and forms the parabolic surface. The rise of liquid \( H \) from the bottom of the parabolic surface is given by Eq. (1):

\[
H = \frac{\omega^2 R^2}{2g} = \frac{v^2}{2g} \tag{1}
\]

where, \( R \): Half the diameter of vessel (3.6 cm).

Therefore, the flow velocity is obtained by measuring \( H \). In Table 1, the rise of the liquid is shown when the Wood's metal is rotated in an open cylindrical vessel of the same diameter as that of the EMV. The rotating velocity is mathematically calculated from Eq. (1). However, the surface of the rotating liquid is distorted at the periphery by the friction between the liquid and the wall. As a result, the rise of the liquid is less than that would otherwise occur. The difference between the theoretical and measured values is known to increase with the increase of the Reynolds number \( (Re) \). In Fig. 7, the ratio of measured value \( (h_m) \) to theoretical value \( (h_p) \) by Akimoto et al. is shown in relation to \( Re \). Here, \( h_m \) and \( h_p \) are the heights from the liquid surface when the liquid is at rest.

The density of Wood's metal is 8.80 and the viscosity was assumed as 0.057 poise. Hence, the Reynolds number is calculated for the angular velocity.

Table 1. Stirring intensity, rise of liquid and rotating velocity.

| Stirring intensity (V) | 10 | 20 | 30 | 40 | 50 |
|-----------------------|----|----|----|----|----|
| \( H \) (cm)          | 2.8| 8.4| 13.1|17.0|18.4|
| \( h_m \) (cm)        | 0.8| 2.3| 4.4 | 6.1 | 6.5 |
| \( \omega \) (rad/s)  | 22.2|36.1|51.7|61.2|63.9|

Here, half the diameter of the cylindrical vessel is used as the characteristic length, and the velocity of Wood's metal at the periphery is used to calculate the Reynolds number, assuming that the velocity at the periphery is the product of half the diameter and the angular velocity. From the Reynolds number, Fig. 7 and Eq. (1), \( h_m \) and \( h_p \) are obtained in relation to angular velocity as shown in Fig. 8. The measured height \( h_m \) is about half of the theoretical height \( h_p \), and it shows the friction between the liquid and the wall much influences the shape of meniscus. From Fig. 8 and the measured height \( h_m \), the angular velocity \( \omega \) is obtained and shown in Table 1.

In Fig. 9, the relation between angular velocity and flow rate is shown. The relation between angular velocity and theoretical flow rate \( (Q) \) calculated from Eq. (2) is also shown in Fig. 8.

\[
Q = \frac{\pi r^4 \rho \sqrt{2gH - \omega^2 R^2}}{2} \tag{2}
\]

where, \( g \): Acceleration of gravity (980 cm/s²)

\( H \): Head of liquid metal (31.4 cm)

\( Q \): Flow rate (g/s)

\( r \): Half diameter of nozzle (0.7 cm)

\( \rho \): Density of wood metal (8.8 g/cm³)

\( \omega \): Angular velocity (rad/s).

As shown in Fig. 9, the flow rate is not influenced by the stirring at the low stirring velocity of 22.2 rad/s, and it is reduced rapidly over 36.1 rad/s. This is considered to be due to the disturbance of rotation by the vertical flow under low velocity stirring. In contrast, the flow rate is reduced by the high velocity rotation because under high intensity stirring, the
rotation of the liquid is less influenced by the vertical flow. The difference between the theoretical and the measured flow rates is considered to be due to the friction of the flow. Moreover, it is estimated that the flow rate can be reduced to 0 at the rotating velocity of 70 rad/s.

4. Experiment Using 200 kg of Molten Steel

4.1. Experimental Method

Based on the model experiment, an experimental EMV was made as shown in Fig. 10. The apparatus is composed of upper and lower refractory vessels, a stainless steel case and a rotary-type stirrer. The diameter of the eccentric bore between the upper and lower vessels is 30 mm, and the diameter of the nozzle at the bottom of the lower vessel is 20 mm. The refractory of the vessel is made of chamotte. The specifications of the stirrer are shown in Table 2. 200 kg steel of 0.6% C was melted in the induction furnace and poured into the upper refractory vessel. Fig. 11 shows the teeming into the EMV. After pouring the steel and filling the upper and lower vessels, the stirring was started. The weight of the molten steel teemed into the pot was measured by load cell, and from the change of the weight the flow rate of the molten steel was obtained.

During the experiment, an improved EMV was devised as shown in Fig. 12. This new type of EMV was found to be superior in the control of the teeming stream at lower stirring intensity. In addition, the number of refractory parts in the new type EMV is smaller so that the construction of the EMV is easier than the former type. In the new type of EMV, there is no eccentric bore between the upper and lower vessels, and the gap between the stopper and the periphery of the lower vessel is used instead of the eccentric bore. The stopper was fixed and a gap of 36 mm was held during the experiment. Moreover, the stopper can be used to stop the teeming immediately if some trouble should happen in the teeming operation.

4.2. Experimental Results

The experimental results are shown in Fig. 13. In this experiment, it was difficult to keep the head in the upper vessel constant, so that the flow rates at various stirring intensities had to be confirmed by repeating the experiment. As shown in Fig. 13, the difference with flow rate is small between the experiments. The difference in flow rates between the two types of the EMV is due to the difference in the head in the upper vessel because the time necessary to fill up the lower vessel is longer with the former type than

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**Table 2. Specification of rotary-type stirrer.**

| Item          | Specification            |
|---------------|--------------------------|
| Size          | Outer diameter: 500 mm   |
|               | Inner diameter: 280 mm   |
|               | Height: 300 mm           |
| Coil current  | 400 A (max.)            |
| Pole          | 2                        |
| Phase         | 2                        |
| Frequency     | 60 Hz                    |
| Magnetic flux density | 33 mT (max.) |
be as follows: in the former type of EMV, the downward flow from the eccentric bore disturbs the rotating flow especially at lower stirring intensities, and as a result, the velocity of the rotating flow is lowered. In contrast, the downward velocity of the new type of EMV is smaller than that of the former type, since the downward flow occurs evenly along the periphery in the new EMV. Therefore, with the new type of EMV, the flow rate change occurs even at low stirring intensities.

5. Experiment Using 2 t of Molten Steel

5.1. Experimental Method

Following the experiment with 200 kg of molten steel, an experiment using 2 t of molten steel was carried out. The experimental apparatus used is shown in Fig. 14. The top inner width of the tundish was 829 mm × 829 mm, and the inner depth was 1100 mm. The depth of the 2 t of molten steel from the bottom of the tundish was 725 mm. In the tundish, a stopper used in the conventional slab caster was attached, and the large bore tundish nozzle is settled on the refractory vessel of the EMV. The inner diameter of the tundish nozzle was 150 mm. The new type of EMV was installed at the bottom of the tundish. The stirrer and the refractory vessel were the same ones used in the 200 kg molten steel experiment, though in this case the refractory vessel was made of alumina graphite. Below the tundish, a refractory pot and a load cell were settled, and the flow rate was measured by the load cell. In Fig. 15, the experimental apparatus is shown.

2 t of molten steel with 0.6 % C content was prepared in a high frequency induction furnace, and poured in the tundish using a small ladle. The stopper was shut during the pouring from the ladle, and opened after pouring. The gap between the stopper and the large bore tundish nozzle was maintained at 36 mm during the experiment. The stirring was carried out just after opening the stopper.

5.2. Experimental Results

In Fig. 16, the relation between the time and the weight of teemed molten steel is shown as stirring intensity is changed. The pouring time increases, as the stirring intensity is increased, and the effect of the EMV is recognizable. In Fig. 17, the relations between electrical current and flow rate are shown when the heights of molten steel in the tundish is 450 or 250 mm, the residual molten steel amounts of which correspond to 1.2 and 0.6 t, respectively.

The flow rate \( Q \) is calculated mathematically by Eq. (2). However, the flow rate is somewhat reduced by the friction between the molten steel and the refractory. In Fig. 18, the flow rate without stirring is shown referring to the theoretically calculated flow rate \( Q_1 \):

\[
Q_1 = A \sqrt{2gH}
\]

(3)

where, \( A = \pi r_0^2 = 3.14 \times 10^4 \times 7 \times 200 \text{ kg/m} \) ......... (4)

The broken line shows the relation in case of non-

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Fig. 11. Teeming of 200 kg molten steel.

Fig. 12. Improved EMV for 200 kg steel experiment.

Fig. 13. Relation between electrical current and flow rate of molten steel.
To know the efficiency of the EMV, it is necessary to confirm how much rotating velocity is obtained. The rotating velocity \( V \) is obtained from Eq. (2), revised as follows:

\[
V = \sqrt{2gH - (Q/fA)^2} \quad \text{.........(5)}
\]

In Fig. 19, the relation between current and flow rate is shown, as calculated from Eq. (5). The maximum rotating velocity is estimated at about 4.0 m/s. As the rotating velocities are little influenced by the head of the molten steel, \( V \) is shown approximately in Eq. (6):

\[
V = 0.014I - 1.65 \quad \text{.........(6)}
\]

where, \( I \): Electrical current of stirrer (A).

From Eqs. (5) and (6), an empirical equation (7) is obtained to show the efficiency of the EMV.

\[
Q = 2.26 \times \sqrt{2gH - (0.014I - 1.65)^2} \quad \text{.........(7)}
\]

In Fig. 20, the flow rates calculated from Eq. (7) are shown in relation to the head of the molten steel compared with the measured values. The heads are estimated from the difference between poured steel weight and the weight of teemed steel in the pot. The calculated flow rates almost correspond to the
measured values. From Fig. 20 the flow rate of 11.3 kg/s without stirring can be reduced to 7.6 kg/s by applying 400 A stirring even when the height of the molten steel from the bottom of the tundish is 800 mm.

For the high stirring intensity of 400 A, the flow rate is considered to become 0 even though some molten steel remains in the tundish. However, some steel leaked out through the nozzle little by little, and it was therefore, impossible to stop the molten steel flow without the help of a stopper.

In Fig. 21, the decrease of the flow rate is shown when the stirring is started instantaneously. The flow rate was rapidly reduced to about half the rate that occurs without stirring. In Fig. 22, the increase of the flow rate is shown when the stirring is suddenly reduced. In this case, the reverse stirring of 400 A for 1 s was carried out just before reducing the stirring intensity. In both cases, it was confirmed that the EMV has quick controllability.

6. Summary and Conclusion

A new electromagnetic valve using a rotary-type stirrer was devised. This EMV is considered to be superior to that using a linear motor-type stirrer, especially for the teeming of high melting-temperature metal because intense stirring is easily obtained in the short stirring path in the EMV using a rotary-type stirrer.

The control behavior of the EMV was investigated through a series of upscale experiments. From the results, it was confirmed that the EMV has a wide range of flow rate control and a quick response to flow rate change. The flow rate with maximum intensity stirring can be reduced to 68–50% of the non-stirred steel flow rate when the height of the molten steel in the tundish is 800–500 mm.

The response to flow rate change is within 1 s, and it is quick enough to control the teeming rate of steel from the c.c. tundish. When the flow rate is increased, the short time reverse stirring is found to be very effective in suppressing the motion of the liquid metal by inertia, and increasing the flow rate instantaneously.

In the new EMV a stopper is used, though a sizable gap can be maintained between the stopper and the tundish nozzle because the stopper is not used to control the flow. Therefore, nozzle clogging, which is one of the main problems of conventional control devices, can be suppressed. The new EMV is considered suitable for controlling the teeming stream of steel from the tundish during continuous casting, and it is expected to be applied widely.

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