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Steel Structure, and Continuous Casting of Steel

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The body can be viewed from the next page.

Control of Molten Steel Flow in Continuous Casting Mold by Two Static Magnetic Fields Covering Whole Width*



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A new device, FC mold (flow control mold), was developed to improve the quality of final products, cast at a high speed. It has two pairs of poles that generate static magnetic fields. In order to optimize steel flow in a continuous casting mold, one of the fields imposed is at the meniscus and the other is below the submerged entry nozzle (SEN). Both of the fields cover the entire width of the mold. The principle and effects of this device were confirmed through mercury model experiment, industrial application to the No. 3 caster at Chiba Works and numerical simulations. The industrial application demonstrated good effects on the surface and internal qualities of the products. Kawasaki Steel has already introduced the FC molds for industrial production at the No. 4 caster in Mizushima as well as the No. 3 caster in Chiba. They are contributing to high productivity and high product quality.

1 Introduction

In continuous casting operations, both high productivity and high product quality are increasingly required. An increase in the rate of casting is a precondition for securing high productivity, but casting powder entrapment also tends to increase in high-speed casting, resulting in deterioration of the quality of cast slabs. For this reason, how to improve cast slab quality in high-speed, high-throughput casting is an important question.

An critical factor which determines the quality of cast slabs is the flow of molten metal in the mold of the continuous casting machine (CCM). The internal flow in the mold dominates the flotation separation of inclusions and deoxidation products of external origin which are carried into the mold, as well as gas bubble separation. On the other hand, the flow at the interface between the molten steel and powder dominates the powder entrapment and the absorption of inclusions into the powder layer. Control of both types of flow in the mold is therefore a necessary task for the improvement of cast slab quality.

Techniques for controlling the flow of molten steel in the CCM mold include (1) the shape of the submerged entry nozzle, or SEN,[1] (2) control of the molten steel surface,[2] (3) the use of a mobile magnetic field[3], and others. Kawasaki Steel has also developed a flow control technology for molten steel in the mold called the EMBR, or electromagnetic brake, using a static magnetic field[4], and has confirmed its effectiveness.[5]

Nevertheless, because the conventional type of EMBR was developed on the basis of the curved type continuous caster, there were problems in applying it in its existing form to the vertical bending type CCM, which is capable of relatively high throughput. As reported in the following, a new electromagnetic flow control technology was therefore developed for use in high-throughput casting[6-9].

2 Mercury Model Experiments

2.1 Experimental Apparatus and Method

First, in order to investigate the macro flow, the flow velocity was measured in mercury model experiments. An outline of the experimental apparatus is shown in **Fig. 1**. A mercury pump is attached to the apparatus, and the measurements are made while causing a circulating flow of mercury.

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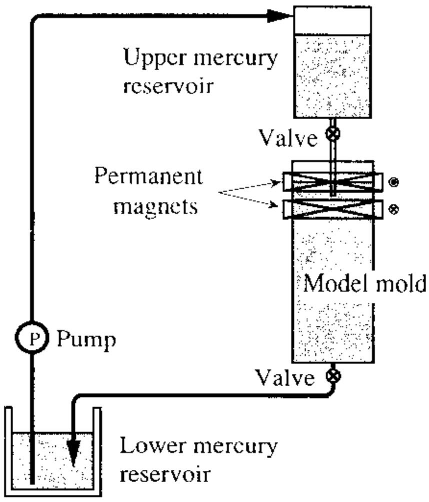

Fig. 1 Experimental apparatus for the mercury model

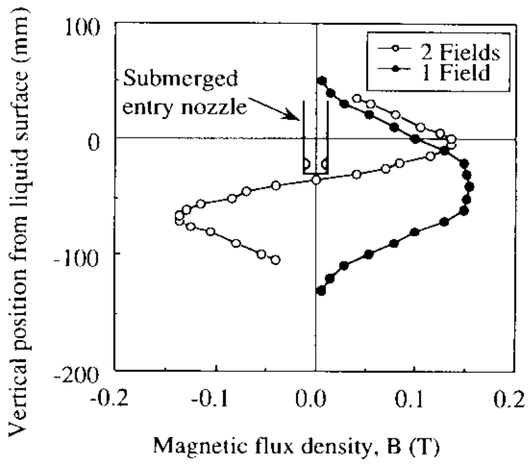

Fig. 2 Distributions of magnetic flux density used for mercury model experiments

The model mold was fabricated from vinyl chloride on a scale of 1/10 the size of the actual equipment Chiba Works No. 3 CCM). The model was 26 mm thick, 120 mm wide, and approximately 500 mm long in the casting direction. The nozzle was a two-port type, and was submerged approximately 30 mm. The discharge ports were 6 mmϕ in diameter, and were inclined downward at an angle of about 30°.

A small electromagnetic flow meter was fabricated for measurement of the mercury flow velocity.[10,11] This device was immersed in the mercury bath and used to measure the vertical direction component of the flow velocity.

2.2 Experimental Conditions

The setting of the flow velocity was performed under uniform conditions of the Froude number ($= V^2/gL$, where V: representative flow velocity, L: representative length, g: acceleration due to gravity). A value of 34 ml was adopted, corresponding to production of 4.5 t/min in an actual machine. The experiments were conducted using two distributions of the imposed magnetic fields, i.e. with one pair and two pairs of magnetic poles, as shown in **Fig. 2**, by employing appropriate combinations of permanent magnets. The flow velocity measurements were conducted at the center of the mold thickness, at depths of 50 mm, 150 mm, and 250 mm below the meniscus.

2.3 Experimental Results

The results of the flow velocity measurements are shown in **Fig. 3**. When no magnetic field was imposed, a sharp peak was observed at $z = 50$ mm at a point 40 mm from the mold center. This peak represents the discharge flow from the nozzle, which becomes weaker when a magnetic field is applied. On the other hand, an upward flow was seen at the mold center in all cases, but its flow velocity was the greatest with the one-stage magnetic field.

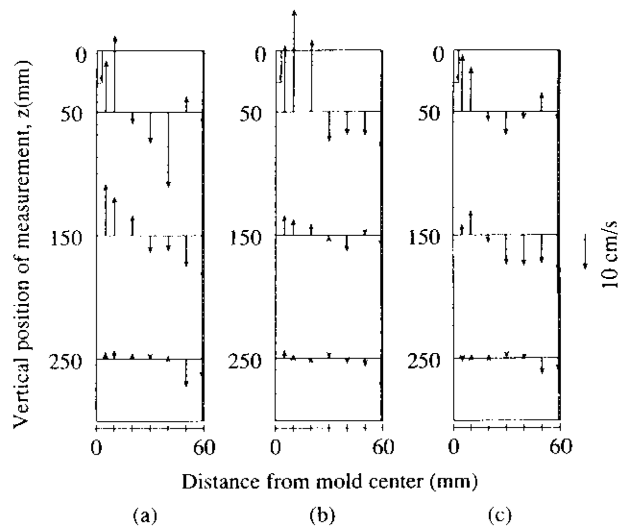

Fig. 3 Profiles of downward flow velocity in the mercury measured by Vivès probe: (a) without magnetic field, (b) with 1 pair of magnetic poles and (c) with 2 pairs of magnetic poles

At $z = 150$ mm, when no magnetic field was imposed, a downward flow was observed at the narrow faces and an upward flow at the mold center. However, the flow showed a tendency to become more uniform when a magnetic field was imposed.

At $z = 250$ mm, a strong downward flow remained when no magnetic field was imposed, but was reduced by a magnetic field. In comparison with the case of no magnetic field, the downward flow velocity was reduced by approximately 1/2 when two magnetic fields were applied.

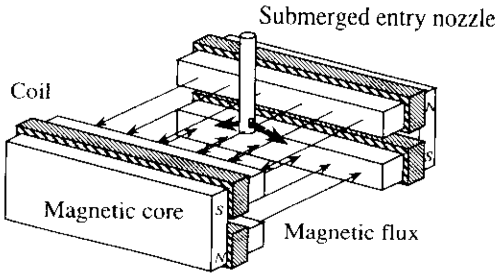

Fig. 4 Schematic illustration of the FC mold

Table 1 The specifications of the FC mold applied to the No. 3 caster at Chiba Works

Width of magnet yoke	(mm)	1 500
Distance from yoke to yoke	(mm)	450
Maximum voltage	(V)	250
Maximum current	(A)	1 200
Maximum magnetic flux density	(T)	0.28

3 Plant Experiments

3.1 Outline of Equipment

The new electromagnetic flow control technology for high-throughput continuous casting is required to be effective in suppressing both the flow velocity at the molten steel surface in the mold and the downward flow velocity in the lower part of the mold. From this viewpoint and the results of the mercury model experiments, a two-field, full-width design was adopted and used in plant experiments at Chiba Works No. 3 CCM. This flow control device is called the FC mold (flow control mold). **Figure 4** shows a schematic illustration of the FC mold. In conventional EMBRs, braking is applied to the discharge flow from the nozzle with the aim of dispersing the flow. In contrast, to secure an adequate braking effect, the FC mold is characterized by two static magnetic fields imposed across the entire width of the mold by upper and lower pairs of poles, with the aims of reducing the molten steel flow velocity at the meniscus and reducing the local downward flow velocity in the lower part of the mold. The specifications of the FC mold as fabricated are given in **Table 1**. At a maximum coil current of 1 200 A, the device produces a static magnetic field with a maximum magnetic flux density of 0.28T.

In the plant experiments, an SEN with four ports having downward angles of 15° was used. The nozzle was immersed at depths of 180 to 230 mm (distance from the meniscus to the top edge of the top ports). The casting speed was varied in the range of 1.0 to 2.0 m/min and slabs 260 mm in thickness and 1 000 to 1 400 mm in width were cast. The object steel grades were low carbon steel and ultra-low carbon steel.

3.2 Operational Results of FC Mold

To investigate the effectiveness of the upper pair of magnetic poles of the FC mold in reducing and stabilizing the molten steel flow velocity at the meniscus, the flow velocity of the molten steel surface was measured. The casting conditions were slab width, 1 200 mm and casting speed, 1.6 m/min; the cast product was low carbon steel. To measure the flow velocity, a rectangular body (25 mm × 20 mm) of refractory (ceramic) material was immersed in the molten steel in the mold to a depth of 130 mm, and the dynamic pressure of the steel was measured with a strain gauge. The unmodified strain gauge output is shown in **Fig. 5**(a) for magnetic flux densities of 0T and 0.28T. From these results, the average output was reduced approximately to 2/3 by applying a magnetic field. As a further characteristic, the value of output fluctuations was also reduced to about 1/3 when the magnetic field was imposed. Figure 5(b) shows the results when the maximum magnetic flux density on the abscissa and the stain gauge output on the ordinate are converted to flow velocity, taking the flow velocity at 0T as 1. When a magnetic flux density of

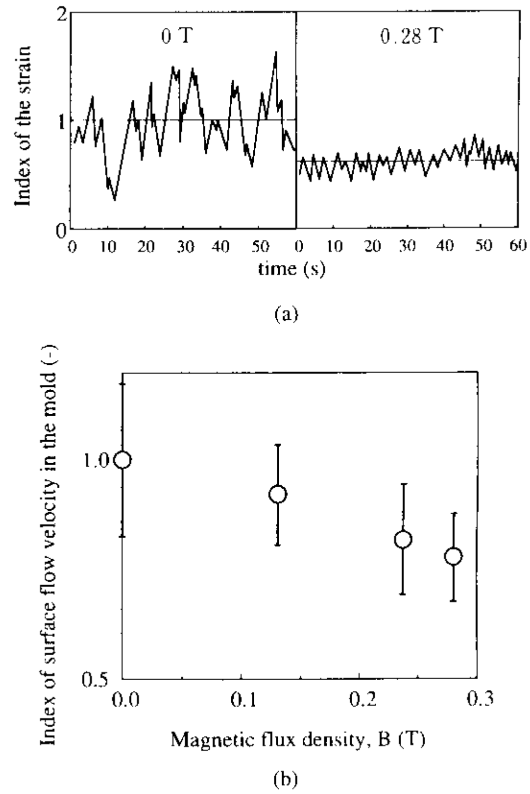

Fig. 5 The effect of the FC mold on the molten steel flow below the meniscus: (a) force exerted by the fluid on the ceramic body with a strain gauge, (b) calibrated velocity as a function of magnetic flux density

0.28T is imposed, the average flow velocity was reduced to 78% and fluctuations decreased to 43%.

Moreover, precisely the same results were obtained for the flow velocity of the molten steel surface by measuring the height of the swelling of the melt surface at the narrow faces (side walls).

Next, changes in the temperature of the molten steel at the meniscus due to the imposed magnetic field were investigated by immersing thermocouples to a depth of 30 mm below the surface of the steel in the mold and measuring the temperature. The casting conditions were the same as when the surface flow velocity was measured. The temperature measurement results are shown in **Fig. 6**, where the open circles indicate temperature change near the submerged entry nozzle and the black circles show changes about 100 mm from the side wall. The temperature of the molten steel at the meniscus rose by 3–5°C both near the SEN and near the side wall, which the authors attribute to the braking effect of the lower pair of poles of the FC mold. Specifically, the lower pair of poles brakes the molten steel streaming from the nozzle and thus suppresses its penetration to the deeper part of the mold, causing high-temperature molten steel to remain near the meniscus.

As described above, the effect of the upper pair of poles of the FC mold in reducing the flow velocity at the molten steel surface and the effect of the lower poles in reducing the penetration depth of the molten steel have been confirmed both directly and indirectly. Moreover, this experiment also made it clear for the first time that the upper poles are remarkably effective in suppressing fluctuations of the flow velocity at the molten steel surface.

3.3 Effect of FC Mold on Cast Slab Quality

The results of a measurement of the pitch of the oscillation marks on the surface of the slab cast described in the previous section are shown in **Fig. 7**. Samples 10 mm wide and 150 mm long were cut from the center of

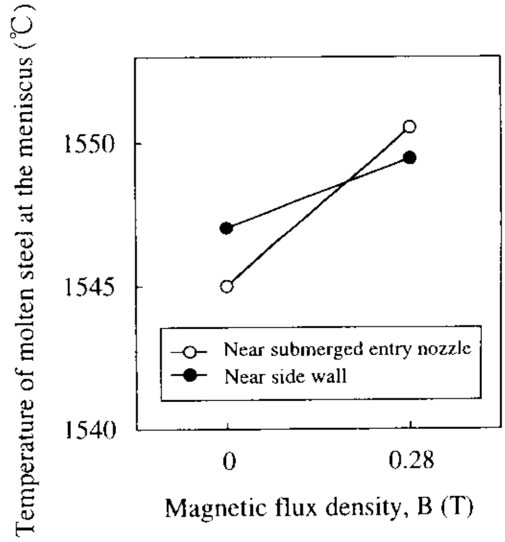

Fig. 6 The effect of the FC mold on the temperature of the molten steel at the meniscus in the mold

the narrow face of the slab and measured with a differential transformer. The average value of the pitch of the oscillation marks was the same as the value calculated from the casting speed and mold oscillation frequency, but it was found that variations in pitch became extremely small when the FC mold was used. This finding is attributed to the fact that the upper poles reduce the fluctuation of the level of the molten steel surface, which results in a more uniform arrangement of the oscillation marks.

The results of a measurement of the amount of inclusions extracted by the slime method from the same slab are shown in **Fig. 8**. The ordinate represents the index of inclusions per volumetric unit of the slab; the abscissa shows the magnetic flux density. The amount of inclu-

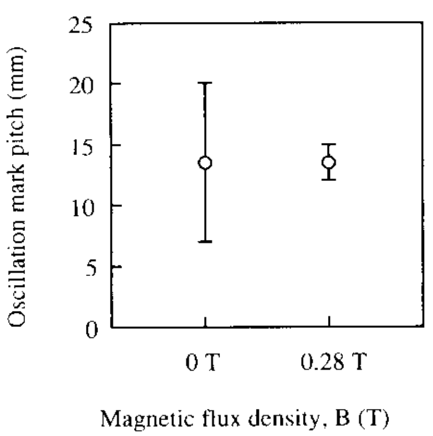

Fig. 7 The effect of the FC mold on the pitch of oscillation mark

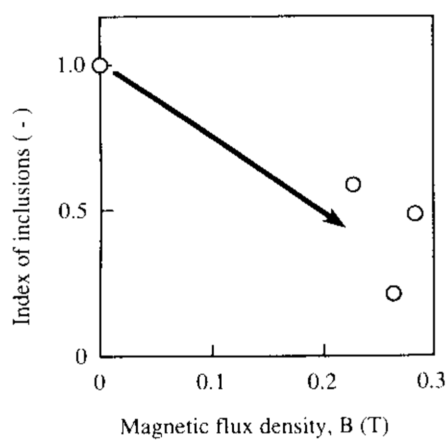

Fig. 8 Index of non-metallic inclusions extracted by slime method as a function of magnetic flux density of the FC mold

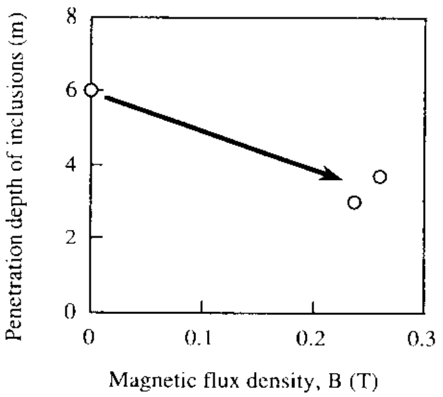

Fig. 9 The effect of the FC mold on the penetration depth of non-metallic inclusions

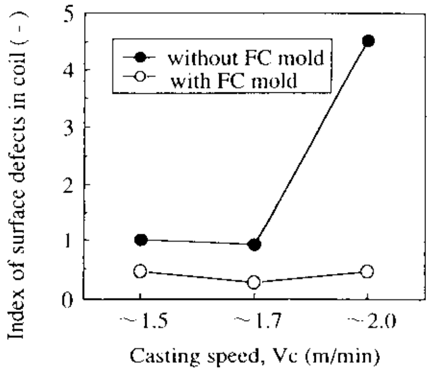

Fig. 10 The effect of the FC mold on the surface quality of the cold rolled coils of steel

sions was reduced to approximately 50% by imposing a static magnetic field. The following relational equations were obtained for the maximum penetration depth of the inclusions, H_p and the position of the inclusion accumulation zone in the slab, T_{max}.[12)]

$$H_p = \frac{4\xi(\alpha^2 L\xi^3 - \alpha L\xi - R/2)}{3\alpha\xi^2 - 1} + \alpha L\xi^2 \quad \cdots\cdots (1)$$

$$\alpha = \frac{V_C L}{k^2},\ \xi = \frac{T_{max}}{L} \quad \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

Here, V_C is the casting speed (m/min), L, the length of the vertical section of the caster (m), R, the bend radius of the bending section of the caster (m), and k, the solidification coefficient (m/min$^{1/2}$).

From the results of a sulfur print investigation of the C cross-section of the slab position of T_{max} decreased from 43 mm to 37 mm using FC mold. Values of H_p obtained by the substitution of the result to the above equations are shown in **Fig. 9**. The depth of inclusion penetration was reduced to approximately 2/3 to 1/2 by imposing a static magnetic field. This reduction in the depth of inclusions, together with the previously mentioned reduction in the amount of inclusions, is a direct indication of the braking effect of the lower magnetic poles on the downward flow of molten steel.

3.4 Effect of FC Mold on Product Quality

This section presents the quality results when products are produced by cold rolling after hot rolling of cast slabs.

Figure 10 is a diagram showing the number of surface defects detected in visual inspection of ultra-low carbon steel sheets for automotive use at the inspection line, plotted against the casting speed on the abscissa. When the FC mold is not used, the occurrence rate of surface defects increases sharply if the casting speed exceeds 1.7 m/min, rising to more than five times the level when the casting speed is held to 1.5 m/min or under. On the other hand, when the FC mold is used, the rate of surface defects was less than half that when the FC mold was not used, and was independent of the casting speed. An X-ray analysis of the surface defects found mold powder components. This positive result was considered to be attributable to reduction of the surface flow velocity and reduction of the fluctuations in the level of the melt surface by the upper poles of the FC mold. In addition, this result also shows that even high-speed casting does not cause deterioration of product quality. From the viewpoint of the surface quality of products, it can therefore be said that this technology is an appropriate process for the purpose of achieving high quality combined with high productivity.

Next, the results of an evaluation of the internal quality of tinned steel sheets for use in cans by magnetic particle testing (MT) are shown in **Fig. 11**. The MT defect index decreased as the imposed magnetic flux density increased, falling to less than 1/2 when 0.28T was imposed. This figure shows a close correspondence to the amount of non-metallic inclusions in the cast slab detected by slime extraction in Fig. 8, and is therefore

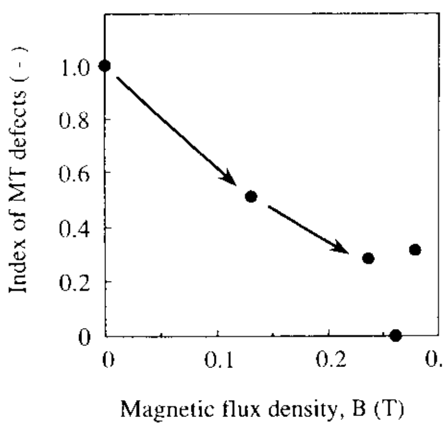

Fig. 11 Index of MT defects in the cold-rolled steel sheets with and without the application of the FC mold

considered to show the effectiveness of the lower poles of the FC mold in reducing the depth of molten steel penetration.

4 Flow Analysis and Discussion

4.1 Analytic Method

To examine the results of the plant experiments, a flow analysis was made by numerical calculation, the conditions of which are shown in **Table 2**. The calculations were made using the finite-domain method as the difference method and a two equation model (k-ε model) as the turbulence model. The submerged entry nozzle was a four-port type with the ports inclined 15° downward, as used in actual equipment, and the immersion depth was 180 mm (depth from meniscus to top of upper discharge ports). The inflow condition used as the boundary conditions were uniform inflow in the nozzle from the upper part of the nozzle and uniform outflow at the extreme lower edge of the calculation region. Other boundary conditions were a slip condition at symmetrical surfaces, the molten steel surface, and the lower edge, and a no-slip condition at other boundary surfaces. The magnetic flux density distribution used in the calculations included the two distributions shown in Fig. 2 (one pair and two pairs of magnetic poles). The effect of the flow of molten steel on the magnetic flux density was so small as to be negligible, and only the thickness direction (x direction) component of the applied magnetic flux density distribution in the mold was considered. The maximum magnetic flux density was fixed at 0.28T. The boundary condition for the calculation of the electrical potential was assumed to be a solidified shell

Table 2 Conditions of numerical calculations

Mold size (mm)	130 (1/2 t) × 600 (1/2 w) × 3 790 (h)
Submerged entry nozzle	With 4 ports inclined at 15° downward
Flow rate (t/min)	4 (V_c = 1.6 m/min)

having the same electrical conductivity as the molten steel outside the no-slip condition (shell growth of 10 mm/m in thickness in the vertical direction was assumed).[13]

4.2 Calculation Results

The flow pattern in the thickness-center cross-section of the slab is shown in **Fig. 12** for the case of (a) no magnetic field, (b) one magnetic field at the meniscus, and (c) two fields arranged top-and-bottom. In the latter cases (b) and (c), in which a magnetic fields were imposed, the figure shows that the flow is suppressed in the lower part of the mold. However, to compare the flow conditions at the near-surface, the flow velocity becomes stronger in (b), when one field is imposed, than in (a), when no magnetic field is imposed. On the other hand, when two fields are imposed in (c), the flow velocity near the surface decreases. This result is qualitatively consistent with the results of the mercury model experiments described in Chapter 2. Because the one-field type is not effective in suppressing the flow near the surface, it would appear that the surface flow becomes stronger in proportion to the flow which is suppressed in the lower part of the mold. In contrast, with the two-field

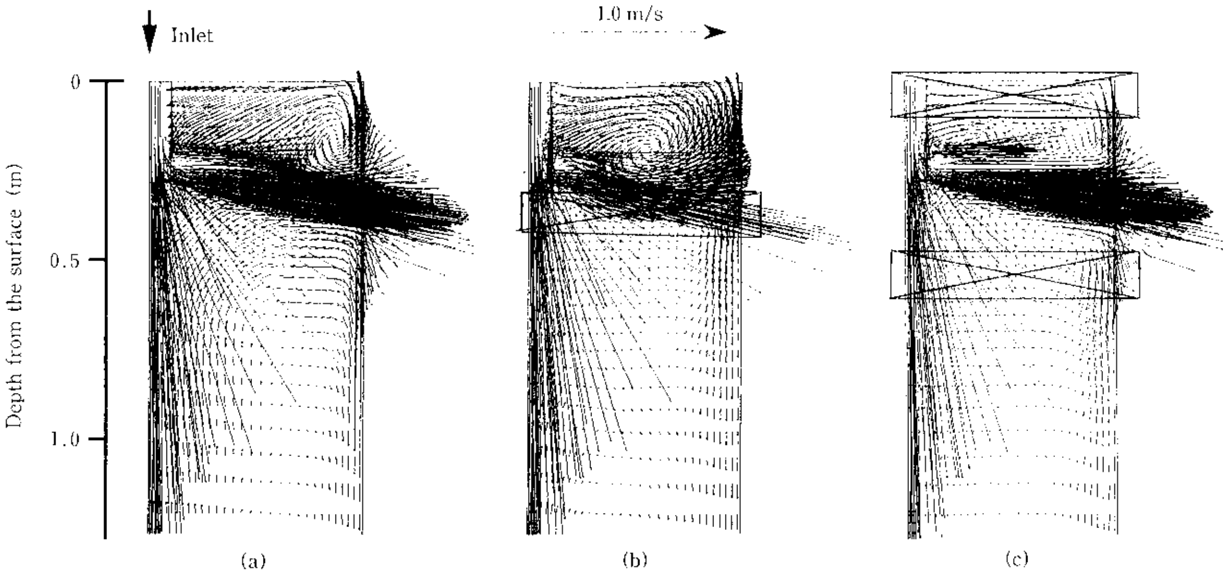

Fig. 12 Calculated velocity patterns of liquid flow in the centerline section of a mold: (a) without magnetic field, (b) with 1 pair of magnetic poles, (c) with 2 pairs of magnetic poles (FC mold)

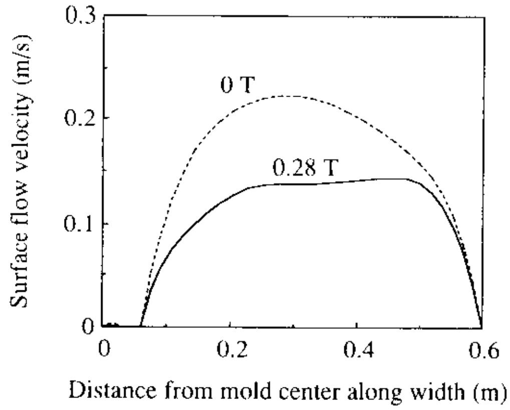

Fig. 13 Distribution of horizontal surface flow velocity at a depth of 40 mm in the center of mold thickness (calculated)

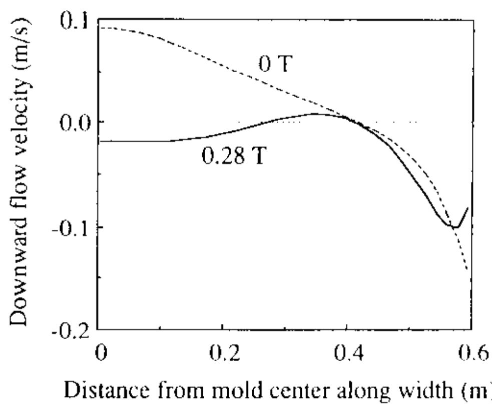

Fig. 14 Distribution of downward flow velocity at a depth of 1 m in the center of mold thickness (calculated)

arrangement, it is possible to suppress this kind of back flow when the downward flow is controlled by the lower magnetic poles.

4.3 Comparison with Plant Experiments

In this section, the calculated results for the two-field device (FC mold) are compared with the results of the plant experiments described in Chapter 3. **Figure 13** shows the calculated results of the transverse distribution of the horizontal flow velocity 40 mm below the surface (2nd mesh). The broken line shows the case when a magnetic field is not impressed; the solid line is the case when a 0.28T field is applied. At 0T, the maximum flow velocity is 0.23 m/s, but this falls to 0.15 m/s at 0.28T, for a velocity reduction of approximately 65%. Although this value is slightly different from that in the flow velocity measurements in Fig. 5, from the viewpoint of measurement accuracy, it may be said that sufficient agreement was obtained.

Next, we will attempt to consider semi-quantitatively the penetration depth of inclusions based on the results of numerical calculations. **Figure 14** shows the results of a calculation of the downward flow velocity distribution at a point 1 m below the surface. The maximum downward flow velocity is reduced from 0.15 m/s to 0.10 m/s by imposing a 0.28T magnetic field. In all cases, the maximum value is near the narrow faces. Here, the downward flow at the narrow faces is considered to be a two-dimensional wall-surface jet stream. Although the discharge flow from the SEN is actually a three-dimensional free jet, this description is adopted because it is considered that the jet stream spreads adequately before striking the narrow faces, is "sandwiched" between the two wide faces, and then cannot spread further. The maximum velocity of the two-dimensional wall surface jet stream is proportional to the initial velocity of the jet stream and is inversely proportional to the 1/2 power of the distance.[14] To consider the behavior of inclusions carried into the deep part of the mold by the downward flow in the mold, because the downward flow velocity is attenuated in the deep part of the mold in inverse proportion to the 1/2 power of the depth, the downward velocity and the flotation velocity of the inclusions come into balance at a certain position, and deeper penetration is not possible. This depth can be interpreted as the being the maximum penetration depth of inclusions. Accordingly, the maximum depth of inclusions becomes deeper as the downward flow at the narrow faces becomes larger, and is proportional to the square of the initial velocity of the flow. Assuming hypothetically that the initial velocity is equal to the downward velocity 1 m below the surface, then from the results of the downward flow velocity obtained by numerical calculation in Fig. 14, the ratio of the penetration depth is 2.25:1. This result is generally in agreement with the results in Fig. 9 (approximately 1.7:1).

5 Conclusion

In the development of a new electromagnetic flow control technology for the continuous casting mold which is capable of meeting the requirements of high-throughput operation, mercury model experiments were performed for the flow in the mold. As a result, it was found that a two-field, full-width electromagnetic device having one pair of poles at the mold meniscus and a second pair below the submerged entry nozzle ports is more effective in reducing the surface flow velocity at the meniscus and in suppressing the downward flow near the narrow faces of the mold than a one-field full-width type having only one pair of poles. Based on these results, a proof experiment was performed with actual equipment at Kawasaki Steel's Chiba Works No. 3 CCM using a two-field full-width electromagnetic brake (FC mold), confirming the effectiveness of the upper pair of poles in controlling the surface flow of the molten steel and that of the lower pair of poles in suppressing the flow in the lower part of the mold. These effects were also examined by flow analysis using numerical calculation.

At present, the FC mold is in practical operation at Kawasaki Steel's Chiba Works No. 3 CCM and Mizushima Works No. 4 CCM, and has become an indispensable process for achieving high product quality simultaneously with high productivity.

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