NUMERICAL SIMULATION OF ALTERNATIVE HORIZONTAL LEVITATION ELECTROMAGNETIC CONTINUOUS CASTING(II) ①

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ABSTRACT Electromagnetic problem of horizontal electromagnetic continuous casting (HEMC) had been studied. The influence of structure of apparatus and power frequency on maximum electromagnetic levitation pressure had been analyzed. The results show that, in order to get large electromagnetic levitation pressure at high frequency, the screen must be wide but can be thin, and the width of the sheet should be closed to the distance of the flanges.

Key words horizontal electromagnetic continuous casting electromagnetic levitation numerical simulation

1 INTRODUCTION

As a new type of continuous casting technology, electromagnetic continuous casting (EMC) is emphasized by more and more people[1, 7]. In this technology, an electromagnetic coil works as a "mould", and an electromagnetic force is produced to sustain or levitate molten metal by an electromagnetic field in the coil. The metal in the "mould" solidifies without contact with the wall of the "mould", thus non-mould casting is realized. The main characteristic of elecrtromagnetic casting is the non-contact between the metal and the mould during the process. This leads to a crystallization condition very different from the conventional casting and the defects on the surface of ingot such as adhension and segregation can be avoided. Another characteristic is that the electromagnetic field stirs the molten metal, which can refine the grains and get rid of shrinkage[2].

So far, two types of electromagnetic casting have been developed, one is vertical[1, 5, 6], the other is horizontal[2- 4, 7, 8]. Vertical electromagnetic continuous casting has been investigated extensively since 1960s, and is used widely in industry now. The horizontal levitation electromagnetic continunous casting, however, was put forward only several years ago. It is apparent that this process is more interesting and valuable. During the process the metal solidifies under the condition of being levitated and constrained into certain shape by the electromagnetic force. Owing to its advantages in horizontal shaping, it can cast metal materials in the manner of near net shape of final product.

The key point of the technology is the special structure of the levitation apparatus and the distribution of the electromagnetic field. Optimization of the structure and the distribution will produce the highest induction current and electromagnetic levitation force in the molten metal at a certain source current.

As one part of serial investigations, this paper will investigate the effect of the structure of the levitation apparatus and the frequency of the power on the electromagnetic levitation force, which will set a base for the optimal design of the levitation apparatus and electromagnetic field.

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2 LEVITATION APPARATUS AND MODEL OF ELECTROMAGNETIC FIELD

Horizontal electromagnetic apparatus is schematically illustrated in Fig. 1[3]. It was

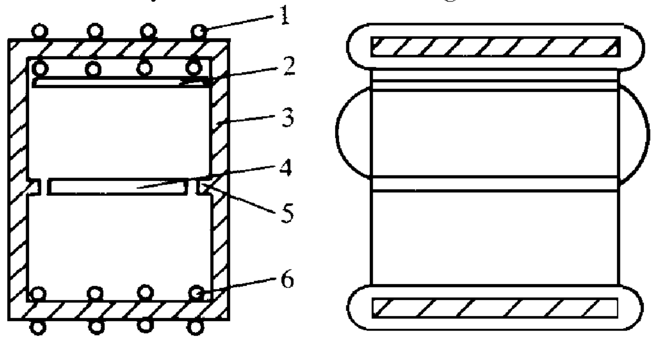

Fig. 1 Apparatus for horizontal electromagnetic casting

1 —upper induction coil; 2 —screen; 3 —yoke; 4 —aluminium sheet (represents molten aluminium); 5 —flange; 6 —bottom induction coil

made up of upper and bottom induction coils, yokes, screen, metal sheet (aluminium) and flanges. The aluminum sheet was set between the yokes. The screen was made of pure copper because of its high electric conductivity, and connected with the metal sheet to form a conducting loop. In the loop, an induction current would be generated in the alternative magnetic field, which was produced by the upper and bottom coil. The reaction of the current with the magnetic field generated electromagnetic levitation pressure on the screen and the metal sheet. The screen was pushed downward by the pressure and the aluminium sheet was levitated upward. Since the screen was fixed, the aluminium sheet was levitated. When the molten metal was levitated, coolant was sprayed from its upper and bottom surfaces. The solidified metal sheet was drawn away by a leading rod, with adding molten metal into the apparatus, and a continuous casting process was thus formed. If the sheet deviates downward by disturbance, the area of the S-M loop increases, and the induction current also increases, which leads to increase of the levitation pressure. As a result the sheet moves back to the previous position. On the contrary, the current will decrease, and the sheet restores to the original position. Hence the apparatus is self-stable.

In order to calculate the electromagnetic field of the caster with finite element method, the following assumptions were made:

(1) The electromagnetic field is quasi-stable field, and the displacement current and movement effect are ignored;

(2) The apparatus is infinitely long, the electromagnetic field is two dimensional;

(3) Boundary effect is ignored.

$$\nabla \times \dot{\boldsymbol{E}} = -j\omega \dot{\boldsymbol{B}} \quad \text{(Farady's law)} \tag{1}$$

$$\nabla \times \dot{\boldsymbol{B}} = \mu \dot{\boldsymbol{J}} \quad \text{(Ampere's law)} \tag{2}$$

$$\nabla \cdot \dot{\boldsymbol{B}} = 0$$
$$\text{(magnetic flux continuity law)} \tag{3}$$

$$\dot{\boldsymbol{J}} = \sigma \dot{\boldsymbol{E}} \quad \text{(Ohm's law)} \tag{4}$$

$$\nabla \cdot \dot{\boldsymbol{J}} = 0 \quad \text{(current continuity law)} \tag{5}$$

where top marks represent complex variables.

Applying vector potential $\dot{\boldsymbol{A}}$ and scalar electric potential $\dot{\varphi}$ to eqs. (1) and (2), and let $\dot{B} = \nabla \times \dot{\boldsymbol{A}}$, and $\nabla \cdot \dot{\boldsymbol{A}} = 0$, the following eqs. are obtained,

$$\dot{\boldsymbol{E}} = -j\omega \dot{\boldsymbol{A}} - \nabla \dot{\varphi} \tag{6}$$

$$\nabla^2 \dot{\boldsymbol{A}} = -\mu \dot{\boldsymbol{J}} \tag{7}$$

The boundary value eqs. of em field are[9]

$$\begin{cases} \dfrac{\partial}{\partial x}\left(\dfrac{\nu \partial \dot{A}_z}{\partial x}\right) + \dfrac{\partial}{\partial y}\left(\dfrac{\nu \partial \dot{A}_z}{\partial y}\right) = \\ \quad - \dot{J}_z + j\sigma\omega \dot{A}_z \\ \Gamma_1:\ \dot{A}_z = \dot{A}_{z0} \\ \Gamma_2:\ \dfrac{\partial \dot{A}_z}{\partial n} = -\dfrac{\dot{H}_t}{\nu} \quad s \quad a \end{cases} \tag{8}$$

where $\dot{A}_z$ and $\dot{J}_z$ are the z-component of $\dot{\boldsymbol{A}}$ and $\dot{\boldsymbol{J}}$, $\dot{A}_{z0}$ is the known value of $\dot{A}_z$ at the boundary, $\dot{H}_t$ is the known value of tangential component of intensity of magnetic field, and Γ_1, Γ_2 represent the 1st, 2nd boundary conditions respectively. The half of Fig. 1 is taken as calculation zone. On the symmetric line the 1st boundary condition is met, and the 2nd boundary condition is met on the other boundary.

The finite element discrete method was used to solve eq. (8), and other variables were calculated based on the results.

$\dot{J} = j\omega\sigma\dot{A}$ (induction current) (9)

$\dot{B} = -(j/\sigma\omega)\ \nabla \times \dot{J}$

(magnetic flux density) (10)

$\dot{F} = (\dot{J} \times \dot{B}^*)/2$

(electromagnetic force) (11)

$p_m = (\dot{B} \cdot \dot{B}^*)/(4\mu)$

(electromagnetic pressure) (12)

where the marks * represent conjugate complexs. Apparently, the necessary condition under which the melt can be levitated is that the hydro-static pressure of the melt is balanced by the electromagnetic pressure produced by alternatively magnetic field on the surface of the melt. At the same time, the electromagnetic stirring in the melt will be produced, and the intensity of the stirring is determined by the rotationary part of electromagnetic force F

$$\dot{F}_s = \frac{1}{2\mu}\mathrm{Re}(\dot{B} \cdot \nabla\dot{B}) \quad (13)$$

3 RESULTS AND DISCUSSION

The numerical calculation of electromagnetic field in the apparatus (Fig. 1, 12 cm × 20 cm × 20 cm) was carried out in the case of casting the aluminium sheet with width of 100 mm and thickness of 4 mm. The resulted electromagnetic field and electromagnetic force field are illustrated in Fig. 2 and Fig. 3 respectively.

From Fig. 2 and Fig. 3, one can see that

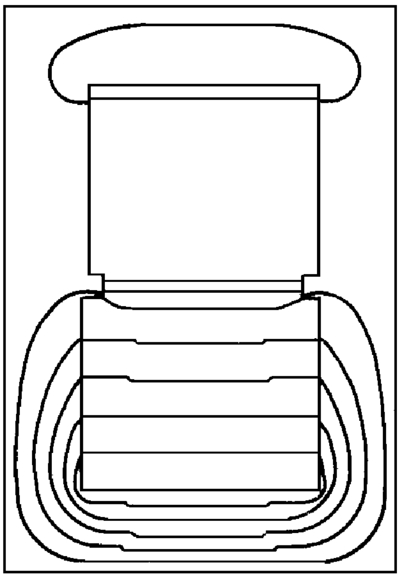

Fig. 2 Schematical illustration of calculated result of magnetic flux distribution

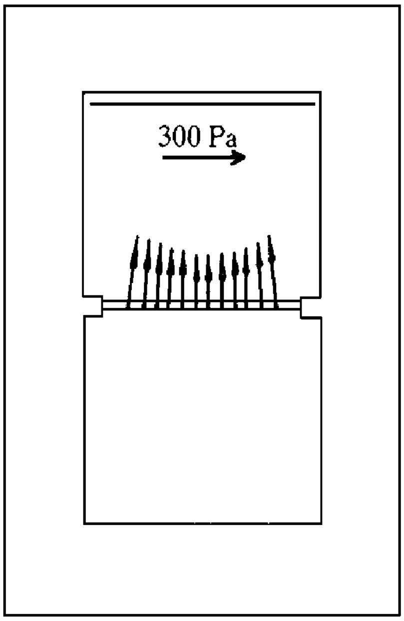

Fig. 3 Calculated result of electromagnetic pressure distribution

during the horizontal casting for aluminium sheet, the magnetic lines on the surface of the sheet are parallel with the outline of the sheet. The induction current J is perpendicular to the paper surface. Hence the electromagnetic force $F = J \times B$ is in direction of inner normal line of the sheet surface. Thus when the electromagnetic pressure on the bottom surface of the sheet is balanced with the hydrostatic pressure, the sheet is levitated. Morever, when the sheet lowers due to any disturbance, the electromagnetic field under the sheet is pressed and its intensity increases. Thus the electromagnetic field increases and the sheet moves to the previous position. So the horizontal electromagnetic casting is a self-stable and self-balanced process.

During the horizontal electromagnetic continuous casting, the frequency of the alternative magnetic field and the structure of the levitation apparatus are the key factors which determine the magnetic induction and magnetic levitation.

The relations of the maximum electromagnetic levitation pressure with the width and the thickness at different frequencies during the casting process are shown in Fig. 4 and Fig. 5 respectively. From Fig. 4, it can be seen that along with increase of the width of the screen, the maximum levitation pressure increases at first, then decreases after it reaches the peak value where the width of the screen is 96 mm, closing to the width of the sheet. This indicates that the same width of the screen as that of the metal sheet may be the best for getting the largest levitation pressure. Fig. 4 also shows that the tendency of changing pressure was prominent when the frequency was over 500 Hz. This indicates that the shielding effect of the screen is intensive when the frequency is high.

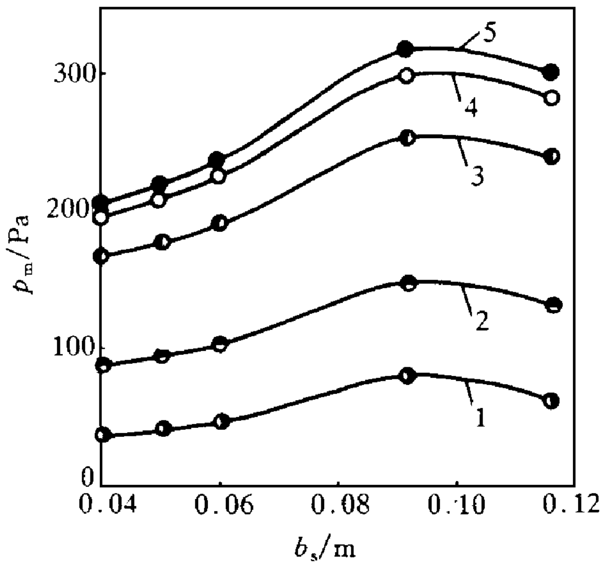

Fig. 4 Relation of maximum levitation pressure with width of screen

1—f = 50 Hz; 2—f = 100 Hz; 3—f = 500 Hz; 4—f = 1 000 Hz; 5—f = 1 500 Hz

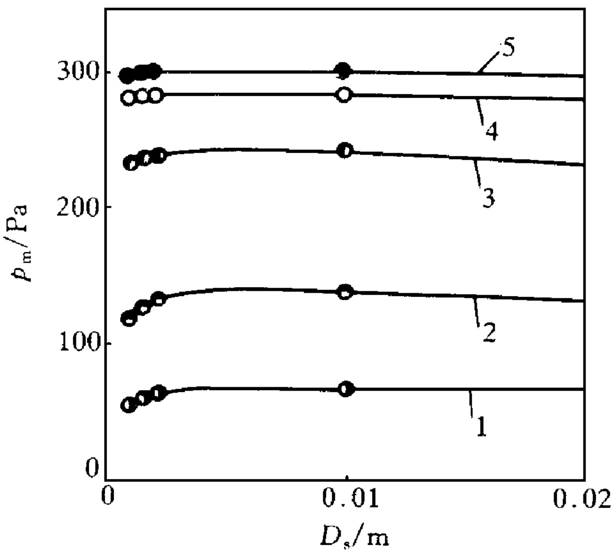

Fig. 5 Relation of maximum levitation pressure with thickness of screen

1—f = 50 Hz; 2—f = 100 Hz; 3—f = 500 Hz; 4—f = 1 000 Hz; 5—f = 1 500 Hz

From Fig. 5, one can notice that for the power frequencies in this calculation, when the thickness of the screen is less than 2 mm, the maximum electromagnetic levitation pressure increases sharply as the thickness of the screen increases, but it almost does not change when the thickness is over 2 mm. Therefore, the thickness of the screen should be more than 2 mm. From Fig. 5, it can also be seen that for high power frequency, the thickness of the screen at which the pressure begins to be stable decreased. So, the screen should be thick at low frequency, and can be thin at high frequency.

Fig. 6 shows the change of the maximum levitation pressure with changing position of the screen. One can learn that the effect of the position of the screen on the levitation pressure is not apparent. Only when the power frequency is very low, the levitation pressure varies a little. So the distance between the screen and sheet can be adjusted in a large range at high frequency.

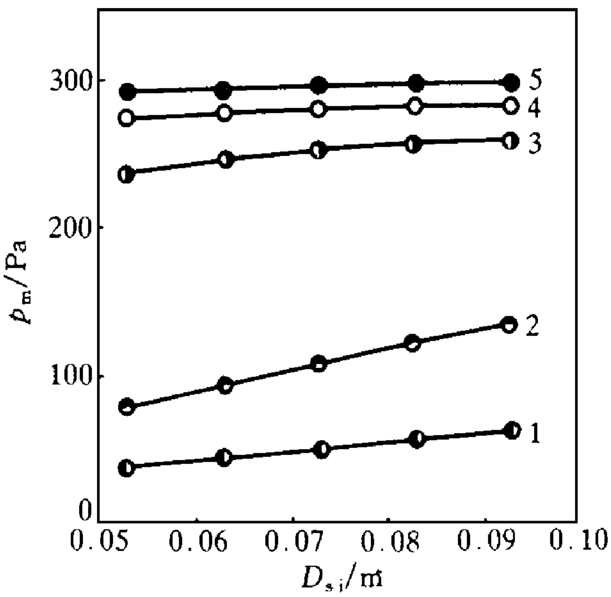

Fig. 6 Effect of position of screen on maximum levitation pressure

1—f = 50 Hz; 2—f = 100 Hz; 3—f = 500 Hz; 4—f = 1 000 Hz; 5—f = 1 500 Hz

Fig. 7 shows the relations between the maximum levitation pressure and the width of the sheet at different frequencies. One can notice that, when the width of the sheet is less than 90 mm, along with the increase of width of the sheet, the levitation pressure increases slowly at low frequency, but decreases at high frequency. However, when the width of the sheet is more than 90 mm, the levitation pressure in two cases increases dramatically as the width of the sheet increases, until the sheet is connected with the flanges. Hence, in order to get large levitation pressure, the width of the sheet should be close to the distance between the two flanges. From Fig. 8 one can notice that, the maximum levitation pressure increases as the frequency increases. However, the magnitude of increasing becomes small when $f > 10000$ Hz. This is because high frequency magnetic field can generate large induction current which results in large levitation pressure. Therefore, for the sake of getting large electromagnetic levitation pressure, the frequency of about 10 000 Hz is reasonable.

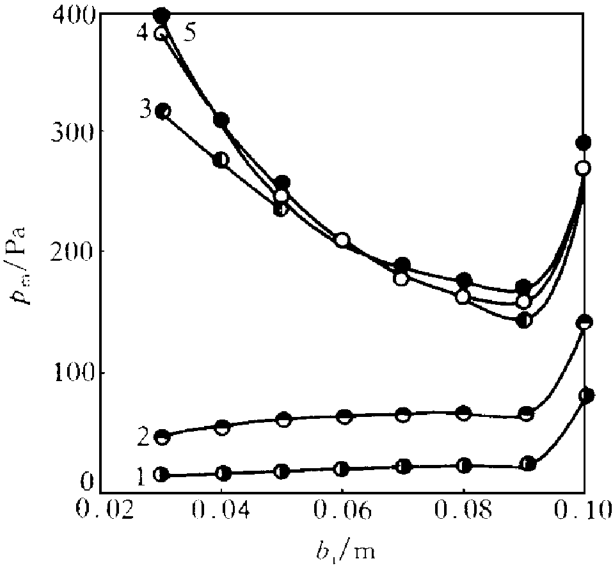

Fig. 7 Effect of width of aluminium sheet on maximum levitation pressure

1 — f = 50 Hz; 2 — f = 100 Hz; 3 — f = 500 Hz; 4 — f = 1 000 Hz; 5 — f = 1 500 Hz

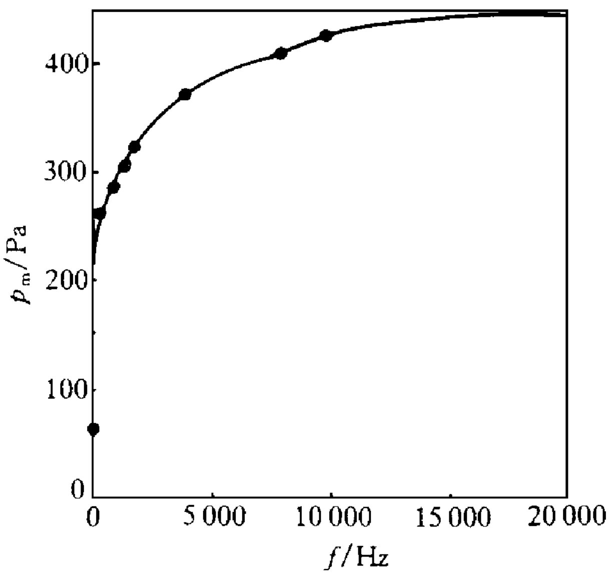

Fig. 8 Relation of maximum levitation pressure with power frequency

4 CONCLUSIONS

Magnetohydrodynamically alternative horizontal electromagnetic continuous casting is self-balanced and self-stable. During horizontal electromagnetic continuous casting, the effect of power frequency on electromagnetic levitation pressure is large. In the case of the horizontal electromagnetic continuous casting in this calculation, reasonable frequency is about 10 000 Hz. The application of screen is essential for generating levitation pressure in the sheet. The width of the screen should be closed to that of the aluminium sheet, and at high frequency, the screen should be wide but can be thin.

SYMBOLS

A —vector magnetic potential; B —magnetic flux density; E —intensity of electric field; F —electromagnetic force; F_s —rotational component of electromagnetic force; H —intensity of magnetic field; J —density of current; j $\sqrt{-1}$ —n normal sign; p_m —electromagnetic levitation pressure; t —tangential sign; μ —permeability; σ —electric conductivity; φ —scalar electric potential; ω —pulsation; υ —reluctivity

REFERENCES

1 Sakane J *et al*. Metall Trans, 1988, 9B(3): 397.

2 Asai S. Tetsu to Hagane, 1989, 75(1): 32.

3 Ren Zhongming *et al*. The Chinese Journal of Nonferrous Metals, (in Chinese), 1994, 4(4): 78.

4 Ren Zhongming *et al*. The Chinese Journal of Nonferrous Metals, (in Chinese), 1993, 3(2): 93.

5 Ren Zhongming *et al*. Journal of Dalian Univ of Tech, (in Chinese), 1991, 31(4): 419.

6 Ren Zhongming *et al*. Journal of Dalian Univ of Tech, (in Chinese), 1992, 32(1): 121.

7 Reng Zhongming *et al*. Journal of Dalian Univ of Tech, (in Chinese), 1994, 34(5): 556.

8 Ren Zhongming *et al*. The Chinese Journal of Nonferrous Metals, Society of China(Chinese), 1996, 6(1): 108.

9 Zhu Shoujun *et al*. Trans Shanghai Univ, (in Chinese), 1995, 1(1): 68.

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