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(71) Applicant: **Sumitomo Metal Industries, Ltd.**
Osaka 541-0041 (JP)

(72) Inventors:
- **OKADA, Nobuhiro**
Osaka-shi
Osaka 541-0041 (JP)
- **TAKATANI, Kouji**
Osaka-shi
Osaka 541-0041 (JP)
- **KAWAMOTO, Masayuki**
Osaka-shi
Osaka 541-0041 (JP)

(74) Representative: **Jackson, Martin Peter**
J.A. Kemp & Co.
14 South Square
Gray's Inn
London WC1R 5JJ (GB)

(54) STEEL CONTINUOUS CASTING METHOD AND IN-MOLD MOLTEN STEEL FLUIDITY CONTROLLER

(57) PROBLEM:

To provide improved electromagnetic stirring properties below the meniscus using a dual-purpose coil that performs both electromagnetic braking and electromagnetic stirring.

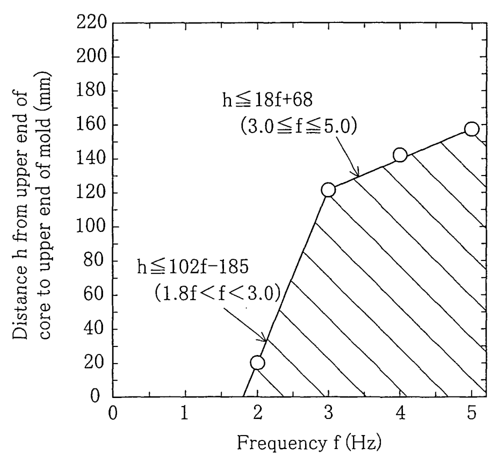
MEANS:

A method of continuous steel casting which selectively causes electromagnetic braking or electromagnetic stirring to act on molten steel in a mold by applying direct current or 3-phase alternating current to an electromagnetic coil disposed on a wide side of a mold. The electromagnetic coil 5 has n teeth 5a disposed on each wide side. The teeth 5a are provided with inner winding 5c around each tooth. An outer winding 5d is further provided around every two teeth which have been provided with inner winding 5c, so as to form a single unit. A core 5b of the electromagnetic coil 5, which includes the teeth 5a, is disposed within a vertical region of the mold, with the vertical region extending from a meniscus of the molten steel to a position of an outlet port 1a of immersion nozzle 1 of the mold. An electromagnetic force is induced in the molten steel 2 below the meniscus when electromagnetically stirring the molten steel 2 in the mold 3. The electromagnetic force is preferably at least twice the electromagnetic force induced at the position where the outlet port 1a of the immersion nozzle 1 is placed.

ADVANTAGEOUS EFFECT:

A favorable swirling flow can be formed even under the meniscus of the molten steel.

Figure 3



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Description

TECHNICAL FIELD

[0001] The present invention relates to a method of continuous casting of steel employing an electromagnetic coil configured to selectively activate electromagnetic braking or electromagnetic stirring, and an in-mold molten steel flow controller for implementing this continuous casting method.

BACKGROUND ART

[0002] In typical continuous casting of steel, molten steel is injected into a mold using an immersion nozzle with two outlet ports. FIG. 13 is a schematic sectional view of a fluid state of molten steel within a mold in this typical continuous casting. Molten steel 2, which is discharged from an outlet port 1a of an immersion nozzle 1, collides against a solidifying shell 2c on a narrow side 3a of a mold 3. The molten steel then separates into an upward flow 2a and a downward flow 2b. The upward flow 2a then forms a horizontal flow below the meniscus and moves in the direction of the immersion nozzle 1. Reference Numeral 4 in FIG. 13 illustrates a mold powder.

[0003] Control of the flow of molten steel in the mold is of the utmost importance in the casting operation and in quality control of cast slabs. There are various methods for achieving flow control of molten steel, such as improving the shape of the immersion nozzle, or applying an electromagnetic force to the molten steel in the mold. In recent years, the method of applying an electromagnetic force to the molten steel has come to be widely used. There are two methods of applying an electromagnetic force to the molten steel: using an electromagnetic brake to apply a braking force to the molten steel flow that is discharged from the immersion nozzle (referred to below as a discharge flow), and using electromagnetic stirring to stir the molten steel by means of an electromagnetic force.

[0004] Electromagnetic braking is used to prevent a reduction in product quality and to prevent the occurrence of break-out, which accompanies re-melting of a solidifying shell, when the discharge flow collides against the solidifying shell on the narrow sides of the mold. Electromagnetic braking can also be used to increase the casting velocity by controlling the molten steel flow velocity below the meniscus. On the other hand, electromagnetic stirring is known to have the effect of improving product quality, and is primarily used in the casting of high-grade materials.

[0005] These electromagnetic brake and electromagnetic stirrer are formed as electromagnetic coil devices with windings around their respective magnetic cores. A magnetic core often employs a ferromagnetic material such as an iron material, and is often also referred to as an iron core. In this specification, the magnetic core will subsequently be referred to simply as a core. Soft iron is often used as a core in an electromagnetic brake. On the other hand, an electromagnetic steel plate is typically employed in electromagnetic stirring, which uses alternating current, in order to reduce core loss due to electromagnetic induction.

[0006] Ordinarily, these electromagnetic coil devices have only a single function of either an electromagnetic brake or an electromagnetic stirrer. Accordingly, for some time now, electromagnetic coil devices have been developed with the capability of functioning both as electromagnetic brakes and as electromagnetic stirrers (referred to below as dual-purpose coils).

[0007] For example, Patent Reference 1 discloses a method for selectively applying direct current, multi-phase alternating current, or direct and indirect superimposed current, to a dual-purpose coil having an odd number (equal to or more than 3) of teeth with a central teeth portion positioned at the outlet port of the immersion nozzle. This method makes it possible to selectively activate electromagnetic braking or electromagnetic stirring.

Patent Reference 1: Japanese Patent Application Kokai Publication No. S63-188461

[0008] However, in the technology disclosed in Patent Reference 1, when electromagnetic braking is activated, a direct magnetic flux is passed through the immersion nozzle. Passing a direct magnetic flux through the immersion nozzle often causes casting defects known as longitudinal cracks. Moreover, when activating electromagnetic braking, it is generally necessary to increase the density of the magnetic flux that penetrates the mold in the direction of the thickness. In order to increase the density of the magnetic flux, the width of the teeth portion must be increased.

[0009] On the other hand, when activating electromagnetic stirring, the flow of molten steel in the vicinity of opposite mold wall surfaces flows in mutually opposing directions. The resulting swirling flow is effective in enhancing product quality. Since a magnetic flux passing through in the direction of the thickness of the mold is not effective in this case, the width of the teeth portion cannot be increased.

[0010] Accordingly, since it is more difficult to obtain electromagnetic stirring than electromagnetic braking by using a dual-purpose coil, the apparatus is designed with priority being given to electromagnetic stirring performance. Since the dual-purpose coil disclosed in Patent Reference 1 is a linear coil with a teeth portion having a narrow width, it is suited to electromagnetic stirring. However, it is unable to sufficiently ensure electromagnetic braking performance, since the width of the teeth portion is narrow.

[0011] In order to address the problem, the assignee of the present application proposed in Patent Reference 2 the use of an electromagnetic coil in which windings around the respective teeth portions, and windings around the outer side of two teeth portions are united.

Patent Reference 2: Japanese Patent Application Kokai Publication No. S60-44157

[0012] Since the two teeth portions and the yoke portion of this electromagnetic coil resemble the Greek letter π (pi), it is called a pi-electromagnetic stirring coil (referred to below as a pi-coil).

[0013] Furthermore, in Patent Reference 3, the present inventors disclosed a dual-purpose coil technology employing a pi-coil. This pi-coil, as described above, forms a single unit by having windings around the outer side of two teeth portions. Therefore, when activating electromagnetic braking, the problem of the teeth portion having a narrower width can be solved by magnetization of the two teeth portions together.

Patent Reference 3: Japanese Patent Application Kokai Publication No. 2007-7719

[0014] The dual-purpose coil configuration of the present invention is similar to that of Patent Reference 3. This dual-purpose coil configuration is shown in FIG. 14.

[0015] FIG. 14 shows the continuous structure of two pi-coils 5 on a wide side 3b of a mold 3. In such a structure, the optimal numbers and widths of teeth 5a depend on the desired size of the mold 3. In the past, these numbers and widths were set on the basis of experience, and performance was confirmed by numerical analysis. That is to say, lengthy experience and a great amount of time were required to suitably select the number and width of the teeth 5a. In FIG. 14, 5b is a core, 5c is an inner winding, and 5d is an outer winding.

[0016] In order to enhance the surface quality of cast slabs, electromagnetic stirring of molten steel must be performed below the meniscus. However, skillfully stirring molten steel below the meniscus is a technique that is difficult to accomplish. In order to accomplish this, it is first necessary to have knowledge of flow distribution in an original mold observed under the condition in the absent of electromagnetic force.

[0017] A perpendicular cross section of the flow distribution of in-mold molten steel is shown in FIG. 13. FIG. 15 shows a horizontal cross section below the meniscus [FIG. 15 (a)] and at the position where the outlet port is placed [FIG. 15 (b)]. As explained above with FIG. 13, molten steel 2 injected through the outlet port 1a of the immersion nozzle 1 collides against the solidifying shell 2c on the narrow side 3a of the mold 3, after which the molten steel is separated into the upward flow 2a, which moves toward the meniscus, and the downward flow 2b, which moves in the direction of withdrawal.

[0018] Accordingly, as shown in FIG. 15 (b), a molten steel flow 9b is formed at the position of the outlet port 1a and moves from the immersion nozzle 1 toward the narrow side 3a. On the other hand, molten steel flow 9a forms below the meniscus, moving from the narrow side 3a toward the immersion nozzle 1, as shown in FIG. 15 (a).

[0019] When an electromagnetic force is applied so as to form a swirling flow 8 in a clockwise direction, as shown in FIG. 15 as the molten steel moves between the narrow side 3a and the immersion nozzle 1, there are regions in the forward direction of the original molten steel flow (referred to below as the forward direction region) and regions in the reverse direction (referred to below as the reverse direction region).

[0020] In the reverse direction region, a large electromagnetic force is required to reverse the flow. However, if an electromagnetic force required for the reverse direction region is applied uniformly in the direction of the wide side of the mold, a problem arises in that the molten steel flow in the forward direction region is further accelerated.

[0021] If the molten steel flow at the outlet port position is accelerated excessively, the solidifying shell becomes thin, cracks develop shortly thereafter, and break-out occurs. Even if break-out does not result, the flow from the narrow side of the mold below the meniscus toward the immersion nozzle intensifies since there is increased upward flow. Consequently, it becomes difficult to obtain a swirling flow below the meniscus. Moreover, the direction of the electromagnetic force to be applied in order to reverse the flow below the meniscus matches the direction for accelerating the molten steel at the outlet port position. Accordingly, application of a suitable electromagnetic force to achieve the swirling flow below the meniscus poses a significant problem.

[0022] In order to solve this problem, an electromagnetic stirring coil 6 in the direction of the wide side 3b of the mold 3 was divided into two parts, EMS-A and EMS-B, and EMS-C and EMS-D, respectively. A technology for controlling the current applied to each of the further divided coils is disclosed in Patent Reference 4 (see FIG. 16).

Patent Reference 4: Japanese Patent No. 2965438

[0023] Patent Reference 5 discloses a technology that causes the electromagnetic force in the direction from the immersion nozzle 1 to the narrow side 3a of the mold 3 (EMS-B and EMS-C in FIG. 16) to be greater than the electromagnetic force in the direction from the narrow side 3a to the immersion nozzle 1 (EMS-A and EMS-D). However, since this technology gives priority to an electromagnetic force which forms a swirling flow below the meniscus, the problem of accelerating the molten steel flow velocity at the position where the outlet port is placed exists.

Patent Reference 5: Japanese Patent No. 2948443

[0024] Patent Reference 6 discloses a technology for applying an electromagnetic force to molten steel, such that Vs ≥ Ve, where Vs is the starting point flow velocity along the wide side, and Ve is the terminal side flow velocity along the wide side, at the ¼ point of the wide side of the mold in the position where the outlet port is placed (see FIG. 16).

Patent Reference 6: Japanese Patent No. 3577389

[0025] The technology of Patent Reference 6 is able to produce a current applied to EMS-B and EMS-C shown in FIG. 16 which is equal to or less than 0.5 times of that applied to EMS-A and EMS-D (claim 5 of Patent Reference 6). This method gives priority to reducing the acceleration of molten steel flow at the outlet port position, which is the opposite of the method of Patent Reference 4 above. As a result, there is insufficient electromagnetic force in the reverse direction region below the meniscus, thereby causing the problem that stirring does not sufficiently reach the corner areas of the mold.

[0026] Patent Reference 7 discloses a technology for arranging the core of the electromagnetic stirring coil only near the meniscus. In this technology, since electromagnetic force is applied only below the meniscus, the problem of accelerating the discharge flow can be avoided. However, this technology cannot be applied to dual-purpose coils, since electromagnetic braking must generate a magnetic flux at the position where the outlet port is placed.

Patent Reference 7: Japanese Patent Application Kokai Publication No. H07-314104

DISCLOSURE OF THE INVENTION

PROBLEM TO BE SOLVED BY THE INVENTION

[0027] The problem to be solved by the present invention is that there is a need to improve the electromagnetic stirring performance below the meniscus, since electromagnetic braking performance is given priority in continuous casting, which employs an electromagnetic coil device capable of functioning both as an electromagnetic brake and as an electromagnetic stirrer, in the prior art.

MEANS FOR SOLVING THESE PROBLEMS

[0028] The method of continuous casting of steel according to an embodiment of the present invention is a method for continuous casting of steel that selectively causes electromagnetic braking or electromagnetic stirring to act on molten steel in a mold by applying direct current or 3-phase alternating current to an electromagnetic coil disposed around a wide side of a mold, so as to achieve electromagnetic stirring performance below the meniscus. This method may include the acts of:

arranging the electromagnetic coil so that it has 2n teeth on each wide side, wherein n is a natural number greater than or equal to two;

providing the teeth with an inner winding around each tooth, and an outer winding around every two teeth provided with the inner winding, the outer winding thereby forming a single unit excitation coil comprising two teeth having inner and outer windings,

disposing a core of the electromagnetic coil within a vertical region of a mold, the vertical region extending from a meniscus of molten steel to a position of an outlet port of an immersion nozzle of the mold, wherein the core is a magnet that comprises the teeth; and

inducing an electromagnetic force in the molten steel below the meniscus when electromagnetically stirring the molten steel in the mold, the electromagnetic force being at least twice the electromagnetic force induced at the position where the outlet port of the immersion nozzle is placed.

[0029] The method of continuous casting of steel may be implemented by employing an in-mold molten steel flow controller. The in-mold molten steel controller may include:

an electromagnetic coil having 2n teeth, wherein n is a natural number greater than or equal to 2 and n teeth are arranged on each of wide side of a mold, wherein each tooth is provided with an inner winding, and wherein an outer winding is disposed around every two teeth, the outer winding thereby forming a single unit excitation coil comprising two teeth having the inner and outer windings;

a direct current source;

a 3-phase alternating current source;

a mold; and

a core of the electromagnetic coil, the core being a magnet, wherein the core is disposed within a vertical region of the mold, the vertical region extending from a meniscus of molten steel disposed in the mold to a position of an outlet port of an immersion nozzle of the mold,

wherein each tooth has a width W and the mold has a width L, wherein the number of the electromagnetic coils n disposed on each wide side, each of which unifies two teeth, satisfies $(L - 80) / (3W + 400) \leq n \leq (L + 200) / (3W + 200)$.

ADVANTAGEOUS EFFECTS OF THE INVENTION

[0030] According to the present invention, a dual-purpose coil which can be used for electromagnetic braking and for electromagnetic stirring induces an electromagnetic force , below the meniscus during electromagnetic stirring, which is greater than the electromagnetic force at the position where the outlet port of the immersion nozzle is placed. This makes it possible to form a favorable swirling flow of molten steel below the meniscus. It is also possible to easily determine the basic shape of the dual-purpose coil, thereby making it possible to greatly reduce the time required to design the dual-purpose coil.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031]

FIG. 1 shows a computation model of electromagnetic field analysis of an embodiment of the present invention. FIG. 1 (a) is a drawing showing the entire model. FIG. 1 (b) is a horizontal sectional view. FIG. 1 (c) is a vertical sectional view.

FIG. 2 is a graph showing a ratio of the electromagnetic force below the meniscus to the electromagnetic force at the outlet port position (electromagnetic force ratio), and the distance relationships from the upper end of the core to the upper end of the copper mold in an embodiment of the present invention.

FIG. 3 is a graph showing the relationship between the frequency and the distance from the upper end of the core to the upper end of the copper mold when the electromagnetic force ratio is at least 2.0-fold according to an embodiment of the present invention.

FIG. 4 is a diagram showing the shape parameters of a dual-purpose coil of an embodiment of the present invention.

FIG. 5 is a graph showing the relationship between the width of the teeth and the magnetic flux density at the center of the mold thickness direction according to an embodiment of the present invention.

FIG. 6 shows graphs of flow velocity distribution near the wide side of the mold below the meniscus according to an embodiment of the present invention.

FIG. 7 shows diagrams of flow velocity distribution below the meniscus or at the immersion nozzle outlet port position in the case of current phase pattern X or current phase pattern Y in an embodiment of the present invention.

FIG. 8 shows graphs of horizontal flow velocity below the meniscus and at the immersion nozzle outlet port position, at a position 10 mm from the wide side wall of the mold, according to an embodiment of the present invention.

FIG. 9 shows diagrams of the results of flow analysis when a linear coil is applied.

FIG. 10 shows graphs of flow velocity distribution near the wide side in current phase pattern Y in an embodiment of the present invention.

FIG. 11 shows diagrams of the results of flow analysis when a dual-purpose coil of the present invention is utilized for electromagnetic stirring when the mold width is 1100 mm and the casting velocity is 2.0 m/min.

FIG. 12 shows diagrams of magnetization patterns when electromagnetic braking is activated in the present invention. FIG. 12 (a) shows an NNSS pattern, and FIG. 12 (b) shows an NSNS pattern.

FIG. 13 is a vertical sectional view schematically showing the flow state of in-mold molten steel in conventional continuous casting.

FIG. 14 shows diagrams illustrating dual-purpose coil configurations of the present invention.

FIG. 14 (a) is a horizontal sectional view, and FIG. 14 (b) is a vertical sectional view of the dual-purpose coil of FIG. 14.

FIG. 15 (a) is a diagram illustrating the flow distribution below the meniscus, and FIG. 15 (b) is a diagram illustrating the flow distribution at the immersion nozzle outlet port position.

FIG. 16 is a diagram illustrating the case where the electromagnetic stirring coil is divided in two in the direction of the wide side.

BRIEF DESCRIPTION OF THE REFERENCE NUMERALS

[0032]

1	Immersion nozzle
1a	Outlet port
2	Molten steel
2a	Upward flow
2b	Downward flow
3	Mold
3a	Narrow side
3b	Wide side
5	Pi-coil
5a	Teeth
5b	Core
5c	Inner winding
5d	Outer winding

PREFERRED EMBODIMENTS

[0033] In conventional continuous casting of steel employing a dual-purpose coil capable of serving the functions of both electromagnetic braking and electromagnetic stirring, it was desired that the molten steel flow did not accelerate at the position where the outlet port of the immersion nozzle is placed, while achieving a favorable swirling flow of molten steel below the meniscus. The present invention solves these problems by providing an electromagnetic force distribution in which the electromagnetic force below the meniscus is greater than the electromagnetic force at the position where the outlet port is placed.

EMBODIMENTS

[0034] FIGS. 1-12 illustrate a process from its initial conception of the present invention to its solution of the problems of the prior art and illustrate the embodiments for implementing the present invention. As described above, the prior art dual-purpose coil does not solve the problem that it is not desirable for the molten steel flow to accelerate at the position where the outlet port of the immersion nozzle is placed, while needing obtain a favorable swirling flow of molten steel by applying a large electromagnetic force to the flow of molten steel below the meniscus.

[0035] The reason why this problem could not be solved is that the electromagnetic force generated by a prior art dual-purpose coil is uniform in the perpendicular direction. Thus, if a dual-purpose coil is able to provide an electromagnetic force distribution such that the electromagnetic force below the meniscus is greater than the electromagnetic force at the position where the outlet port is placed, then this problem can be solved.

[0036] Accordingly, the inventors have developed a dual-purpose coil capable of applying an electromagnetic force below the meniscus that is greater than the electromagnetic force at the position where the outlet port is placed. Moreover, the inventors have developed a method of determining the number and width of teeth of the dual-purpose coil by using a formula which takes into consideration the desired mold width, instead of determining the number and width of the teeth on the basis of trial and error experience as is required in the prior art.

[0037] The inventors employed numerical analysis to make electromagnetic field analysis in order to find conditions under which the electromagnetic force below the meniscus is greater than the electromagnetic force at the position where the outlet port is placed. As a result, the inventors have discovered that an electromagnetic force distribution can be achieved where the electromagnetic force below the meniscus is at least twice the electromagnetic force at the position where the outlet port is placed, by adjusting the electrical current frequency and by adjusting the length from the upper end of the core to the upper end of the copper mold.

[0038] FIG. 1 illustrates a computation model of electromagnetic field analysis. FIG. 1 (a) shows the entire model, FIG. 1 (b) shows a horizontal sectional view, and FIG. 1 (c) shows a vertical sectional view. Non-magnetic stainless steel is installed on the outer side of the mold 3 as back-up plate 7. The upper end of the core 5b is at the same height as the meniscus. The width of the windings 5c and 5d is 50 mm.

[0039] As described above, the electromagnetic coil in the present invention has 2n (n is a natural number 2 or greater) teeth 5a at each wide side 3b of the mold 3. These teeth 5a are provided with inner windings 5c on each of their respective outer sides. The teeth 5a, which are provided with the inner winding 5c around each tooth, are further formed into a single unit by the outer winding 5d disposed around the outer side of every two teeth.

[0040] The inner winding 5c is provided on the outer surface of each tooth 5a. The inner winding 5c, which is a coil, is referred to as an excitation coil. Moreover, the teeth 5a that are provided with the inner winding 5c around each tooth are further provided with the outer winding 5d disposed around the outer side of every two teeth. The outer winding 5d is also referred to as an excitation coil. Therefore, these three excitation coils (5c and 5d) are united to form a single electromagnetic coil for each unit of two teeth. That is, the three excitation coils 5c and d form the pi-coil 5.

[0041] A current of 45,000 ampere turns (abbreviated below as AT) was applied to each excitation coil of the windings 5c and 5d, and numerical analysis was performed on the electromagnetic steel sheet laminate of the core 5b. The numerical analysis conditions for the subsequent electromagnetic stirring serve as the basic conditions, and only places where there are modifications will be indicated below.

[0042] The distance h (mm) is the distance from the upper end of the core 5b to the upper end of the copper mold 3 shown in FIG. 1 (c). In addition, f (Hz) is the current frequency. FIG. 2 shows the ratio of the electromagnetic force below the meniscus to the electromagnetic force at the position where the outlet port is placed (referred to below as the "electromagnetic force ratio" below) when the values of h and f are varied. Here, the electromagnetic force was used to evaluate the electromagnetic force component in the direction of the wide side on the wide side wall of the mold, on the inner side below the meniscus, and at the position where the outlet port is placed, respectively. The position of the outlet port of the immersion nozzle was set at 270 mm from the meniscus on the downstream side.

[0043] FIG. 2 illustrates that the lower the value of h and the higher the value of f, the greater the ratio of the electromagnetic force below the meniscus to the electromagnetic force at the position of the outlet port. In addition, as a result of examining the relationship between h and f when the electromagnetic force ratio is double, the relationship shown in FIG. 3 is obtained. In the region of FIG. 3 is illustrated with diagonal lines, the electromagnetic force below the meniscus can be made to be at least twice the electromagnetic force at the position of the outlet port of the immersion nozzle. This region is defined as the two straight lines resulting from Equations (1) and (2) below.

$$h \leq 102f - 185 \text{ when } 1.8 < f < 3.0 \ \ldots \ (1)$$

$$h \leq 18f + 68 \text{ when } 3.0 \leq f \leq 5.0 \ \ldots \ (2)$$

[0044] The following is a description of a method for determining the appropriate width of the teeth of the dual-purpose coil and the number of pi-coils.

Molds for continuous casting typically have a structure such that the narrow side of the mold is movable in the direction of the slab width, and the length of the wide side of the mold (referred to below as the mold width) can be adjusted during casting. Therefore, slabs with different widths can be cast even while casting is in progress. Variations in mold with are on the order of 500 mm, and it is desirable for dual-purpose coils to be adaptable to changes in mold width.

[0045] When designing prior art dual-purpose coils, the number and width of teeth are selected on the basis of experience, depending on the width, thickness, and height of the mold to be used, and numerical analysis may be used to test whether or not these were appropriate. However, lengthy computation time is required for this numerical analysis, and a long time was needed to study the optimal design of dual-purpose coils since the mold width could change.

[0046] As a result of their work in developing dual-purpose coils, the inventors have found that Equation (3) below can be used to determine the number and width of teeth most suited for the desired mold size.

$$(L - 80) / (3W + 400) \leq n \leq (L + 200) / (3W + 200) \quad \ldots \quad (3)$$

Here, L is the width of the mold (mm), W is the width of the teeth (mm), and n is the number of pi-coils.
The width W of the teeth is on the order of 80-200 mm, and preferably 120-170 mm.

[0047] FIG. 4 shows the shape parameters which are the determining factors in design of the dual-purpose coils. The following is a description of the process used to derive Equation (3). Initially, teeth of a certain width are required to ensure electromagnetic braking performance. FIG. 5 shows the relationship between the width of the teeth and the magnetic flux density at the center of the mold in the direction of the mold thickness.

[0048] FIG. 5 shows the results of numerical analysis when the thickness of the copper mold 3 is 40 mm, the thickness of the back-up plate 7 is 70 mm, and the length t in the direction of the mold thickness (see FIG. 4) is 270 mm or 300 mm.

[0049] A magnetic flux density of at least 2,000 Gauss, and preferably at least 2,500 Gauss is required to ensure adequate electromagnetic braking performance. Accordingly, we see from FIG. 5 that a dual-purpose coil teeth width W of at least 80 mm, and preferably 120 mm or more, is desirable.

[0050] Next, the shape of the dual-purpose coil is adjusted according to the electromagnetic stirring performance. In a dual-purpose coil, n pi-coils are arranged in parallel so that the yoke on the wide side is continuous. When the interval D between teeth of the pi-coils is equal to the width W of the teeth, a good balance between electromagnetic braking performance and electromagnetic stirring performance is achieved.

[0051] Accordingly, on the wide side of the mold, the width which takes up n pi-coils is 3Wn. The distance M between pi-coils, and the distance S from the outermost teeth end to the narrow side of the mold are added to this 3Wn, and should equal the mold width L, as in Equation (4) below.

$$3Wn + M(n-1) + 2S = L \quad \ldots \quad (4)$$

[0052] When Equation (4) is solved for n, Equation (5) results.

$$n = (L + M - 2S) / (3W + M) \quad \ldots \quad (5)$$

[0053] The inventors conducted flow analysis for the 8 cases shown in Table 1 below in order to determine the range of W, M, and S at which electromagnetic stirring functions sufficiently. Flow analysis was performed with the casting velocity set at 1.6 m/min. As a result of repeated study of excitation coil current phases during electromagnetic stirring, the combinations shown in Tables 2 and 3 below were found to be favorable. Table 2 is referred to as current phase pattern X, and Table 3 is referred to as current phase pattern Y.

[0054] A, B, and C in Tables 2 and 3 show various phases of 3-phase alternating current where the mutual phase difference is 120°. Tables 2 and 3 show combinations of current phases applied to excitation coils corresponding to the excitation coil numbers given in FIG. 4. Examination computations of shape parameters utilizing the current phase pattern X are listed in Table 2. Current frequency f was set at 4.0 Hz and the distance h from the upper end of the core of the electromagnetic coil to the upper end of the copper mold was set at 100 mm.

[0055]

TABLE 1

Case No.	Teeth width W (mm)	Distance M (mm) between Pi-coils	Distance S (mm) from end of outermost teeth to narrow end of mold
1	120	200	350
2	140	200	290

(continued)

Case No.	Teeth width W (mm)	Distance M (mm) between Pi-coils	Distance S (mm) from end of outermost teeth to narrow end of mold
3	140	300	240
4	140	400	190
5	140	500	140
6	140	600	90
7	170	400	100
8	170	500	90

[0056]

TABLE 2

Coil No.	(7)	(8)	(9)	(10)	(11)	(12)
Current phase	-C	+A	+B	+C	-A	-B
Coil No.	(1)	(2)	(3)	(4)	(5)	(6)
Current phase	-C	+B	+A	+C	-B	-A

[0057]

TABLE 3

Coil No.	(7)	(8)	(9)	(10)	(11)	(12)
Current phase	+B	-C	-A	+C	-A	-B
Coil No.	(1)	(2)	(3)	(4)	(5)	(6)
Current phase	-C	+B	+A	-B	+A	+C

[0058] The results of flow analysis are given in FIG. 6, with the flow velocity distribution near the wide side of the mold below the meniscus. FIG. 6 confirms that molten steel is flowing near the wide side of the mold in each instance from Case 1 to Case 8. Thus, when the teeth width W is 120 mm-170 mm, electromagnetic stirring of in-mold molten steel is considered to be possible.

[0059] However, reversing the flow velocity in the corner areas of the mold (Cases 1 and 2) and reducing the flow velocity near the immersion nozzle 10 cm/s or less (Cases 6 and 8) is not good for improving the quality of steel slabs.

[0060] Accordingly, if an inappropriate coil shape (Cases 1, 2, 6, and 8) listed in Table 1 is eliminated, then a range of S of 240 mm or less and a range of M of 400 mm or less is suitable. In Case 5, an M of 500 mm is suitable, but an M of 500 mm is not suitable in Case 8. Accordingly, M was set at 400 or less. In addition, space is required for the windings between the pi-coils. This space must be a minimum of 200 mm, so the range of M is set at 200 mm to 400 mm. These values are substituted into Equation (5) to obtain Equation (3).

[0061] The following is a description of examples of dual-purpose coil design based on the present invention. Thickness t of the mold in question is 270 mm, and the mold width is 1100 mm and 1620 mm. When suitable values of W, M, and S are substituted into Equations (3) and (4), it creates a condition in which $S \leq 200$ and $200 \leq M \leq 400$ can be easily applied, as shown in Table 4 below. In the Judgment column in Table 4, o indicates that the results are judged to be suitable, and × indicates that the results are judged to be unsuitable.

[0062]

TABLE 4

L (mm)	W (mm)	n (number)	M (mm)	S (mm)	Judgment
1620	100	3	320	200	○
1620	120	3	140	200	×

(continued)

L (mm)	W (mm)	n (number)	M (mm)	S (mm)	Judgment
1620	130	2	440	200	×
1620	140	2	380	200	○
1620	150	2	320	200	○
1620	160	2	260	200	○
1620	170	2	200	200	×
1620	180	2	140	200	×
1620	190	2	80	200	×
1100	100	2	500	0	×
1100	120	2	380	0	○
1100	130	2	320	0	○
1100	140	2	260	0	○
1100	150	1	650	0	×
1100	160	1	620	0	×
1100	170	1	590	0	×
1100	180	1	560	0	×
1100	190	1	530	0	×

[0063] Table 4 shows that when L = 1620 and when L = 1100, dual-purpose coil shape parameters which yield favorable results are n = 2 and W = 140 mm. It was found that in this case, M is suitably 260 mm - 380 mm.

[0064] Subsequently, suitable shape parameters for the dual-purpose coil were set at n = 2, W = 140 mm, M = 320 mm, and h = 100 mm, based on a detailed study using numerical analysis. Using this dual-purpose coil, electromagnetic stirring of in-mold molten steel was performed at a casting velocity of 1.6 m/min. The results are shown in FIG. 7 and FIG. 8.

[0065] The frequency f and the distance h from the upper end of the core of the pi-coil to the upper end of the mold, are set at h = 100 mm and f = 4.0 Hz, respectively, thereby satisfying the conditions of claim 2. FIG. 7 shows the results of flow analysis conducted using the current phase patterns X and Y given in Tables 2 and 3.

[0066] FIG. 7 (a) shows the flow velocity distribution below the meniscus under current phase pattern X, and FIG. 7 (b) shows the flow velocity distribution at the position of the outlet port of the immersion nozzle under current phase pattern X. FIG. 7 (c) shows the flow velocity distribution below the meniscus under current phase pattern Y, and FIG. 7 (d) shows the flow velocity distribution at the position of the outlet port of the immersion nozzle under current phase pattern Y.

[0067] FIG. 8 (a) and (b) show the horizontal flow velocity distribution at a position 10 mm from the wide side wall of the mold shown by the line A-A' in FIG. 7 (a) and the line B-B' in FIG. 7 (b). FIG. 8 (a) shows the horizontal flow velocity distribution under the condition of current phase pattern X. FIG. 8 (b) shows the horizontal flow velocity distribution under the condition of current phase pattern Y.

[0068] Based on FIG. 7 (a)-(d), current phase pattern X and current phase pattern Y are both able to form a swirling flow below the meniscus. However, current phase pattern Y [FIG. 7 (d)] provides a better flow in the reverse direction region. This is because an electromagnetic force generated by interference between adjacent pi-coils is more suitable for electromagnetic stirring in the case of current phase pattern Y.

[0069] Based on FIG. 8 (a) and (b), it can be determined that according to the present invention, the flow velocity below the meniscus is greater than the flow velocity at the position of the outlet port of the immersion nozzle, and that stirring can reach the corners of the mold in most regions.

[0070] For the sake of comparison with the above described embodiment of the present invention, FIG. 9 shows the results of flow analysis when a linear coil disclosed in Patent Reference 6 is used. Note that the currents in the electromagnetic coils on the right and on the left were calculated as having identical values, without using a technology which applies different electromagnetic forces to the electromagnetic coils on the right and on the left, such as that as disclosed in Patent Reference 6.

[0071] For the sake of comparison with the computational results of the embodiment of the present invention shown in FIGS. 7 and 8, the current was set at 40,000 AT and the frequency was set at 3.0 Hz for the linear coil, so that the flow velocity near the wide side of the mold below the meniscus would be on the order of 55 cm/s, which is the same as in FIGS. 7 and 8.

[0072] Based on FIG. 9 (c), it was determined that in the case of a linear coil, the flow velocity in the forward direction region at the position of the discharge position of the immersion nozzle is greatly accelerated, and that the flow velocity was reversed at the corner areas of the mold below the meniscus.

[0073] Accordingly, when a linear coil is used, and no measures are taken, such as adjusting the current in the electromagnetic coils on the right and on the left, then break-out occurs because the discharge flow accelerates too much. This scenario also results in deteriorating product quality because the stirring motion is not able to reach the corner areas of the mold below the meniscus.

[0074] FIG. 10 shows the flow velocity distribution near the wide side of the mold when the current frequency f is 1.0 Hz, 2.0 Hz, and 3.0 Hz, under current phase pattern Y in the above described embodiment of the present invention.

[0075] In cases where the frequency is 3.0 Hz, as recited in claim 2 of the present application, the electromagnetic force below the meniscus is at least twice the electromagnetic force at the position of the outlet port of the immersion nozzle (see FIG. 3). Therefore, as shown in FIG. 10 (c), stirring can reach the corner areas of the mold below the meniscus, without reversing the flow velocity.

[0076] By contrast, if the frequency f shown in FIG. 10 (a) is 1.0 Hz, and if the frequency shown in FIG. 10 (b) is 2.0 Hz, these are conditions which do not satisfy claim 2 of the present application. Therefore, the electromagnetic force below the meniscus was not at least twice the electromagnetic force at the position of the outlet port of the immersion nozzle (see FIG. 3). Accordingly, the flow velocity is reversed in the corner areas of the mold below the meniscus, thereby resulting in insufficient stirring and a reduction in product quality.

[0077] That is to say, in the present invention, due to the fact that the electromagnetic force below the meniscus is at least twice the electromagnetic force at the position of the outlet port of the immersion nozzle, the flow velocity does not accelerate excessively at the position of the outlet port, even when the current in the electromagnetic coils on the right and on the left is not adjusted. In addition, stirring is able to reach the corner areas of the mold even below the meniscus without reversing the flow velocity.

[0078] FIG. 11 shows the results of flow analysis when the dual-purpose coil of the present invention shown in FIG. 1 is applied to electromagnetic stirring when the mold width L is 1100 mm, and the casting velocity is 2.0 m/min.

[0079] FIG. 11 (a) shows the flow velocity distribution below the meniscus, and FIG. 11 (b) shows the flow velocity distribution at the position where the outlet port of the immersion nozzle is placed. FIG. 11 (c) illustrates the horizontal flow velocity at a position 10 mm from the wide side of the mold below the meniscus and at the position of the outlet port of the immersion nozzle.

[0080] Based on FIG. 11 (a), it can be determined that a swirling flow is produced below the meniscus, even in cases where the mold width is 1100 mm. Moreover, based on FIG. 11 (b), it can be determined that stirring can reach the corner areas of the mold below the meniscus without excessively accelerating the flow velocity at the position of the outlet port of the immersion nozzle, as in cases where the mold width is 1620 mm.

[0081] Table 5 below shows working examples in which a dual-purpose coil of the present invention is used as an electromagnetic brake, when the mold width is 1620 mm and 1100 mm. The electromagnetic braking performance can be evaluated by the degree to which there is a decrease in the maximum flow velocity and the flow velocity fluctuation, in comparison to cases in which there is no electromagnetic braking. Since the maximum flow velocity decreases at least 5 cm/s, and the flow velocity fluctuation decreases at least 10 cm/s, it can be determined that sufficient electromagnetic brake performance is achieved.

[0082]

TABLE 5

Mold width L (mm)	Casting velocity (m/min)	Method of Magnetization	Maximum Flow Velocity (cm/s)	Flow Velocity Fluctuation (cm/s)
1620	1.8	No electromagnetic brake	37.3	29.2
		NNSS	32.3	13.0
		NSNS	29.6	17.8
1100	2.0	No electromagnetic brake	37.3	29.2
		NNSS	32.3	13.0

[0083] The method of generating magnetic flux density in a dual-purpose coil of FIG. 1 during electromagnetic braking is basically the NNSS pattern shown in FIG. 12 (a). However, the NSNS pattern, in which the orientation of magnetic flux density alternates, is also possible.

[0084] In Patent Reference 3, the inventors disclosed that, the NSNS pattern, which is more effective in suppressing the maximum flow velocity, is better in terms of electromagnetic braking performance than the NNSS pattern, which is superior from the standpoint of suppressing flow velocity fluctuation, as long as magnetic flux density can be obtained to the same degree.

[0085] If the number of pi-coils n is 4 or more, then it is possible to alternately generate large magnetic flux densities by magnetizing two adjacent teeth as a single entity. However, in cases where n = 2, as in FIG. 1, the magnetic flux density is significantly lower than when two teeth are magnetized as a single entity, since only one tooth is magnetized in order to implement the NSNS pattern which alternately generates flux densities.

[0086] Incidentally, when n = 2 in the NNSS pattern, a current of 54,000 AT is applied, making it possible to obtain a magnetic flux density of 3,000 Gauss or greater. However, even if a current of 54,000 AT is applied in the NSNS pattern, it was possible to obtain only a magnetic flux density of 1,060 Gauss.

[0087] Table 5 shows that in the case of the NNSS pattern, the maximum flow velocity decreases on the order of 5 cm/s and the flow velocity fluctuation decreases on the order of 16 cm/s in comparison to when electromagnetic braking is not activated. On the other hand, in the case of the NSNS pattern, the maximum flow velocity decreases on the order of 8 cm/s and the flow velocity fluctuation decreases on the order of 12 cm/s, even though the magnetic flux density is low. Therefore, in the present invention, the electromagnetic braking performed by the dual-purpose coil is able to ensure sufficient performance whether the magnetization pattern is NNSS or NSNS.

[0088] The present invention is of course not limited to the foregoing examples, and the embodiments can of course be suitably modified, as long as they are within the scope of the technical ideas recited in the claims.

[0089] For example: a) In the present invention as described above, the immersion nozzle is positioned in the center of the mold, but the immersion nozzle does not necessarily have to be positioned in the center of the mold; b) The alternating current does not have to be 3-phase, but as long as the current phase difference varies from 90˚ to 120˚, it can be multi-phase alternating current on a higher order.

INDUSTRIAL APPLICABILITY

[0090] The present invention described above can be applied to continuous casting using a curved mold, a vertical mold, or any mold shape, as long as it involves continuous casting using an immersion nozzle. Moreover, the present invention can be applied not only to continuous casting of slabs, but also to continuous casting of blooms.

Claims

1. A method of continuous steel casting which selectively causes electromagnetic braking or electromagnetic stirring to act on molten steel in a mold by applying direct current or 3-phase alternating current to an electromagnetic coil disposed around a wide side of a mold, the method comprising:

   arranging the electromagnetic coil so that it has 2n teeth on each wide side, wherein n is a natural number greater than or equal to two;
   providing the teeth with an inner winding around each tooth, and an outer winding around every two teeth provided with the inner winding, the outer winding thereby forming a single unit excitation coil comprising two teeth having inner and outer windings,
   disposing a core of the electromagnetic coil within a vertical region of a mold, the vertical region extending from a meniscus of molten steel to a position of a outlet port of an immersion nozzle of the mold, wherein the core is a magnet that comprises the teeth; and
   inducing an electromagnetic force in the molten steel below the meniscus when electromagnetically stirring the molten steel in the mold, the electromagnetic force being at least twice the electromagnetic force induced at the position where the outlet port of the immersion nozzle is placed.

2. A method of continuous steel casting according to claim 1, wherein a relationship between a distance h from an upper end of the core to an upper end of the mold, and wherein the electromagnetic force is induced by applying a 3-phase alternating current having a frequency f, wherein the 3-phase alternative current is applied to the electromagnetic coil such that when in-mold stirring of the molten steel is performed , $h \leq 102f - 185$ when $1.8 \leq f \leq 3.0$ and $h \leq 18f + 68$ when $3.0 \leq f \leq 5.0$.

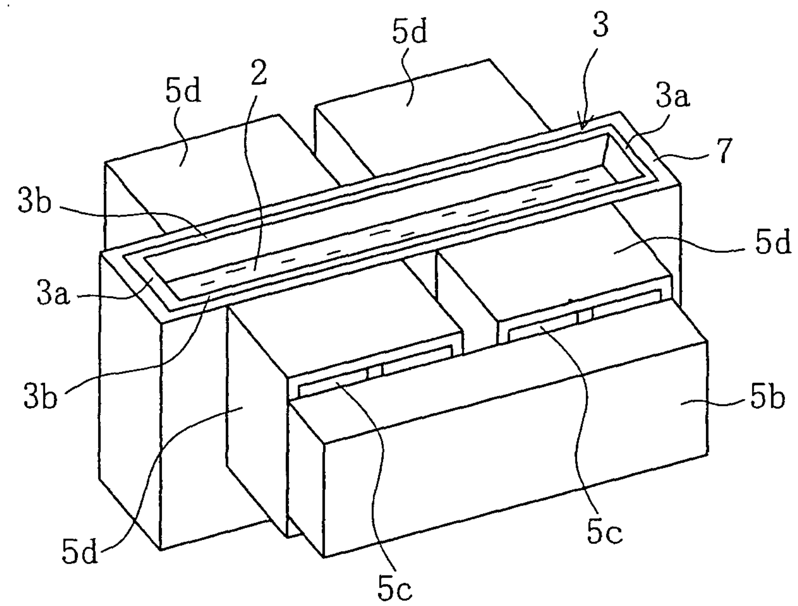
3. A method of continuous steel casting according to claim 1 or claim 2, wherein the core comprises at least 12 coils, wherein coils 1-3 form a first single unit excitation coil, coils 4-6 form a second single unit excitation coil, coils 7-9 form a third single unit excitation coil, and coils 10-12 form a fourth single unit excitation coil, each single unit excitation coil comprising two teeth, each tooth having an inner winding, and an outer winding wrapped around the two teeth,
wherein the first and second single unit excitation coils are disposed on one side of the wide side of the mold and the third and fourth single unit excitation coils are disposed on the opposite side of the wide side of the mold such that the first and second excitation coils face the third and force excitation coils,
wherein the electromagnetic force is induced by applying a 3-phase alternating current having phases A, B, and C, each phase having a positive and negative direction, wherein A, B, and C have a phase difference of 120 degrees, wherein the 3-phase alternating current is applied to the coils such that phases A, B, and C are applied to the inner windings of the coils in a first order or a second order,
wherein, in the first order, coil 1 has a phase of -C, coil 2 has a phase of +B, coil 3 has a phase of +A, coil 4 has a phase of +C, coil 5 has a phase of -B, coil 6 has a phase of -A, coil 7 has a phase of -C, coil 8 has a phase of +A, coil 9 has a phase of +B, coil 10 has a phase of +C, coil 11 has a phase of -A, and coil 12 has a phase of -B,
and wherein, in the second order, coil 1 has a phase of -C, coil 2 has a phase of +B, coil 3 has a phase of +A, coil 4 has a phase of -B, coil 5 has a phase of +A, coil 6 has a phase of +C, coil 7 has a phase of +B, coil 8 has a phase of -C, coil 9 has a phase of -A, coil 10 has a phase of +C, coil 11 has a phase of -A, and coil 12 has a phase of -B.

4. An in-mold molten steel flow controller for continuous steel casting in which electromagnetic braking or electromagnetic stirring is selectively caused to act on the molten steel in a mold by applying direct current or 3-phase alternating current to an electromagnetic coil disposed on the wide side of a mold, the controller comprising:

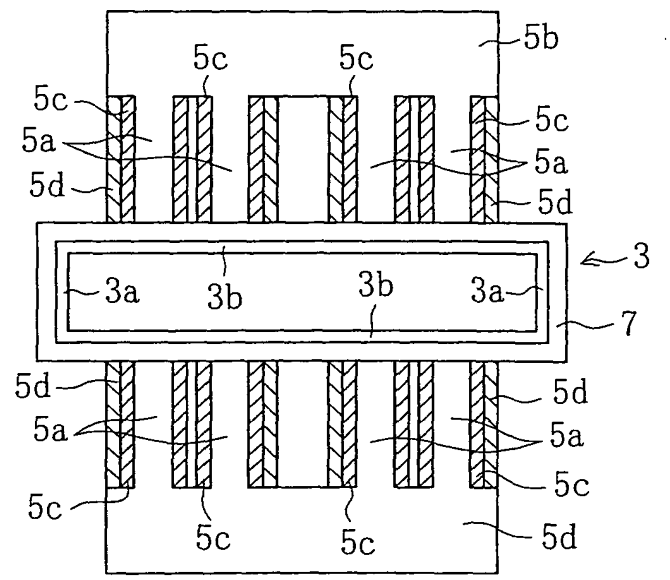
   an electromagnetic coil having 2n teeth, wherein n is a natural number greater than or equal to 2 and n teeth are arranged on each of wide side of a mold, wherein each tooth is provided with an inner winding, and wherein an outer winding is disposed around every two teeth, the outer winding thereby forming a single unit excitation coil comprising two teeth having the inner and outer windings;
   a direct current source;
   a 3-phase alternating current source;
   a mold; and
   a core of the electromagnetic coil, the core being a magnet, wherein the core is disposed within a vertical region of the mold, the vertical region extending from a meniscus of molten steel disposed in the mold to a position of a outlet port of an immersion nozzle of the mold,
   wherein each tooth has a width W and the mold has a width L, wherein the number of the electromagnetic coils n disposed on each wide side, each of which unifies two teeth, satisfies $(L - 80) / (3W + 400) \leq n \leq (L + 200) / (3W + 200)$.

Figure 1

(a)


5d
5d
2
3
3a
7
3b
5d
3a
3b
5b
5d
5c
5c
5d
5c

(b)


5b
5c
5c
5c
5c
5a
5a
5d
5d
3
3a
3b
3b
3a
7
5d
5d
5a
5a
5c
5c
5c
5c
5d

(c)

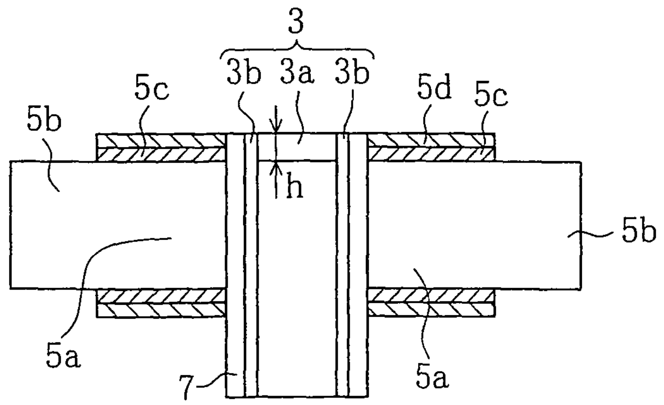

3
3b
3a
3b
5c
5d
5c
5b
h
5b
5a
5a
7

Figure 2

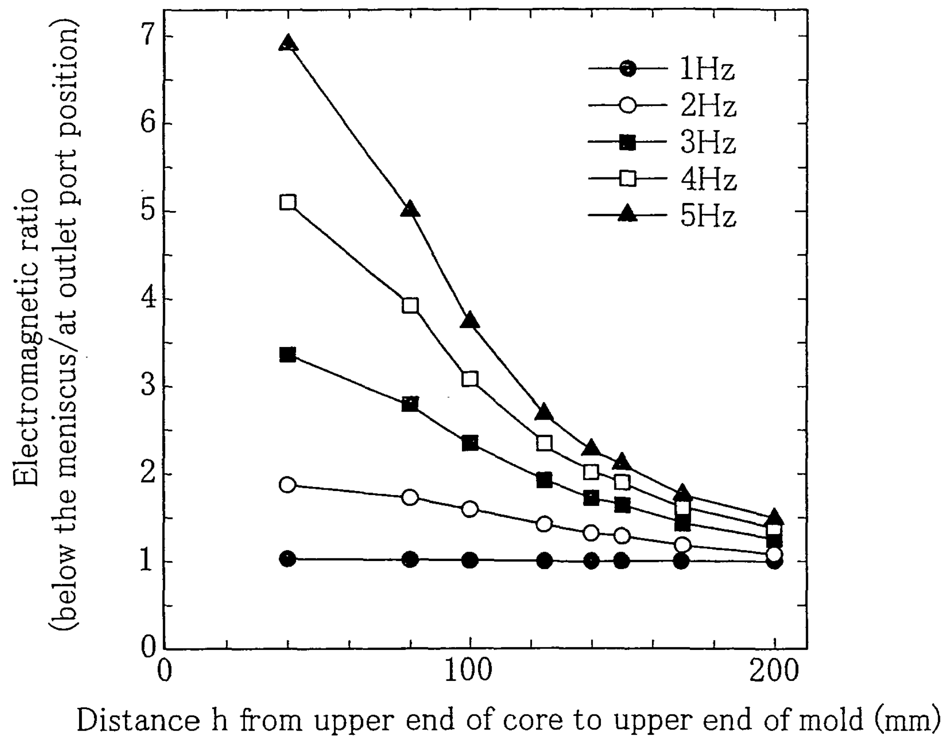


Figure 3

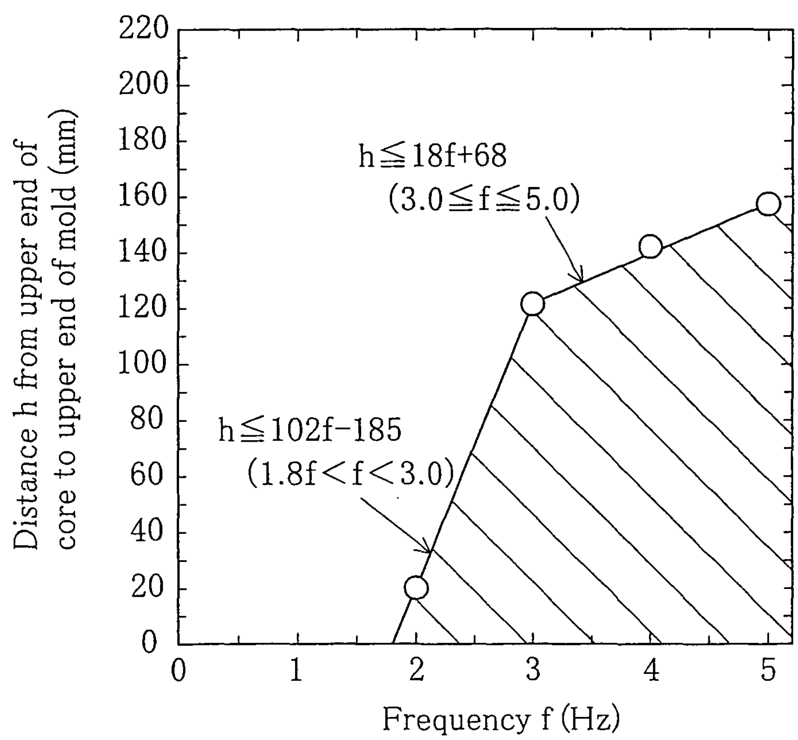


Figure 4

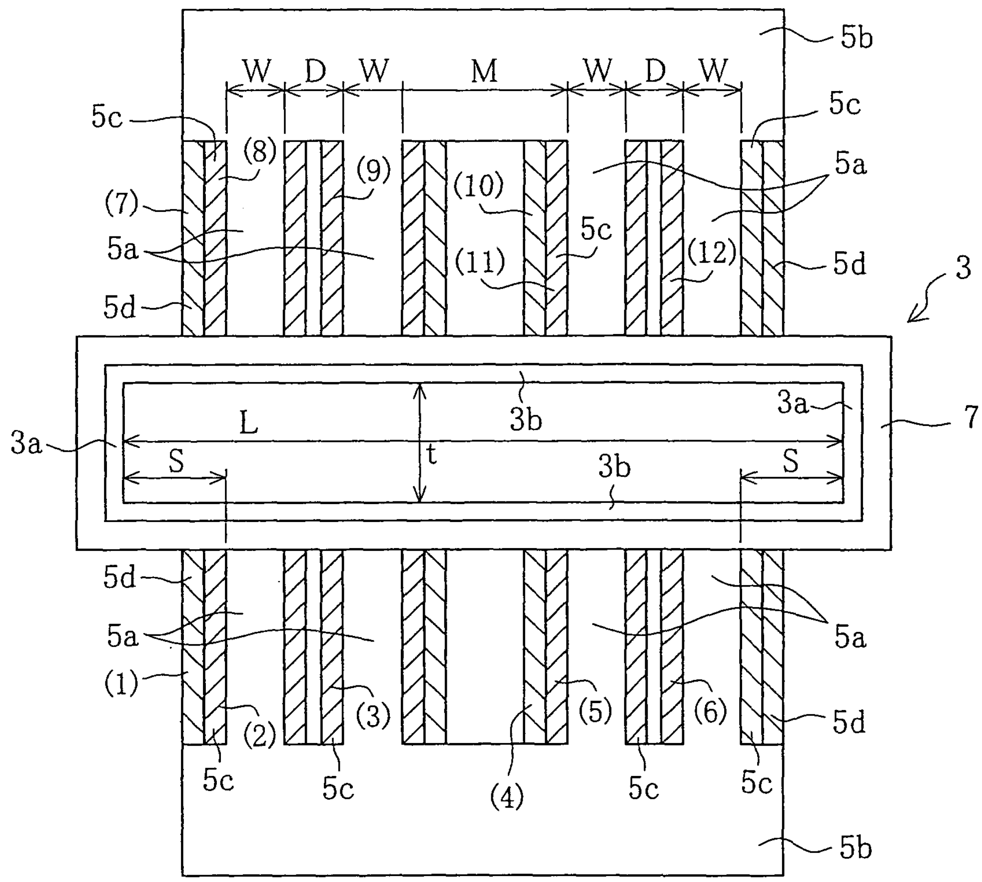


Figure 5

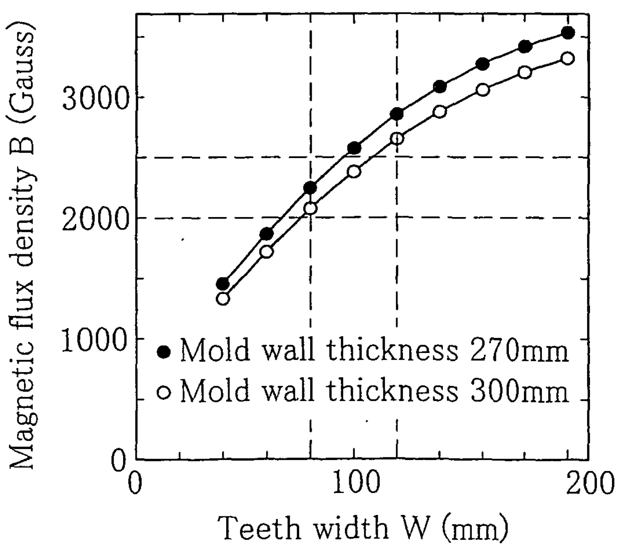


Figure 6

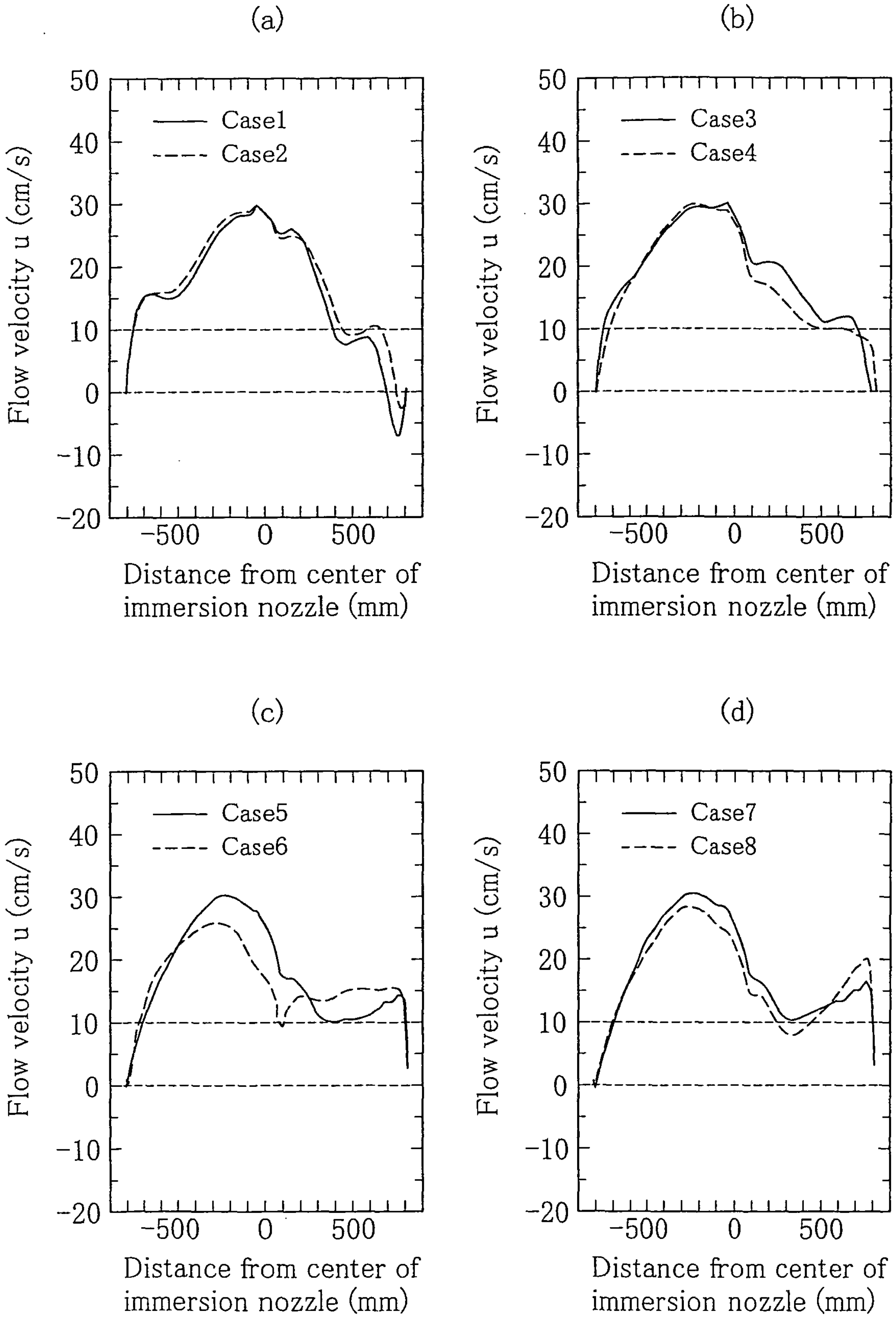
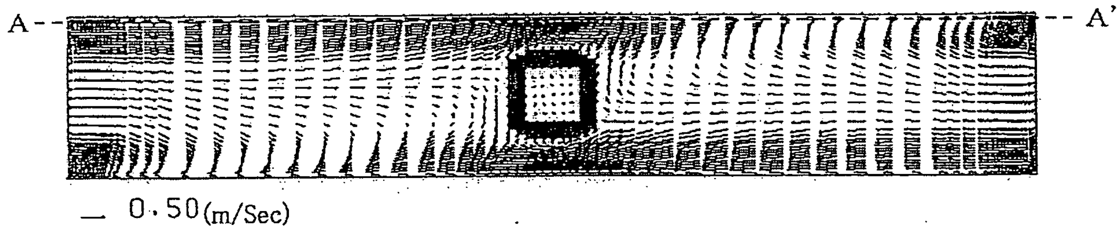
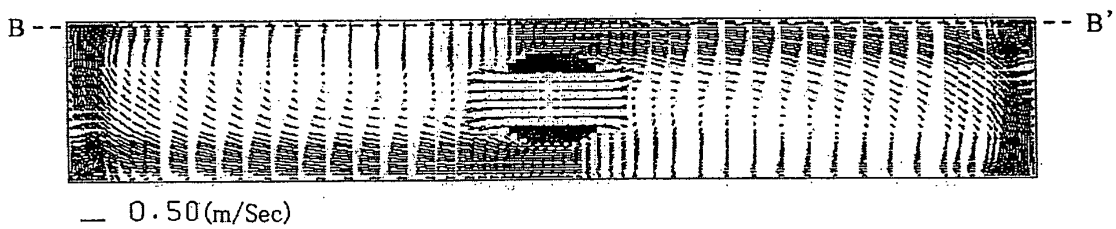

(a)
Case1
Case2
(b)
Case3
Case4
(c)
Case5
Case6
(d)
Case7
Case8
Flow velocity u (cm/s)
50
40
30
20
10
0
-10
-20
-500
0
500
Distance from center of immersion nozzle (mm)

Figure 7

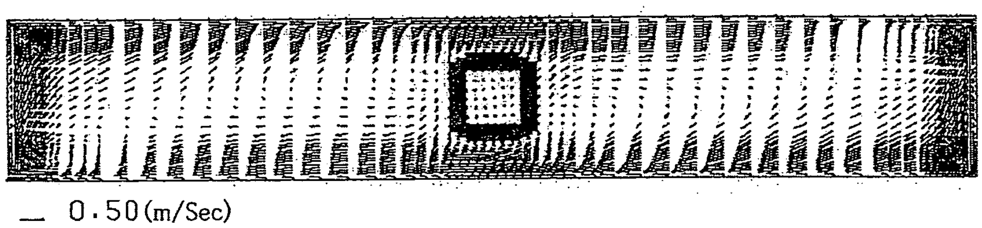
(a)



(b)



(c)



(d)

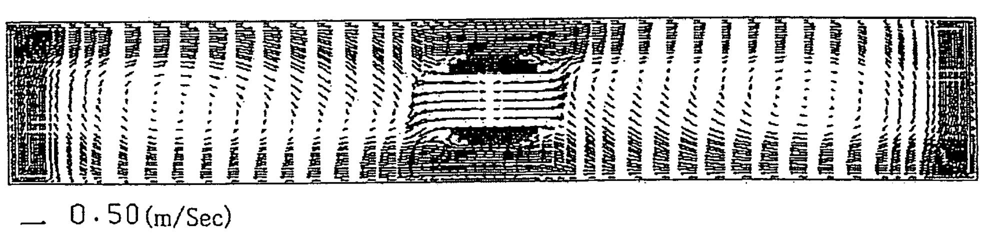
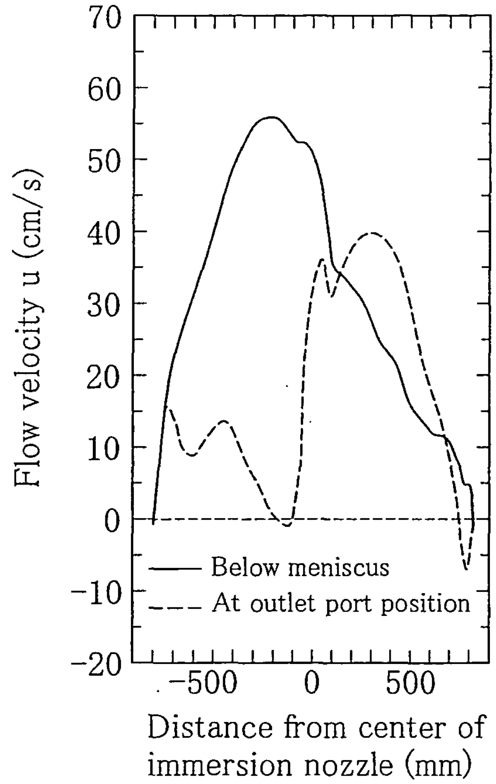


Figure 8

(a)


70
60
50
40
30
20
10
0
-10
-20
Flow velocity u (cm/s)
Below meniscus
At outlet port position
-500
0
500
Distance from center of immersion nozzle (mm)

(b)

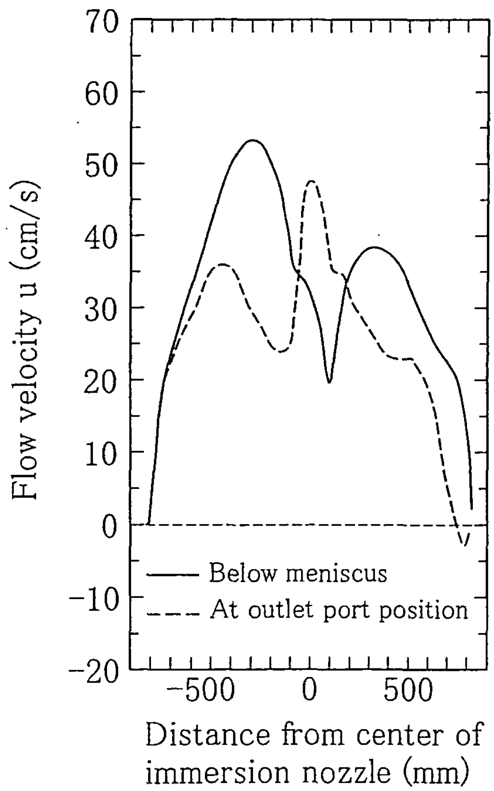
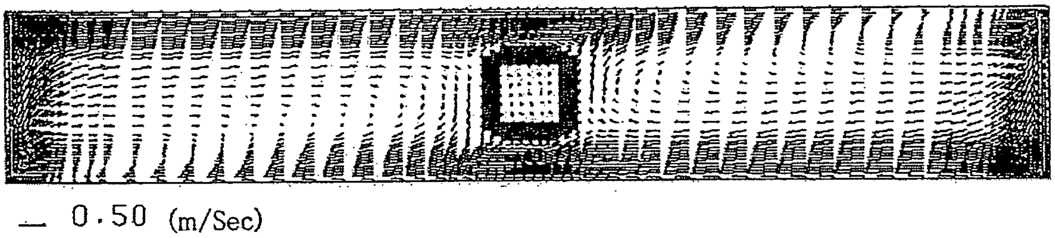
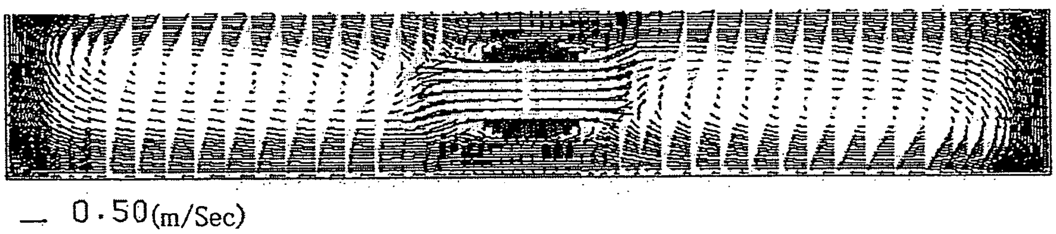

70
60
50
40
30
20
10
0
-10
-20
Flow velocity u (cm/s)
Below meniscus
At outlet port position
-500
0
500
Distance from center of immersion nozzle (mm)

Figure 9

(a)


0.50 (m/Sec)

(b)


0.50(m/Sec)

(c)

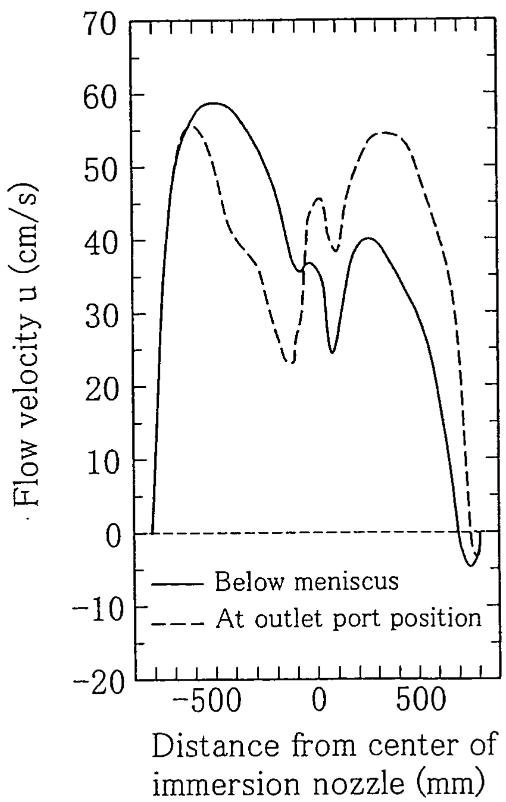

70
60
50
40
30
20
10
0
-10
-20
Flow velocity u (cm/s)
-500
0
500
Distance from center of immersion nozzle (mm)
Below meniscus
At outlet port position

Figure 10

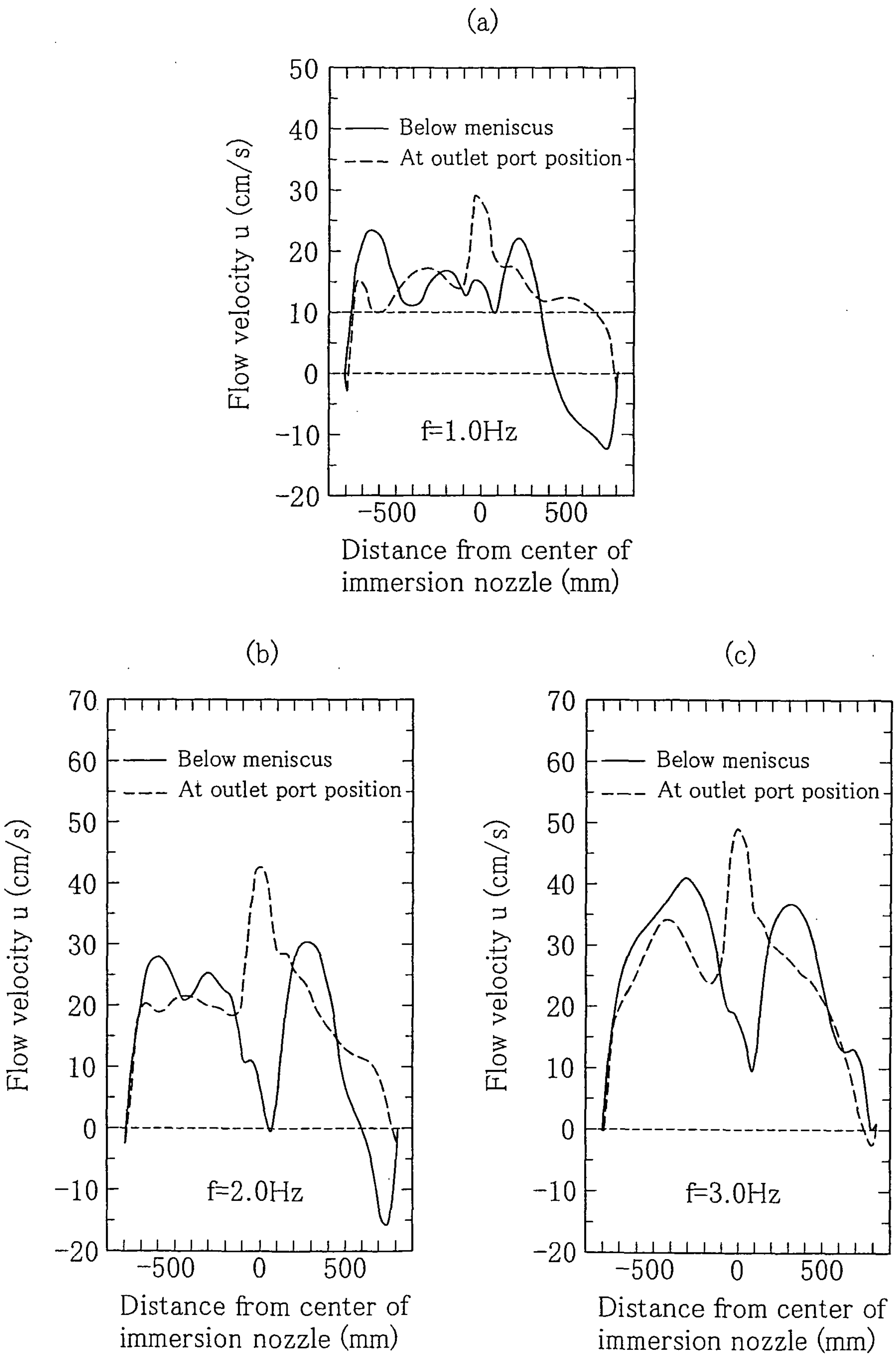
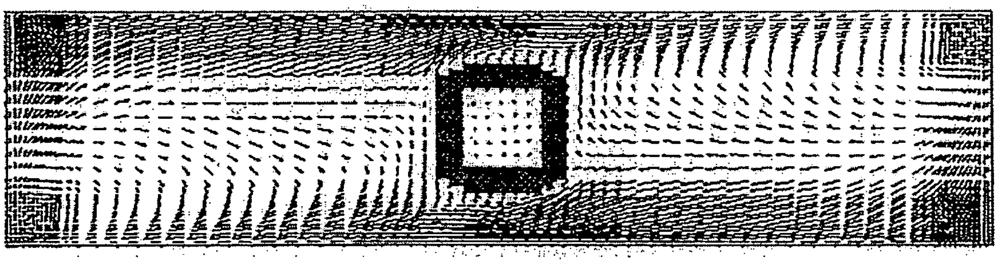
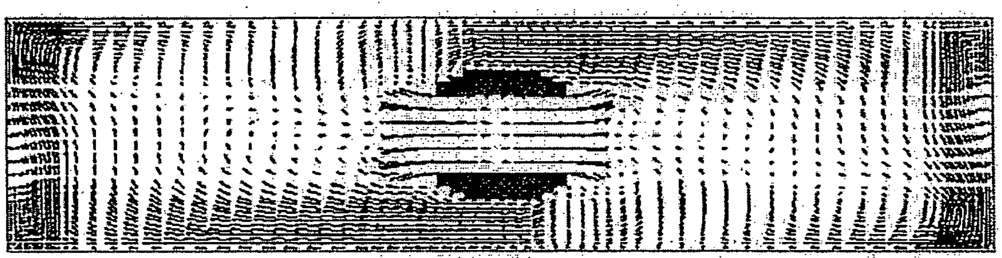

(a)
Below meniscus
At outlet port position
Flow velocity u (cm/s)
50
40
30
20
10
0
-10
-20
f=1.0Hz
-500
0
500
Distance from center of immersion nozzle (mm)
(b)
Below meniscus
At outlet port position
Flow velocity u (cm/s)
70
60
50
40
30
20
10
0
-10
-20
f=2.0Hz
-500
0
500
Distance from center of immersion nozzle (mm)
(c)
Below meniscus
At outlet port position
Flow velocity u (cm/s)
70
60
50
40
30
20
10
0
-10
-20
f=3.0Hz
-500
0
500
Distance from center of immersion nozzle (mm)

Figure 11

(a)



(b)



(c)

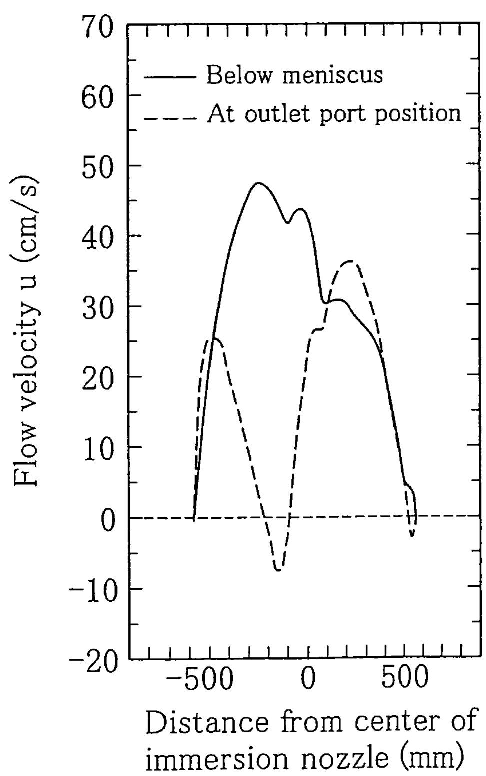
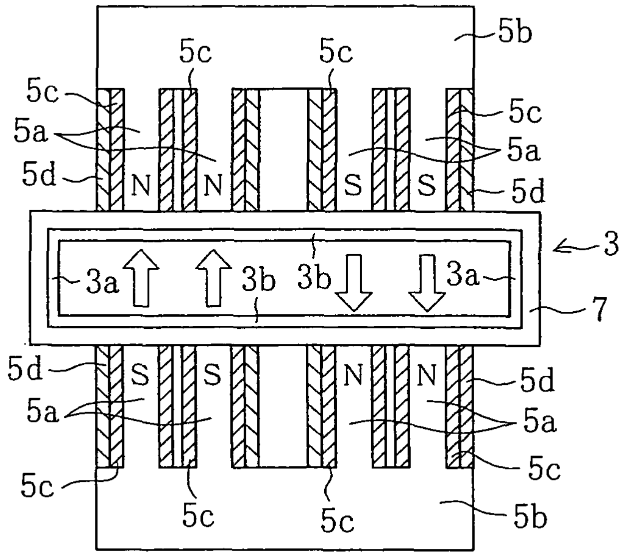


Figure 12

(a)


5b
5c
5c
5c
5c
5a
5a
5d
N
N
S
S
5d
3
3a
3b
3b
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7
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S
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5d
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5c
5c
5b

(b)

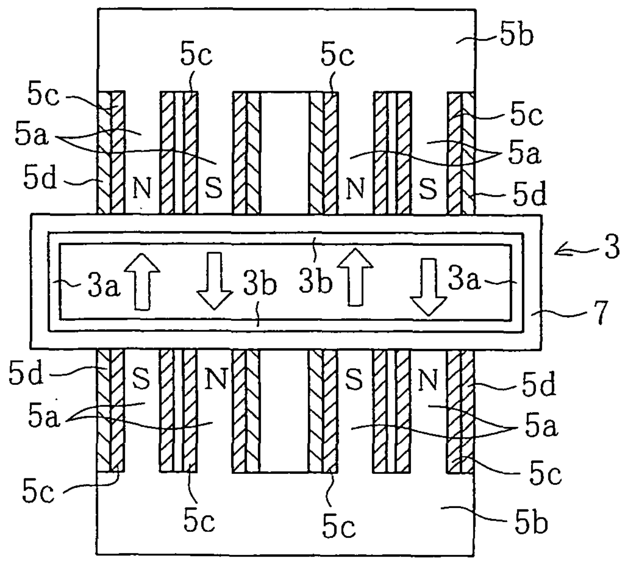

5b
5c
5c
5c
5c
5a
5a
5d
N
S
N
S
5d
3
3a
3b
3b
3a
7
5d
S
N
S
N
5d
5a
5a
5c
5c
5c
5c
5b

Figure 13

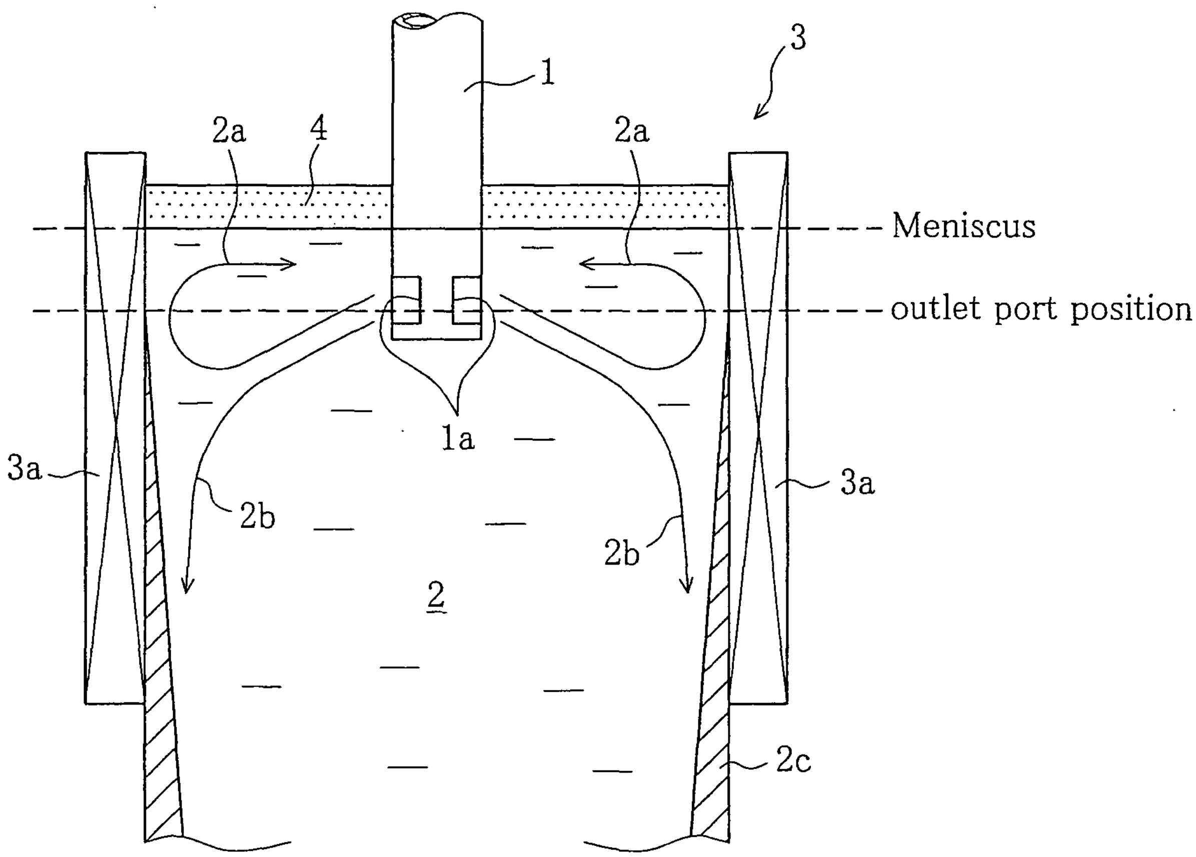


Figure 14

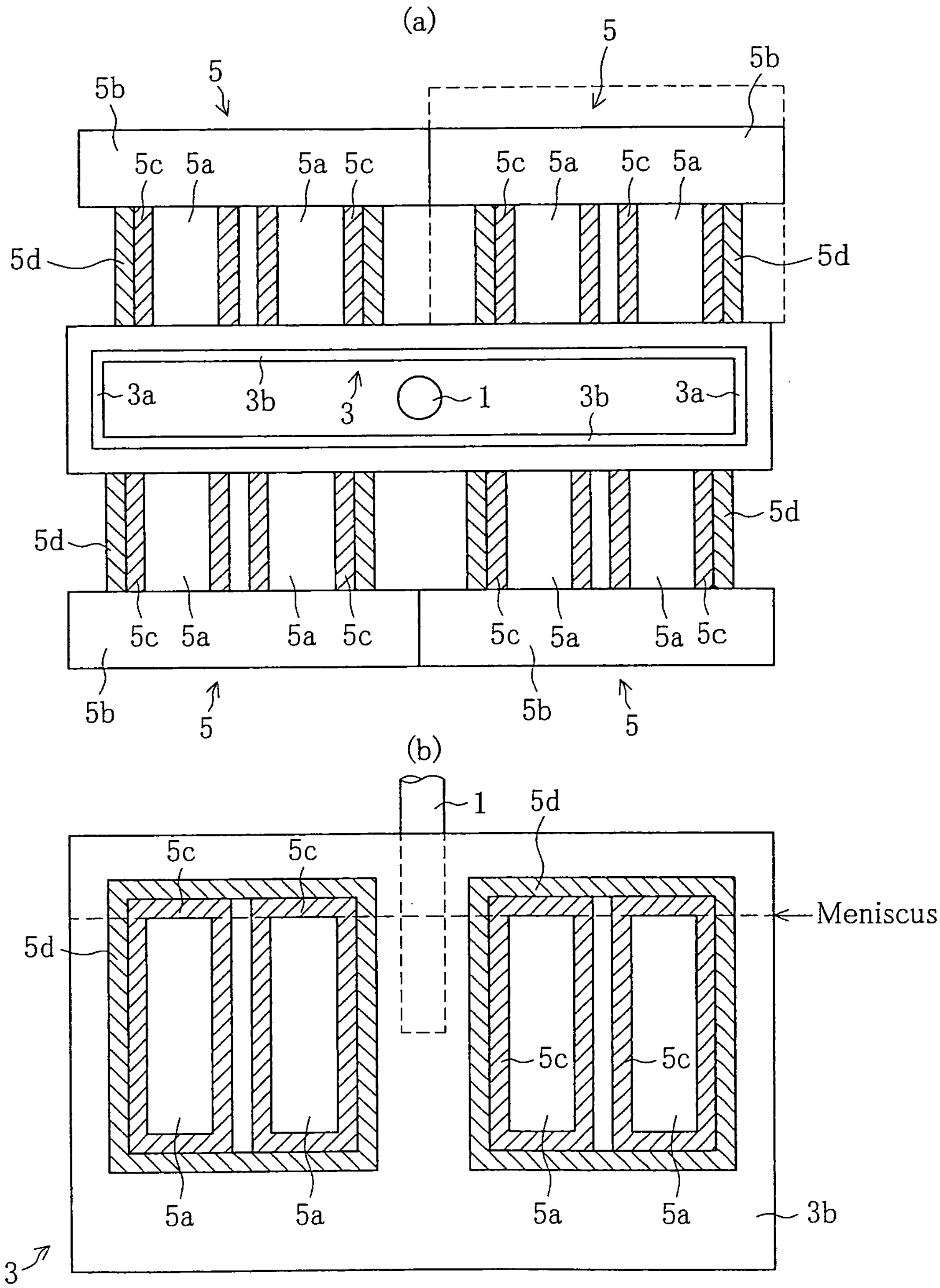

(a)
5
5b
5
5b
5c
5a
5a
5c
5c
5a
5c
5a
5d
5d
3a
3b
3
1
3b
3a
5d
5d
5c
5a
5a
5c
5c
5a
5a
5c
5b
5
5b
5
(b)
1
5d
5c
5c
Meniscus
5d
5c
5c
5a
5a
5a
5a
3b
3

Figure 15

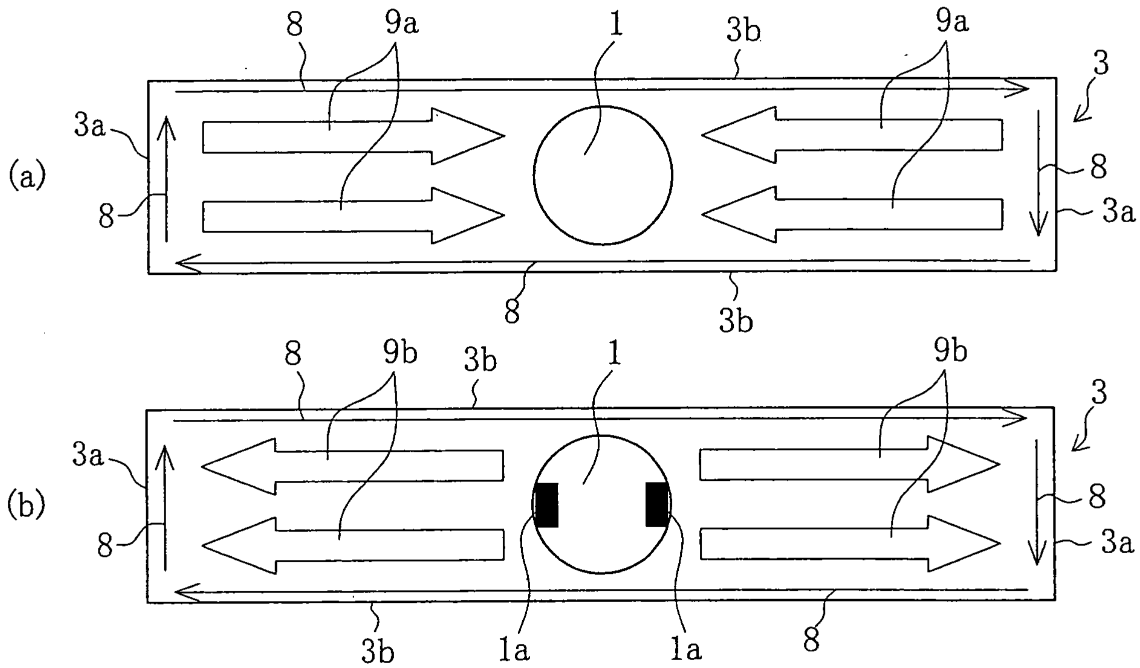
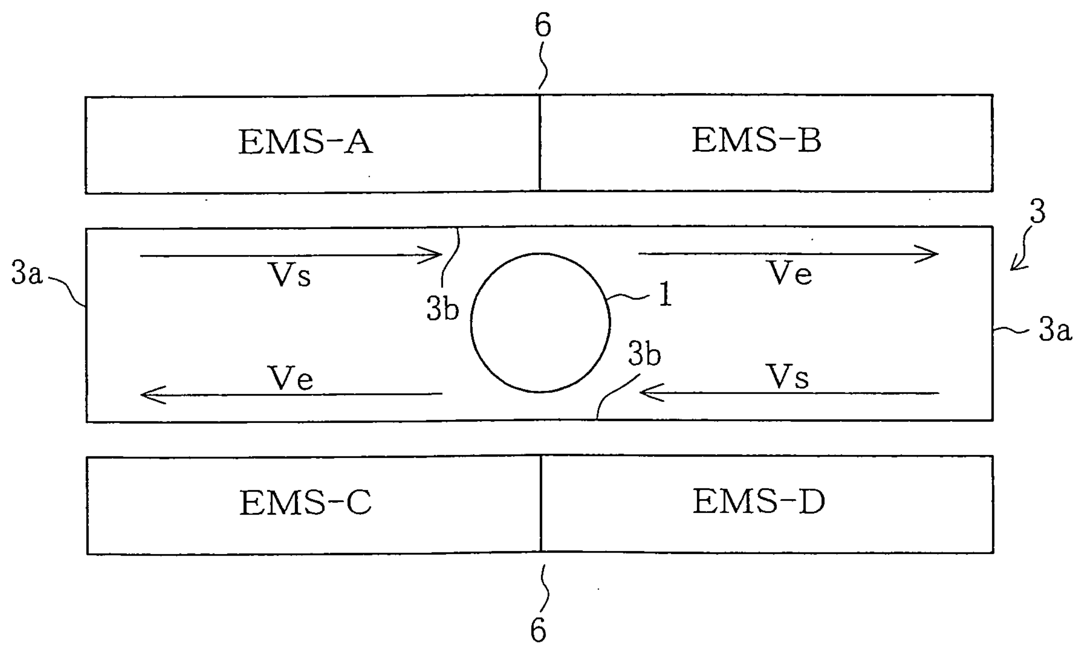


Figure 16



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2008/057510

A. CLASSIFICATION OF SUBJECT MATTER
B22D11/115(2006.01)i, *B22D11/11*(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B22D11/115, B22D11/11

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho	1922-1996	Jitsuyo Shinan Toroku Koho	1996-2008
Kokai Jitsuyo Shinan Koho	1971-2008	Toroku Jitsuyo Shinan Koho	1994-2008

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2007-7719 A (Sumitomo Metal Industries, Ltd.), 18 January, 2007 (18.01.07), Claims (Family: none)	1-4
A	JP 2005-349454 A (Sumitomo Metal Industries, Ltd.), 22 December, 2005 (22.12.05), Claims (Family: none)	1-4

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
08 July, 2008 (08.07.08)	15 July, 2008 (15.07.08)

Name and mailing address of the ISA/	Authorized officer
Japanese Patent Office	
Facsimile No.	Telephone No.

Form PCT/ISA/210 (second sheet) (April 2007)

REFERENCES CITED IN THE DESCRIPTION

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