NIPPON STEEL TECHNICAL REPORT No. 89 JANUARY 2004

UDC 621 . 318. 4 : 537 . 84

Electromagnetic Coil Designed by Magneto-Hydro-Dynamic-Simulation

Ken YOKOTA*[1] Keisuke FUJISAKI*[1]

Abstract

Linear induction motor type In-Mold Electro-Magnetic Stirrer "M-EMS" is equipped in most of the slab continuous caster in Nippon Steel Corp. to improve slab surface quality by stirring the molten steel flow. To satisfy the customer's permanent demand for high quality steel, the molten steel flow patterns in the casting mold, which reflects on the steel quality deeply, must be clarified and the flow control must be optimized against each casting conditions. Authors are carrying out "Electromagnetic process solution" in the casting field by applying Magneto-Hydro-Dynamic simulation to the molten steel flow process in order to evaluate and clarify quantitatively, and finally to control. In this paper, the established specification designing method using Magneto-Hydro-Dynamic simulation for M-EMS and other electromagnetic coils is shown.

1. Introduction

Nippon Steel developed an In-Mold Electromagnetic Stirrer, hereinafter abbreviated to "M-EMS", a linear induction type motor, to control molten steel flow in the casting mold of a continuous caster, hereinafter abbreviated to CC, in order to improve slab surface quality. The first M-EMS was installed at Hirohata Ironworks in 1980[1-2], and later in 1982, the second machine was installed at Oita Ironworks. After these two cases, Nippon Steel continued improving and equipping the M-EMS to the main CCs in other Ironworks[3-5].

M-EMS aims at giving a uniform flow to the front of the solidified shell of a slab surface throughout the entire width direction in terms of space and time by applying electromagnetic force. It is reported that giving a uniform flow has result in controlling the dispersion of the molten steel temperature distribution, reducing the occurrence of solidification delay and improving the uniformity of the dispersion in shell thickness[6].

To satisfy the customer's permanent demand for high quality steel, however, it is necessary to clarify molten flow patterns in the casting mold, which greatly reflects on steel quality, as well as to control the flow by optimizing the electromagnetic force applied for each casting conditions.

Based on these viewpoints, the authors are carrying out with the "electromagnetic process solution" in the casting field by applying magneto-hydro-dynamic simulation to evaluate and clarify quantitatively the flow patterns in the casting mold, such as the stream from the submerged nozzle and stirred flow by electromagnetic force, in order to control the molten steel flow.

This paper reports on the establishment of the technique of designing molten steel flow control actuators, such as M-EMS and other electromagnetic coils, by the application of magneto-hydro-dynamic simulation.

2. Outline of the In-Mold Electro-Magnetic Stirrer : M-EMS

As **Fig. 1** shows, M-EMS is composed of a pair of induction type linear motors with each mounted opposite to the upper part of the backside of each casting mold. The linear motors move the magnetic fields opposite to each other. More specifically, the direction of the AC phase applied to the copper coils, lined up sidelong, attached to the iron core is controlled. In the molten steel, a new magnetic field is generated as a counter field in the direction of the moving mag-

---

*[1] Environment & Process Technology Center

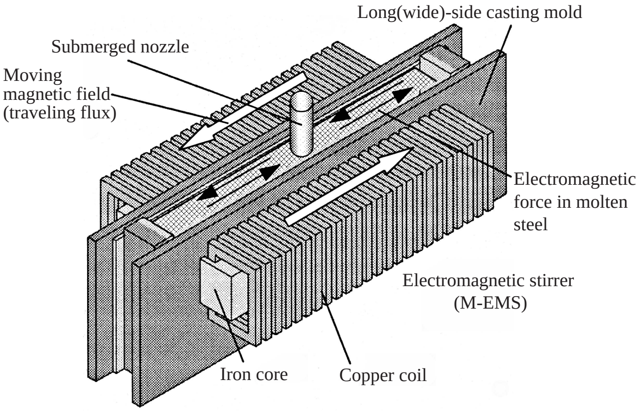


Fig. 1 Schematic diagram of M-EMS

netic field, and another new magnetic field is also generated to retain the moving magnetic field on the opposite side. The generation of a magnetic field accompanies an eddy current, and the outer product of the magnetic field and eddy current vector in the molten steel causes the electromagnetic force generally called Lorentz force. The electromagnetic force vector is distributed circle-wise when viewed above from the molten steel, and in the vicinity of the casting mold wall it works largely in the same direction with the moving magnetic field generated by the controlled coil current. The molten steel is stirred by this force.

The molten steel flow in the casting mold is mainly put under the control of the stream from the submerged nozzle and the electromagnetic force of the M-EMS. The distribution of the nozzle stream depends mostly on the casting conditions, such as casting width and casting rate, and the shape of the nozzle. In the present-day, however, the casting width and rate are varied during casting to enhance productivity in standard CC operation. Therefore the nozzle stream distribution is considered to be varied not only by phenomena, such as nozzle clogging, that tend to occur over the casting time, but also by standard CC operation.

Accordingly, the M-EMS plays a great role as a controllable actuator that gives a stable flow to the front of the solidified shell, the characteristics and specification design as a linear motor becomes important.

3. Technique of Designing M-EMS by the Application of Electro-Magneto-Hydro-Dynamic Simulation

This chapter shows the flowchart of the specification design of M-EMS after summarizing the techniques of hydrodynamic simulation and electromagnetic field analysis that compose magneto hydrodynamic simulation. Note that the explanation of the symbols dealt with in this chapter is described in Section 3.1.3.

3.1 Outline of magneto hydrodynamic simulation technique

In the molten steel stirred by M-EMS, multi physics, such as fluid dynamics, solidification phenomena due to heat transfer and electromagnetic field affect each other in a complicated manner in the mold as short as 1 m. It is not realistic even today when computer technology is making dramatic advancements, however, to simulate coupled multi-physical phenomena in numerical analysis strictly. Therefore, in this paper the molten steel flow and the electromagnetic force affected are taken into consideration in the technique of magneto-hydro-dynamic simulation in terms of controlling the molten steel flow in the casting mold[7].

3.1.1 Fluid dynamic analysis

Fluid dynamic analysis uses the finite difference method for solution, and the continuous equation of flow and Navier-Stokes equation as the basic equation.

$$0 = \nabla \cdot \boldsymbol{U} \qquad (1)$$

$$\frac{\partial \boldsymbol{U}}{\partial t} + \boldsymbol{U} \cdot \nabla \boldsymbol{U} = -\frac{\nabla \boldsymbol{P}}{\rho} + g + \frac{\boldsymbol{F}}{\rho} + \nabla \cdot \nu \nabla \boldsymbol{U} \qquad (2)$$

Molten steel is treated as incompressible (constant density). The electromagnetic force by M-EMS is added to the third member of the right side of equation (2). LES (large eddy simulation) was adopted as a model that enables high accuracy calculation of turbulent flow, an unsteady flow quickly changing over time, mainly to express nozzle stream fluctuation. Simultaneous solution of equations (1) and (2) enables to obtain the flow pattern on which M-EMS-generated electromagnetic force worked.

3.1.2 Electromagnetic field analysis

The basic equation of the electromagnetic field is well known as Maxwell equation[8]. This section shows Maxwell equation and the equation of calculating the electromagnetic force in which variables are reduced by A-ϕ method using the magnetic vector potential instead of treating Maxwell equation directly. References should be referred to concerning the method of derivation[9].

$$\nabla \times \left(\frac{1}{\mu}\right) \nabla \times \boldsymbol{A} + \sigma \left(\frac{\partial \boldsymbol{A}}{\partial t} + \nabla \phi\right) = \boldsymbol{J}_o \qquad (3)$$

$$\boldsymbol{F} = \sigma \left(\frac{\partial \boldsymbol{A}}{\partial t} + \nabla \phi\right) \times (\nabla \times \boldsymbol{A}) \qquad (4)$$

The solution of equation (3) enables to obtain the distribution of magnetic flux density in the iron core or molten steel as well as the heating values of the casting mold from the distribution of the eddy current induced electromagnetically. As regards the conductivity of the model necessary for the solution of equations (3) and (4), its concrete value is derived from the references along with its temperature characteristics[10]. The conductivity is treated as a stationary value on the assumption that it is temperature-constant.

On the other hand, as regards the relative permeability, copper plate and stainless steel plate members which compose the casting mold, and the molten steel far in excess of Curie point temperature may be regarded as 1, same as in a vacuum. However, the iron core, a major component of M-EMS, is laminated by electrical steel sheets, same as a rotating type motor, shows nonlinear characteristics against magnetizing force.

In the actual M-EMS, non-oriented electrical steel sheets made by Nippon Steel are used for iron core members. The logic referring to their magnetization characteristics is incorporated for analysis, resulting in highly accurate analytical findings. **Fig. 2** shows the magnetization curve used[11].

3.1.3 Symbols

The symbols indicated in bold letters are three-component vectors spatially.

$\boldsymbol{A}$: Vector potential against magnetic flux density (Wb/m)
$\boldsymbol{F}$: Electromagnetic force (N/m^3)
g : Gravitational acceleration (m/s^2)
$\boldsymbol{J}_o$: (Forced) current density (A/m^2)
$\boldsymbol{P}$: Pressure (Pa)
t : Time (s)
$\boldsymbol{U}$: Rate of flow (m/s)

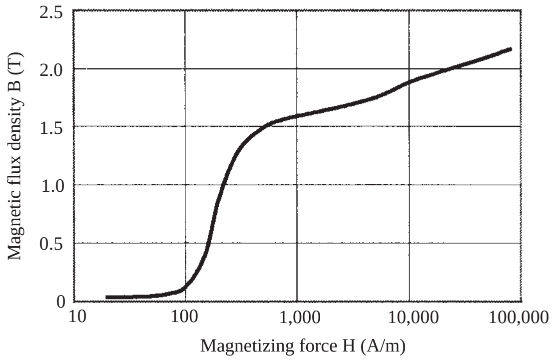


Fig. 2 Magnetization curve of Nippon Steel-made non-oriented electrical steel sheet (50H1300)

μ : Permeability (H/m)
ν : Kinetic viscosity coefficient (m^2/s)
ρ : Density (kg/m^3)
σ : Conductivity (S/m)
ϕ : Scalar potential (V)

3.2 M-EMS design flowchart

Fig. 3 shows the flowchart of M-EMS specification design. The analysis of electromagnetic field is implemented after setting up the M-EMS specification provisionally based on casting and operation conditions or each physical value for mechanical conditions, including the casting mold form .

As a result, Fig. 3 (a) the electromagnetic force distribution in the molten steel and the thrust value integrated by the position equivalent to the slab surface layer at the front of the iron core, (b) the magnetic flux density distribution to evaluate the iron core magnetic saturation, and (c) the heat value induced electromagnetically in the iron core and the casting mold are given.

To evaluate the M-EMS performance, electromagnetic force thrust and magnetic flux density distribution are used in actual measurement. By analysis, electromagnetic force distribution in width direction can also be obtained. A compact-size M-EMS designing and avoidance of local heat generation in the iron core or in the casting mold became possible by calculating their magnetic flux distribution and heat radiate distribution. In the case of the unbalance in width direction of electromagnetic force for stirring, the magnetic saturation or the local heat generation, it is necessary to review not only M-EMS specifications but also mechanical conditions. The mechanical conditions concerning casting mold copper plate will be described later in section 4.2.

If the results of the electromagnetic field analysis meet various conditions as stated above, unsteady fluid dynamic analysis would be carried out with provided prerequisite casting and operation conditions. After the fluid dynamic analysis, Fig. 3 (d) time-averaged flow (steady flow) and unsteady flow mainly by the nozzle stream fluctuation, refers to flow distribution in width direction or downward direction at the position lying on the slab surface layer regarded as the front of the solidified shell, would be evaluated. If the evaluated flow distribution doesn't meet the predetermined stirred flow, the review of the M-EMS specifications or a trial to change the operation conditions, including current value and frequency of M-EMS, should be made in some case.

As described above, the M-EMS specifications are determined to make an ideal uniform stirred flow in width direction in accordance with the flowchart in Fig. 3. By making the best use of numerical analysis characteristics using this flowchart, it would be possible to study a preliminary case that complies with all the casting conditions on the newly installed M-EMS, serving as a tool to replace the manufacture of an online prototype machine. This is also useful for reviewing the existing M-EMS operation conditions.

Since M-EMS requires only a small number of poles and slots as a linear motor, the current between the three-phase won't be the same value. The unbalanced degree of this current will also be solved by the analysis, and therefore, it should be possible to determine the power supply capacity required for driving the M-EMS.

4. Examples of M-EMS Specification Designing

In this section a study on the concrete example of M-EMS specification designing is provided along with the flowchart in Fig. 3 on the assumption of the casting conditions in **Table 1**.

4.1 Establishment of M-EMS conditions

M-EMS generates a magnetic field in an optional direction with copper coils fitted in the iron cores like the teeth of a comb as shown in **Fig. 4**.

Table 1 Example of casting conditions

Casting width	1.0m
Casting thickness	0.24m
Casting rate	1.8m/min
Submerged nozzle depth	0.2m

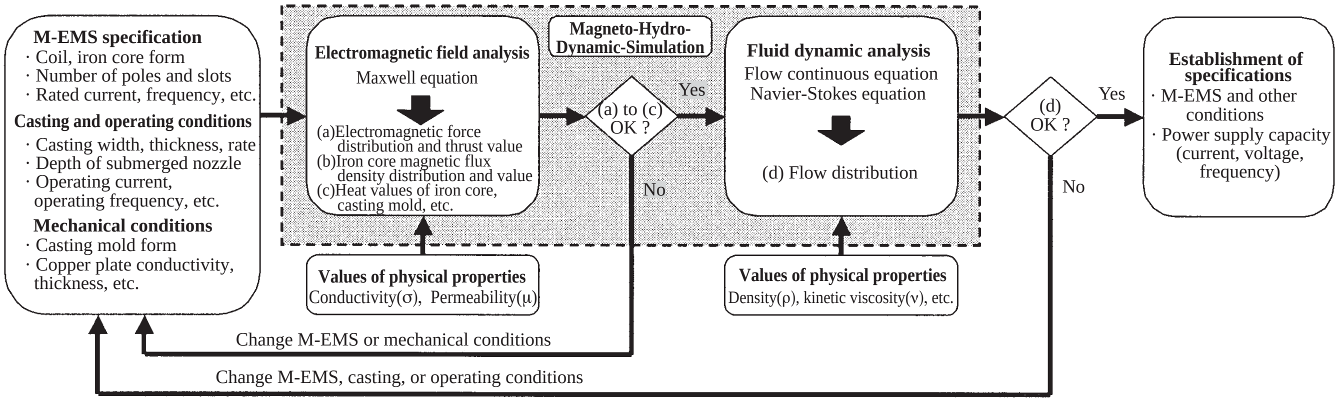


Fig. 3 M-EMS specification design flowchart

The current applied to the coils generates the magnetic fields around them, and penetrate the molten steel through casting mold copper plate from the tips of the teeth, hereinafter called teeth. As described in chapter 2, since electromagnetic force is induced by the moving magnetic field, the force concentrates on the front of the teeth. Therefore the shape of the iron core, including width and thickness, and the position of mounting is the important factors for molten steel flow. Since Nippon Steel's M-EMS is characterized by mounting it on the upper part of the casting mold, the specifications of M-EMS should be determined by the width and the thickness of the iron core, teeth width, the number of poles and slots, and pitches between the poles.

4.1.1 Iron core width

Since M-EMS-generated electromagnetic force concentrates on the front of the iron core as described above, iron core width and the casting width was set up at same 1.0 m.

4.1.2 Number of poles and slots, pitches between poles

If 2 and 4 poles are selected as the general number of poles, the approximate pitches between poles are as shown in **Table 2** respectively. If the number of poles increases, the magnetic field penetrates only into the slab surface, and the electromagnetic force in the molten steel decreases. The number of slots was selected to be 12, the lowest common multiple of 2 and 4 poles, because the iron core is only 1 m wide. **Table 3** shows the phase relationship between the number of poles and each slot.

4.1.3 Iron core thickness

The iron core of M-EMS was set up as thick as 0.3 m particularly in consideration of the shell-washing effect.

4.1.4 Iron core height and teeth width

If the iron core teeth in Fig. 4 are narrow, the magnetic field in molten steel is out of proportion with the current applied to the coil because of magnetic saturation, resulting in poor efficiency. Reversely, expansion of the teeth width narrows the interval between the teeth for copper coil physically, and disturbs the increase of coil current. Teeth width is therefore selected after experimenting several cases of magnetic field analyses, by changing teeth width and coil current to satisfy both conditions.

This trade off condition also applies to iron core height. A short-height iron core cause magnetic saturation, and a long one makes the core large and heavy. A proper height is therefore selected by magnetic field analysis.

Fig. 5 shows the magnetic flux density distribution of the iron core as an example of the analysis finding . The magnetic saturation zone of electrical steel sheets is generally around 2T as in Fig. 2. Fig. 5 shows the finding in which the teeth part is not saturated with magnetism.

4.2 Mechanical conditions

The casting mold of M-EMS is composed of two parts:
one is a copper plate which cools molten steel; and the other, a stainless steel member to keep the casting mold rigid. In terms of applying the electromagnetic force to molten steel, the copper plate should desirably be low in conductivity and thin, while the stainless steel member should also be thin similarly. This is because the magnetic field of M-EMS occurs eddy current in the copper plate and the stainless steel member, and generates a counter-active magnetic field. As a result, the magnetic field in molten steel decrease.

It is necessary, however, to select a highly thermal conductive material for enhancing cooling efficiency in case it is required to endow a copper plate with its intrinsic function of cooling molten steel or to lengthen its life span by decreasing baking. A high thermal conductive material is generally high in electrical conductivity as well. A copper plate is therefore required to have a trade-off property. If it is possible to increase the initial thickness of the copper plate within a coolable range, reusable frequency will also increase by shaving off the molten copper surface. What is more, a stainless steel member becomes more rigid when it is thicker. However, the increase of casting mold thickness means the increase of the dis-

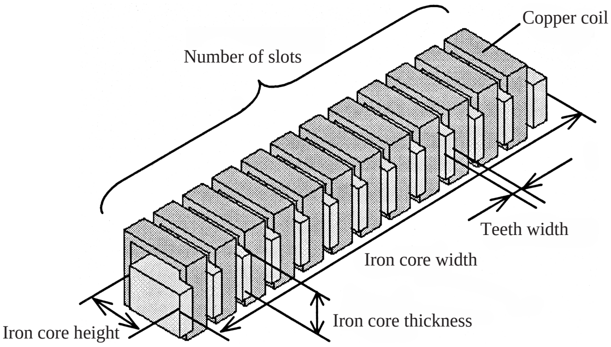


Fig. 4 M-EMS coil model

Table 2 Number of poles and pitches between pole

Iron core width	1.0m	
Number of poles	2 poles	4 poles
Pitch between poles	0.5m	0.25m

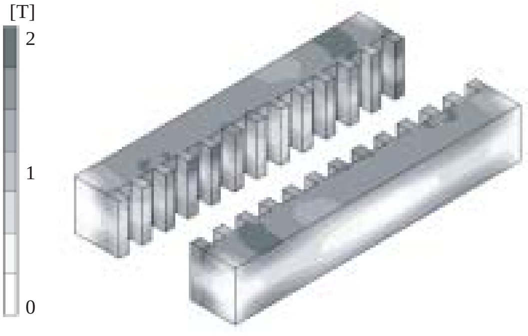


Fig. 5 Analysis example of iron core magnetic flux density distribution

Table 3 AC phase relationship between the number of poles and slots

Number of poles	Slot number and its current phase											
	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12
2 poles	+U		–W		+V		–U		+W		–V	
4 poles	+U	–W	+V	–U	+W	–V	+U	–W	+V	–U	+W	–V

Remarks: “ + ” and “ – ” indicate current directions.

tance between iron core teeth and molten steel, and decreases the electromagnetic force.

The foregoing contents are summarized in **Fig. 6**. At Nippon Steel, a copper plate conductivity, casting mold thickness and mold form are decided by using the analyses of the electromagnetic field and heat transfer. The analyses are used together to solve the trade-off conditions required for casting mold as expressed in Fig. 6. The analysis of heat transfer should be referred to the literature[5)].

4.3 Electromagnetic field analysis

Table 4 shows an example of the finding of the electromagnetic field analysis under the conditions given in **Table 5** with regard to the M-EMS specifications of 2 and 4 poles. (a) and (b) in Table 4 respectively shows the distribution of electromagnetic forces in molten steel at the central heights of the 2-pole and 4-pole M-EMS iron cores. The findings of (a) and (b) in Table 4 show that large electromagnetic forces are generated in the width direction in both of 2 and 4 poles. Fluid analysis was therefore made to compare the findings

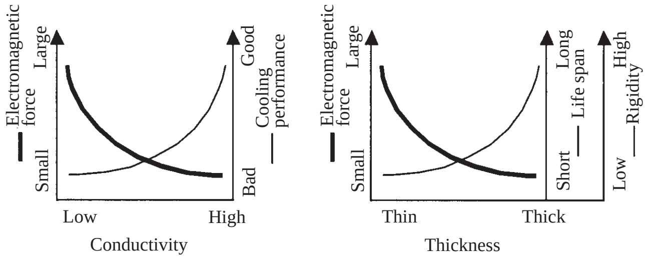
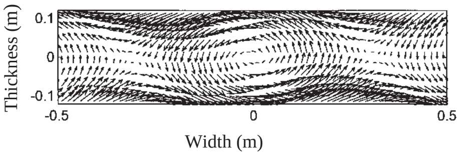
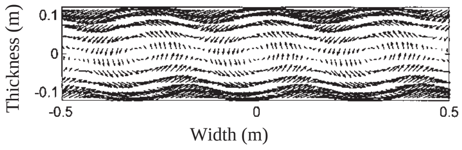
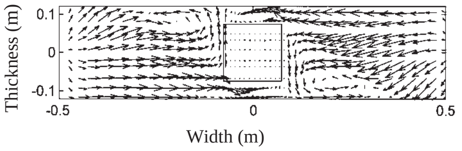
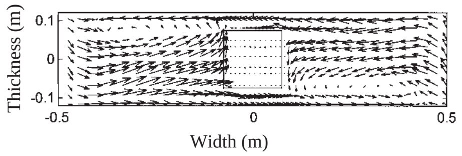
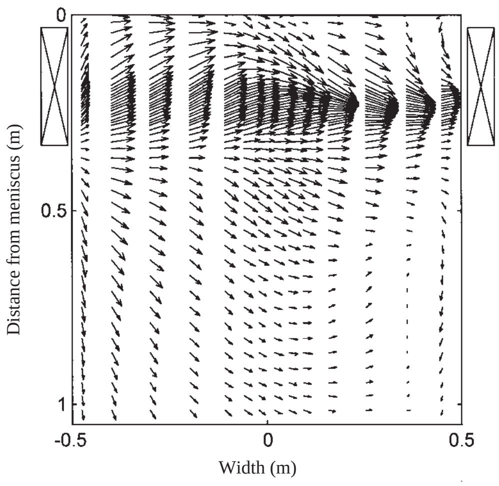
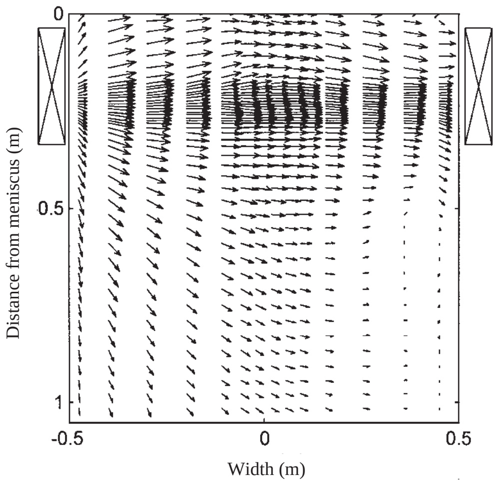


Fig. 6 Relationship between casting mold conductivity and electromagnetic force

Table 5 Conditions of electromagnetic field analysis

Coil current	500A
Frequency	3Hz
Copper plate conductivity	IACS40%

Table 4 Analytical results (based on the number of poles)

	2-pole M-EMS	4-pole M-EMS
Results of electromagnetic field analysis	[← : 10.0kN/m³]  (a) Electromagnetic force distribution at central height of iron core thickness (2 poles)	[← : 10.0kN/m³]  (b) Electromagnetic force distribution at central height of iron core thickness (4 poles)
Results of fluid dynamic analysis	[⟵ : 1.0m/s]  (c) Average flow distribution at meniscus (2 poles)	[⟵ : 1.0m/s]  (d) Average flow distribution at meniscus (4 poles)
	[⟵ : 1.0m/s]  (e) Average flow distribution in front of solidified shell (2 poles)	[⟵ : 1.0m/s]  (f) Average flow distribution in front of solidified shell (4 poles)

on the assumption that no problem is posed to the magnetic saturation and heat value of the iron core.

4.4 Fluid dynamic analysis

Before applying electromagnetic force, fluid dynamic analysis was made under the conditions given in Table 1 to obtain the finding of calculation representing the flow of a nozzle stream. Later, analysis is made in the state nearly equal to the actual CC operation by applying electromagnetic force. (c) to (f) in Table 4 shows the findings of fluid dynamic analysis after applying electromagnetic force, and are the 60-second time-averaged flow distribution at the meniscus and at the front of the solidified shell with the arrows representing flow rate vectors.

The evaluation of the flow distribution and the M-EMS specifications suitable for the casting conditions assumed in Table 1 based on the findings of evaluation is shown below.

4.4.1 Evaluation with flow distribution

The stirring force rotates counter clockwise at the cross section of the meniscus, and works from left to right at the front of the solidified shell. In 2-pole M-EMS in Table 4 (e), the stirred flow goes down from 1/4 width without forming a uniform flow in width direction. This phenomenon can be confirmed also by the vector turning over at the meniscus in the flow distribution in Table 4 (c). The flow that had gone down pushed up to the meniscus after striking the short side mold, and flowed in the direction opposite to that of stirring, thus obstructing stirring. Such a turn over flow ends up in forming a stagnant area with no flow by struggling with the stirred flow, possibly causing nonmetal inclusions and air bubbles entrapped by the solidifying shell.

On the contrary, a uniform flow was given almost in width direction at the M-EMS installed height in case of 4-pole M-EMS in Table 4 (f). Also in Table 4 (d), a stirred flow is formed along the wall to meet our expectation of high cleanability.

4.4.2 M-EMS specifications suitable for provisional casting conditions

As a result of the study of designing the M-EMS specifications based on the flowchart in Fig. 3 as described above, the suitable specifications for provisional casting conditions are summarized in **Table 6**.

Table 6 M-EMS specifications suitable for provisional casting conditions

Items	Specifications
Number of poles	4 poles
Pitch between poles	0.25m
Iron core width	1.0m
Iron core thickness	0.3m
Coil current	500A
Frequency	3.0Hz
Copper plate conductivity	IACS40%

5. Technique of Designing Level DC Magnetic Field

In this section the technique of designing the level DC magnetic field, hereinafter abbreviated to LMF, is described. LMF has effective for enhancing the quality inside the slab by controlling downward flow.

Fig. 7 shows the schematic drawing of LMF. The casting mold is placed between the magnetic poles, and the level DC magnetic field is applied to the thickness direction. The structural member around the casting mold also works as a yoke in the path of the magnetic field.

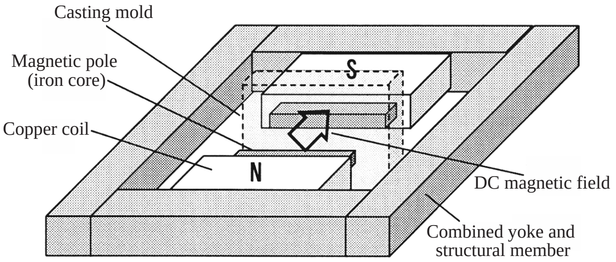


Fig.7 Schematic drawing of LMF

Since LMF is a DC electromagnet, eddy current won't be induced in it's static magnetic field and the M-EMS specifications design flowchart in Fig. 3 can also be applicable to LMF and its process designing by adopting the following equation, with the 2nd member in the left side of equation (3) removed:

$$\nabla \times \left(\frac{1}{\mu} \right) \nabla \times \boldsymbol{A} = \boldsymbol{J}_o \qquad (5)$$

Main points of LMF designing are follows:

(1) To evaluate the level of magnetic flux density required for controlling downward molten steel flow.

(2) To determine the coil current and the number of turns necessary for generating required magnetic flux density.

(3) To design the casting mold structural member size. As an electromagnet yoke, the size should be large to avoid magnetic saturation, but as a structural member, the weight should be reduced.

The technique of fluid dynamic analysis with the LMF-induced static magnetic field should be referred to the literature[12].

6. Conclusion

The "electromagnetic process solution" in the casting field was reported in this paper, for evaluating, clarifying, and controlling the molten steel flow inside the CC casting mold. In order to establish this process solution, magneto-hydro-dynamic simulation technique was applied to design the specifications of electromagnetic coils such as M-EMS and LMF.

Nippon Steel aims at improving slab quality in the future as well by applying suitable electromagnetic force to in-mold molten steel under the casting conditions (mainly casting width and rate) of each ironworks.

References

1) Takeuchi, E. et al.: Tetsu-to-Hagené. 66, 797 (1980)
2) Takeuchi, E. et al.: Tetsu-to-Hagené. 67, 833 (1981)
3) Shirai, T. et al.: Tetsu-to-Hagané. 72, 1014 (1986)
4) Yuyama, H. et al.: CAMP-ISIJ. 1, 1220 (1988)
5) Kittaka, S. et al.: Shinnittetsu-Giho. (376), 63 (2002)
6) Nakajima, J. et al.: Shinnittetsu-Giho. (376), 57 (2002)
7) Fujisaki, K.:In-Mold Electromagnetic Stirring in Continuous Casting. IEEE Trans. IAS. 37(4) (July/August), 1098 (2001)
8) Maxwell, J.C.: A Treatise on Electricity and Magnetism. 3rd. ed. Vol.2. Chaps. IX, XX, 1954
9) Nakata, T., Takahashi, N.: Finite Elements Method of Electrical Engineering. Morikita Shuppan, 1982
10) National Astronomical Observatory (ed.): Chronological Scientific Tables. Maruzen
11) Nippon Steel Corporation: Catalog of Non-Oriented Electrical Steel Sheets
12) Harada, H. et al.: Tetsu-to-Hagané. 86, 76 (2000)