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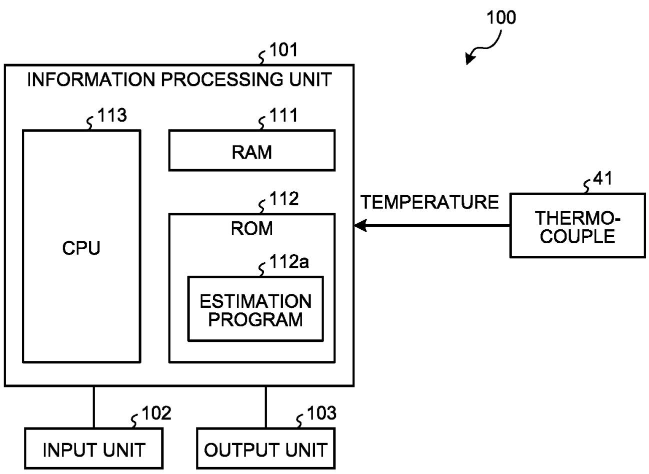
(54) MOLTEN STEEL FLOW-STATE ESTIMATING METHOD AND FLOW-STATE ESTIMATING DEVICE

(57) A molten steel fluidity estimation method estimates fluidity of molten steel in a casting mold of a continuous casting machine in such a manner that a CPU 113 calculates, at positions where thermocouples 41 are arranged in the casting mold of the continuous casting machine, an error between temperature distribution of the molten steel that is measured by using the thermocouples 41 and temperature distribution of the molten steel that is calculated by using a physical model; applies an external force in the vicinity of a discharge opening of a nozzle that discharges the molten steel into the casting mold; and calculates the fluidity of the molten steel in a state in which the external force adjusted to compensate the error is applied.

FIG.9



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Description

Field

[0001] The present invention relates to a technique of estimating fluidity of molten steel in a casting mold with a view to the quality improvement of a cast piece manufactured in a continuous casting machine.

Background

[0002] In a continuous casting machine, molten steel is continuously poured from a tundish into a casting mold in which water-cooled tubes are buried, cooled in the casting mold, and is drawn out from the lower part of the casting mold. In this case, in order to secure a mass balance, the opening degree of a nozzle is adjusted depending on a drawing-out speed. In particular, when performing highspeed casting in the continuous casting machine having such structure, the spouting flow of the molten steel from the discharge opening of the nozzle is easily destabilized and hence, there exists the case that the phenomenon called drift, in which a discharge flow from each of right-and-left discharge openings becomes nonuniform, occurs. Each steel manufacturer has introduced, in order to decrease such instability, a flow control device that applies a braking force to the molten steel by applying a magnetic field from the outside of the casting mold. Furthermore, in order to remove inclusions and bubbles that are trapped on a surface of a solidified shell, a flow control device has been increasingly introduced that applies a dynamic magnetic field to the molten steel to apply a stirring force thereto.

[0003] Conventionally, in order to design such molten-steel flow control device, as described in Patent Literature 1, for example, analyses of fluidity have been performed with water model experiments or numerical computations. However, according to the technique described in Patent Literature 1, the comparison of fluidity between analysis results of model calculations and actual phenomena is performed only by using data at several points in a steady operation. On the other hand, in actual equipment, there exist various disturbances, such as the clogging of the nozzle, turbulence of argon gas, and unstable boundary conditions depending on the opening of the nozzle. The online estimation and control of the fluidity of the molten steel in consideration of the effect of such disturbances can lead to achieving the quality improvement of a product.

[0004] Under such circumstances, a technique has been developed that estimates the fluidity of the molten steel online. For example, Patent Literatures 2 to 4 describe a technique that estimates the fluidity of the molten steel by performing conversion based on temperatures of the molten steel that are measured by using thermocouples buried in the casting mold.

Citation List

Patent Literature

[0005]

Patent Literature 1: Japanese Patent Application Laid-open No. 10-5957
Patent Literature 2: Japanese Patent Application Laid-open No. 2003-1386
Patent Literature 3: Japanese Patent Application Laid-open No. 2003-181609
Patent Literature 4: Japanese Patent No. 3386051 Summary

Technical Problem

[0006] However, as described in Patent Literatures 2 to 4, the technique that estimates the fluidity of the molten steel from the temperature of the molten steel can be applied only in the case of a solidification interface in the vicinity of the casting mold and hence, it is impossible to estimate the fluidity of the molten steel in three dimensions in the whole casting mold.

[0007] The present invention has been made to overcome such problems, and it is an object of the present invention to provide a molten steel fluidity estimation method and a fluidity estimation device in which fluidity of molten steel can be estimated online in three dimensions in the whole casting mold.

Solution to Problem

[0008] To solve the above-described problem and achieve the object, a molten steel fluidity estimation method according to the present invention estimates fluidity of molten steel in a casting mold of a continuous casting machine, and includes: an error calculating step of calculating, at positions of respective sensors arranged in the casting mold, an error between distribution of physical quantities measured by the respective sensors and distribution of physical quantities calculated by using a physical model; an external force applying step of applying an external force in a vicinity of a discharge opening of a nozzle configured to discharge the molten steel into the casting mold; and an estimating step of estimating fluidity by calculating the fluidity in a state in which the external force adjusted to compensate the error is applied.

[0009] Moreover, in the above-described molten steel fluidity estimation method according to the present invention, the estimating step includes: a perturbation calculating step of calculating a difference between fluidity in a state in which the external force is applied and fluidity in a steady state in which the external force is not applied, as perturbation of the fluidity due to the external force; a correction term calculating step of calculating a correction term by adjusting the external force and the perturbation of the fluidity so that the error is compensated; and a fluidity calculating step of calculating the fluidity by superposing the correction term on the fluidity in the steady state.

[0010] Moreover, in the above-described molten steel fluidity estimation method according to the present invention, at the external force applying step, the external force is applied in the vicinity of the discharge opening of the nozzle, with a plurality of types of external forces as bases, the external forces being combined with each other depending on a degree of influence of each external force, the perturbation calculating step calculates, corresponding to each type of the external force, a difference between the distribution of the physical quantities in the state in which the external force is applied and the distribution of the physical quantities in the steady state in which the external force is not applied, and calculates a degree of influence of each type of the external force compensating the error by performing linear regression analyses of the difference and the error, and the correction term calculating step calculates a correction term compensating the error based on the degree of influence and the difference between the fluidity calculated corresponding to each type of external force in the state in which the external force is applied and the fluidity in the steady state in which the external force is not applied.

[0011] Moreover, in the above-described molten steel fluidity estimation method according to the present invention, the sensor is a thermocouple, and the physical quantities represent a temperature of the molten steel at the position in which the thermocouple is arranged.

[0012] To solve the above-described problem and achieve the object, a molten steel fluidity estimation device according to the present invention is adapted to estimate fluidity of molten steel in a casting mold of a continuous casting machine, and includes: an error calculation unit configured to calculate, at positions of respective sensors arranged in the casting mold, an error between distribution of physical quantities measured by the respective sensors and distribution of the physical quantities calculated by using a physical model; an external-force application unit configured to apply an external force in a vicinity of a discharge opening of a nozzle configured to discharge the molten steel into the casting mold; and an estimation unit configured to calculate fluidity in a state in which the external force adjusted to compensate the error is applied. Advantageous Effects of Invention

[0013] With the molten steel fluidity estimation method and the fluidity estimation device according to the present invention, fluidity of molten steel can be estimated online in three dimensions in the whole casting mold.

Brief Description of Drawings

[0014]

FIG. 1 is a schematic view illustrating one constitutional example of a continuous casting machine to which the present invention is applied.

FIG. 2 is a view illustrating arrangement positions of respective thermocouples in a casting mold, as an example.

FIG. 3 is a view illustrating boundary conditions in applying a turbulence model, as an example.

FIG. 4 is a view illustrating, as an example, fluidity of molten steel in the cross section at the center in the thickness direction of a slab, the fluidity being calculated using the turbulence model.

FIG. 5 is a view illustrating, as an example, fluidity of the molten steel in the vicinity of the casting mold in the thickness direction of the slab, the fluidity being calculated using the turbulence model.

FIG. 6 is a view illustrating, as an example, a temperature distribution in the molten steel, the temperature distribution being converted from the fluidity of the molten steel that is calculated using the turbulence model.

FIG. 7 is an explanatory view for explaining procedures of comparing a temperature measured by using the thermocouple with a temperature calculated using the turbulence model.

FIG. 8 is a view illustrating external forces applied in the vicinity of a discharge opening of a nozzle.

FIG. 9 is a block diagram illustrating a configuration of a fluidity estimation device according to one embodiment of the present invention.

FIG. 10 is a flowchart illustrating a flow of fluidity estimation processing according to one embodiment of the present invention.

FIG. 11A is a view illustrating, as an example, fluidity of molten steel that is calculated in a state that the external force is applied only to a left discharge opening of the nozzle in the horizontal direction.

FIG. 11B is a view illustrating, as an example, temperature distribution in the molten steel, the temperature distribution being calculated in a state that the external force is applied only to the left discharge opening of the nozzle in the horizontal direction.

FIG. 12A is a view illustrating, as an example, fluidity of molten steel that is calculated in a state that the external force is applied only to a right discharge opening of the nozzle in the horizontal direction.

FIG. 12B is a view illustrating, as an example, temperature distribution in the molten steel, the temperature distribution being calculated in a state that the external force is applied only to the right discharge opening of the nozzle in the horizontal direction.

FIG. 13A is a view illustrating, as an example, a difference between the fluidity of the molten steel in a state that the external force is applied only to the left discharge opening of the nozzle in the horizontal direction, and fluidity of molten steel in a steady state.

FIG. 13B is a view illustrating, as an example, a difference between the temperature distribution in the molten steel in a state that the external force is applied only to the left discharge opening of the nozzle in the horizontal direction, and temperature distribution in the molten steel in the steady state.

FIG. 14A is a view illustrating, as an example, a difference between the fluidity of the molten steel in a state that the external force is applied only to the right discharge opening of the nozzle in the horizontal direction, and the fluidity of the molten steel in the steady state.

FIG. 14B is a view illustrating, as an example, a difference between the temperature distribution in the molten steel in a state that the external force is applied only to the right discharge opening of the nozzle in the horizontal direction, and the temperature distribution in the molten steel in the steady state.

FIG. 15A is a view illustrating a time transition of the external force that compensates an error between the measured temperature distribution and the temperature distribution calculated in the steady state, in the horizontal direction.

FIG. 15B is a view illustrating a time transition of the external force that compensates the error between the measured temperature distribution and the temperature distribution calculated in the steady state, in the vertical direction.

FIG. 16A is a view illustrating a relation among measured temperature distribution, uncorrected temperature distribution calculated in the steady state, and corrected temperature distribution in a state that the external force is applied.

FIG. 16B is a view illustrating a relation among measured temperature distribution, uncorrected temperature distribution calculated in the steady state, and corrected temperature distribution in a state that the external force is applied.

FIG. 17A is a view illustrating a relation among measured temperature distribution, uncorrected temperature distribution calculated in the steady state, and corrected temperature distribution in a state that an external force is applied.

FIG. 17B is a view illustrating a relation among measured temperature distribution, uncorrected temperature distribution calculated in a steady state, and corrected temperature distribution in a state that the external force is applied.

FIG. 18A is a view illustrating a relation among measured temperature distribution, uncorrected temperature distribution calculated in the steady state, and corrected temperature distribution in a state that the external force is applied.

FIG. 18B is a view illustrating a relation among measured temperature distribution, uncorrected temperature distribution calculated in the steady state, and corrected temperature distribution in a state that the external force is applied.

FIG. 19A is a view illustrating, as an example, uncorrected fluidity of molten steel that is calculated in the steady state.

FIG. 19B is a view illustrating, as an example, fluidity of molten steel that is estimated by the correction of applying the external force.

Description of Embodiments

[0015] Hereinafter, with reference to drawings, fluidity estimation processing performed by a molten steel fluidity estimation device according to one embodiment of the present invention is explained.

Constitution of continuous casting machine

[0016] First of all, with reference to FIG. 1, one constitutional example of the continuous casting machine to which the present invention is applied is explained. As illustrated in FIG. 1, in a continuous casting machines 1, a casting mold 4 is arranged below a tundish 3 filled with molten steel 2 in the vertical direction, and a nozzle 5 that is a feed opening for feeding the molten steel 2 to the casting mold 4 is arranged on the bottom of the tundish 3. The molten steel 2 is continuously poured into the casting mold 4 from the tundish 3, cooled by the casting mold 4 in which water-cooled tubes are buried, and drawn out from the lower part of the casting mold 4 thus forming a slab. In this case, in order to secure a mass balance, the opening degree of the nozzle 5 is adjusted depending on a drawing-out speed.

[0017] For the casting mold 4, as illustrated in FIG. 2, a plurality of thermocouples 41 are arranged on a face F and a face B, the face F and the face B constituting both ends of the slab to be cast in the thickness direction thereof (the vertical direction on the paper on which FIG. 2 is drawn). Each thermocouple 41 measures a temperature of the molten steel 2 at the position at which the thermocouple 41 is arranged. In the present embodiment, the thermocouples 41 are buried on each face so as to be arranged in 7 rows in the height direction and in 16 columns in the width direction. Furthermore, the casting mold 4 includes therein a coil (not illustrated in the drawings) used for generating a stirrer magnetic field that rotates the surface of molten steel.

Physical model for calculating fluidity of molten steel

[0018] Next, the explanation is made with respect to a physical model used for the fluidity estimation processing performed by the molten steel fluidity estimation device according to one embodiment of the present invention. In the fluidity estimation processing performed by the molten steel fluidity estimation device according to the one embodiment of the present invention, the fluidity of the molten steel 2 is calculated using a turbulence model. To be more specific, assuming that operational conditions such as a casting speed, a width and thickness of the slab, and a coil current of the stirrer magnetic field are input conditions, the fluidity (flow speed distribution) of the molten steel 2 is calculated using a standard k-ε model of the turbulence model. In this case, boundary conditions are specified as illustrated in FIG. 3. That is, in an inflow part, a flow speed corresponding to a mass flow depending on the casting speed specified is induced. In an outflow part, under a free outflow boundary condition, no gradient of each of various physical quantities is assumed to be in a flow direction. Furthermore, an inner wall of the casting mold 4 constitutes a solid wall that moves at a speed equal to the casting speed. FIG. 4 and FIG. 5 are views each illustrating, as an example, fluidity of the molten steel 2 that is calculated in this manner. FIG. 4 is a view illustrating, as an example, flow speed distribution of the molten steel 2 in the cross section at the center in the thickness direction of the slab to be cast. Furthermore, FIG. 5 is a view illustrating, as an example, flow speed distribution of the molten steel 2 in the vicinity of the casting mold 4 in the thickness direction of the slab to be cast.

[0019] A heat transfer coefficient between the molten steel 2 and a solidified shell varies depending on the flow speed of a solidification interface, and is reflected in change of the temperature of the casting mold 4 at the position of the thermocouple 41 (see Patent Literature 4). Accordingly, in the present embodiment, the fluidity of the molten steel 2 is calculated using the turbulence model, and converted into temperature distribution thus obtaining the temperature distribution. To be more specific, the temperature-flow speed conversion rule described in Patent Literature 4 is reversely used. FIG. 6 is a view illustrating, as an example, temperature distribution of the molten steel 2 that is calculated in this manner. In FIG. 6, the axis of ordinate and the axis of abscissa correspond to each row position of the thermocouples arranged in 7 rows and each column position of the thermocouples arranged in 16 columns that are illustrated in FIG. 2, respectively. That is, the axis of ordinate indicates the row numbers 1 to 7 of the thermocouples from the bottom, and the axis of abscissa indicates the column numbers 1 to 16 of the thermocouples from the left. Hereinafter, in illustrating temperature distribution at thermocouple positions, the axis of ordinate and the axis of abscissa are used in the same manner as above.

Compensation of error between measurement value and calculated value in temperature distribution

[0020] Next, the principle of the present invention is explained with reference to FIG. 7. In the present invention, as illustrated in FIG. 7, the temperature distribution calculated by the physical model mentioned above (hereinafter, referred to as "T_{calc}"), and the temperature distribution measured by using the thermocouples 41 (hereinafter, referred to as "T_{act}") are compared with each other. Furthermore, the error obtained as above is compensated by the fluidity estimation processing described later thus estimating fluidity of the molten steel 2.

[0021] The difference between the temperature distribution T_{calc} calculated by the physical model mentioned above and the temperature distribution T_{act} measured using the thermocouples 41 can be attributed mainly to the changes in the shape of the nozzle 5, such as clogging due to deposits, (boundary conditions in the vicinity of the nozzle 5). Here, it is assumed that the molten steel 2 discharged from the nozzle 5 moves in accordance with the equation of motion of fluidity. Accordingly, in the present embodiment, since the change in the shape of the nozzle 5 is simply expressed without using a fixed wall, an external force that causes the perturbation of fluidity is applied in the vicinity of the discharge opening of the nozzle 5 thus compensating the error on the physical model. To be more specific, as illustrated in FIG. 8, a horizontal external force Fx (Fx (left), Fx (right)) and a vertical external force Fy (Fy (left), Fy (right)) are applied in the vicinities of respective right-and-left discharge openings 51 of the nozzle 5 depending on the degree of influence of each of the horizontal external force Fx and the vertical external force Fy.

[0022] Hereinafter, corresponding to the above-mentioned four types of external forces, fluidity of the molten steel 2 is referred to as "U_i", the fluidity being calculated using the physical model in a state that each external force is applied. Here, the suffix i means the identification information of the type of the external force to be applied, and takes an integer from 1 to 4. In the same manner as above, temperature distribution of the molten steel 2 that is calculated using the physical model in a state that the external force is applied is referred to as "T_i". A difference between fluidity U_i of the molten steel 2 that is calculated using the physical model in a state that the external force is applied, and fluidity of molten steel 2 that is calculated using the physical model in the steady state in which the external force is not applied (hereinafter, referred to as "U_{calc}") is referred to as "ΔU_i". In the same manner as above, a difference between temperature distribution T_i of the molten steel 2 that is calculated using the physical model in a state in which the external force is applied and temperature distribution T_{calc} of the molten steel 2 that is calculated using the physical model in the steady state is referred to as "ΔT_i". Here, the following expressions (1) and (2) are established.

$$\Delta T_i = T_i - T_{calc} \tag{1}$$

$$\Delta U_i = U_i - U_{calc} \tag{2}$$

Constitution of fluidity estimation device

[0023] Next, with reference to FIG. 9, the constitution of the molten steel fluidity estimation device according to one embodiment of the present invention is explained. FIG. 9 is a block diagram illustrating the constitution of the molten steel fluidity estimation device according to one embodiment of the present invention. As illustrated in FIG. 9, a fluidity estimation device 100 of molten steel according to one embodiment of the present invention is provided with an information processing unit 101, an input unit 102, and an output unit 103.

[0024] The information processing unit 101 is constituted of a general-purpose information processing unit, such as a personal computer or a workstation, and provided with a RAM 111, a ROM 112, and a CPU 113. The RAM 111 temporarily stores a control program and control data with respect to processing executed by the CPU 113, and functions as a working area for the CPU 113.

[0025] The ROM 112 stores an estimation program 112a that executes fluidity estimation processing of molten steel according to one embodiment of the present invention, a control program that controls overall operation of the information processing unit 101, and control data. The CPU 113 controls overall operation of the information processing unit 101 in accordance with the estimation program 112a and the control program that are stored in the ROM 112. To be more specific, the CPU113 calculates, as described later, fluidity based on input operation information and a known physical model, and converts the fluidity calculated into temperature distribution thus obtaining the temperature distribution. Furthermore, the CPU 113 analyzes a difference between the calculated temperature distribution and the temperature distribution measured by using the thermocouples 41 buried in the casting mold 4 thus estimating the fluidity of the molten steel 2.

[0026] The input unit 102 is constituted of input units, such as a keyboard, a mouse pointer, and a numeric keypad, and operated in inputting the various kinds of information to the information processing unit 101. The output unit 103 is constituted of output units, such as a display and a printer, and outputs various kinds of processing information from the information processing unit 101.

Fluidity estimation processing

[0027] Next, with reference to the flowchart illustrated in FIG. 10, a flow of fluidity estimation processing of molten steel according to one embodiment of the present invention is explained. FIG. 10 is the flowchart illustrating the flow of the fluidity estimation processing of the molten steel according to one embodiment of the present invention. The flowchart illustrated in FIG. 10 is started at a timing where an operator has operated the input unit 102 to instruct the information processing unit 101 to execute the fluidity estimation processing, and the fluidity estimation processing advances to S1. Here, the fluidity estimation processing mentioned below is achieved by the fact that the CPU 113 executes the estimation program 112a stored in the ROM 112.

[0028] In the processing of S1, the CPU 113 uses the operation information acquired from an outside DB (not illustrated in the drawings) as an input condition, and the turbulence model to calculate the fluidity U_{calc} and the temperature distribution T_{calc} of the molten steel 2 in the steady state. Then, the processing of S1 is completed, and the fluidity estimation processing advances to S2.

[0029] In the processing of S2, the CPU 113 calculates, using the turbulence model, the fluidity U_i and the temperature distribution T_i of the molten steel 2 in a state in which the above-mentioned external force is applied in the vicinity of the discharge opening 51 of the nozzle 5. Then, the processing of S2 is completed, and the fluidity estimation processing advances to S3.

[0030] FIG. 11A to FIG. 12B are views each illustrating, as an example, fluidity and temperature distribution of the molten steel 2, the fluidity and temperature distribution being calculated in a state in which the external force is applied. FIG. 11A illustrates fluidity U_1 of the molten steel 2 that is calculated in a state in which Fx (left) (i= 1, for example) is applied only to the left discharge opening 51 of the nozzle 5 in the horizontal direction, and FIG. 11B illustrates temperature distribution T_1 of the molten steel 2 that is calculated in the same manner as the case above. Furthermore, FIG. 12A illustrates fluidity U_2 of the molten steel 2 that is calculated in a state in which Fx (right) (i= 2, for example) is applied only to the right discharge opening 51 of the nozzle 5 in the horizontal direction, and FIG. 12B illustrates temperature distribution T_2 of the molten steel 2 that is calculated in the same manner as the case above.

[0031] In the processing of S3, the CPU 113 performs a sensitivity analysis. That is, in terms of the fluidity of the molten steel 2, the CPU 113 calculates a difference ΔU_i between the fluidity U_i calculated in a state in which the external force is applied and the fluidity U_{calc} calculated in the steady state. Furthermore, in terms of the temperature distribution of the molten steel 2, the CPU 113 calculates a difference ΔT_i between temperature distribution T_i calculated in a state in which the external force is applied, and temperature distribution T_{calc} calculated in the steady state. Here, ΔU_i and ΔT_i that are calculated mean the fluidity and the temperature distribution that are affected by the external force; that is, the fluidity and the temperature distribution in a state in which the external force is applied, respectively. Then, the processing of S3 is completed, and the fluidity estimation processing advances to S4.

[0032] FIG. 13A to FIG. 14B are views illustrating, as examples, ΔU_i and ΔT_i that are calculated, respectively. FIG. 13A illustrates DU_1 in a state in which Fx (left) (i= 1, for example) is applied only to the left discharge opening 51 of the nozzle 5 in the horizontal direction, and FIG. 13B illustrates ΔT_1 in the same state as above. Furthermore, FIG. 14A illustrates ΔU_2 in a state in which Fx (right) (i= 2, for example) is applied only to the right discharge opening 51 of the nozzle 5 in the horizontal direction, and FIG. 14B illustrates ΔT_2 in the same state as above.

[0033] In the processing of S4, the CPU 113 compares temperature distribution T_{act} of the molten steel 2 that is measured by using the thermocouples 41, with temperature distribution T_{calc} of the molten steel 2 that is calculated in the steady state, and calculates an error between the temperature distribution T_{act} and the temperature distribution T_{calc}. Then, the processing of S4 is completed, and the fluidity estimation processing advances to S5.

[0034] In the processing of S5, the CPU 113 performs a linear regression analysis of the error calculated in the processing of S4 depending on ΔT_i, which is a result of the sensitivity analysis, calculated in the processing of S3. To be more specific, the CPU 113 performs, as illustrated in the following expressions (3) to (7), the linear regression analysis of the error between T_{act} and T_{calc} depending on a total of nine bases (regression variables) including four bases corresponding to the respective four types of external forces, and five bias-correction-use bases corresponding to the respective five rows in which the thermocouples 41 are arranged.

$$\mathbf{T}_{\mathrm{act}} - \mathbf{T}_{\mathrm{calc}} \approx \mathbf{M}\mathbf{w} \tag{3}$$

$$M = \begin{pmatrix} \Delta\mathbf{T}_1 & \Delta\mathbf{T}_2 & \Delta\mathbf{T}_3 & \Delta\mathbf{T}_4 & \mathbf{B} \end{pmatrix} \tag{4}$$

$$\mathbf{w} = \left(\mathbf{M}^T\mathbf{M}\right)^{-1}\mathbf{M}^T\left(\mathbf{T}_{\mathrm{act}} - \mathbf{T}_{\mathrm{calc}}\right) \tag{5}$$

$$\mathbf{B} = \begin{pmatrix} \mathbf{1} & & & & \\ & \mathbf{1} & & & \\ & & \mathbf{1} & & \\ & & & \mathbf{1} & \\ & & & & \mathbf{1} \end{pmatrix} \tag{6}$$

$$\mathbf{1} = \begin{pmatrix} 1 \\ 1 \\ 1 \\ \cdot \\ \cdot \\ 1 \end{pmatrix} \tag{7}$$

[0035] Here, measurement values corresponding to the respective five rows of the thermocouples 41 out of seven rows of the thermocouples 41 are used for the fluidity estimation processing. Assuming that, with respect to each of the five rows of the thermocouples 41 to be used, a certain bias is on both the face F and the face B that is not influenced by the external force, five bases are provided corresponding to the respective bias corrections for five rows. The number of lines of a bias matrix B illustrated in the above-mentioned expressions (4) and (6) is the total number of the thermocouples 41 arranged in five rows (sum total of the thermocouples 41 arranged in the face F and the face B), and the number of columns of the bias matrix B is five, which corresponds to the respective five rows of the thermocouples 41. Furthermore, the number of elements of a vector 1 illustrated in the above-mentioned expressions (6) and (7) is the number of the thermocouples 41 arranged in each row (sum total of the thermocouples 41 arranged in the face F and the face B). Then, the processing of S5 is completed, and the fluidity estimation processing advances to S6.

[0036] Each element of a vector w', which is composed of only the first to fourth elements corresponding to the respective bases of four external forces out of regression coefficient vectors w to be obtained here, may indicate the degree of influence of each of the above-mentioned four types of external forces in terms of an external force that compensates the error. Accordingly, the external force that compensates the error can be obtained from the vector w'. FIG. 15A is a view illustrating a time transition of the external force Fx (defined as positive in the outward direction) applied to each of the right-and-left discharge openings 51 of the nozzle 5 in the horizontal direction. FIG. 15B is a view illustrating a time transition of the external force Fy (defined as positive in the downward direction) applied to each of the right-and-left discharge openings 51 of the nozzle 5 in the vertical direction.

[0037] Furthermore, a correction term $T_{correct}$ obtained by multiplying the element of the vector w' by the difference ΔT_i of the above-mentioned temperature distribution is superposed on the temperature distribution T_{calc} in the steady state thus calculating a temperature distribution Test corrected by applying the external force (the error is compensated). FIG. 16A to FIG. 18B are views each illustrating the relation among the measured (observed) temperature distribution T_{act}, the temperature distribution T_{calc} calculated in a steady state before being corrected, and the temperature distribution Test after being corrected by applying the external force. Each pair of FIG. 16A and FIG. 16B, FIG. 17A and FIG. 17B, and FIG. 18A and FIG. 18B illustrates temperature distribution at positions of the thermocouples 41 buried in a different face (face F or face B) in the same row. It is understood that the temperature distribution T_{est} after being corrected by applying the external force follows the difference between the respective temperature distributions T_{calc} observed in the face F and the face B, each of which is incapable of being expressed in terms of the temperature distribution T_{calc} before being corrected.

[0038] In the processing of S6, the CPU 113 superposes a correction term $U_{correct}$ obtained by multiplying the element of the vector w' indicating a regression coefficient by the difference ΔU_i of the above-mentioned fluidity on the fluidity U_{calc} in the steady state thus calculating (estimating) the fluidity U_{est} of the molten steel 2 after being corrected. Here, both the fluidity U_{calc} in the steady state and the fluidity U_i in a state in which the external force is applied satisfy a continuous turbulence model formula and hence, the difference ΔU_i therebetween also satisfies the continuous turbulence model formula. Accordingly, even when the correction term $U_{correct}$ is added to the fluidity U_{calc} in the steady state, the law of conservation of mass is satisfied, and thus the fluidity U_{est} after being corrected can be estimated. To be more specific, the CPU 113 estimates the fluidity U_{est} of the molten steel 2 after being corrected, by calculating the following expressions (8) and (9). Then, the processing of S6 is completed, and a series of fluidity estimation processes are terminated.

$$\mathbf{U}_{\text{correct}} = \left(\Delta\mathbf{U}_1 \quad \Delta\mathbf{U}_2 \quad \Delta\mathbf{U}_3 \quad \Delta\mathbf{U}_4\right)\mathbf{w}' \tag{8}$$

$$\mathbf{U}_{\text{est}} = \mathbf{U}_{\text{calc}} + \mathbf{U}_{\text{correct}} \tag{9}$$

[0039] FIG. 19A is a view illustrating, as an example, the fluidity U_{calc} before being corrected in the steady state. FIG. 19B is a view illustrating, as an example, fluidity (after being corrected) estimated by the fluidity estimation processing of the present embodiment.

[0040] As explained clearly by the explanation above, in the fluidity estimation processing according to one embodiment of the present invention, the CPU 113 analyzes the difference between temperature distribution calculated based on a physical model and observed temperature distribution to correct the fluidity calculated based on the physical model. Accordingly, the fluidity calculated based on the physical model is corrected with the law of conservation of mass satisfied, and thus, while excellent physical consistency is being maintained, fluidity is estimated online in three dimensions for the whole casting mold 4.

[0041] Although the embodiment to which the invention made by the inventors is applied has been specifically explained in conjunction with drawings, the present invention is not limited to the above-described embodiment that merely constitutes one embodiment of the present invention. That is, various modifications and applications made by those skilled in the art or the like based on the present embodiment are arbitrarily conceivable without departing from the gist of the present invention.

Industrial Applicability

[0042] As described above, the molten steel fluidity estimation method and the fluidity estimation device according to the present invention are capable of estimating online the fluidity of the molten steel in three dimensions for the whole casting mold thus being applicable to the continuous casting process in the continuous casting machine.

Reference Signs List

[0043]

1	continuous casting machine
2	molten steel
3	tundish
4	casting mold
41	thermocouple
5	nozzle
51	discharge opening
100	fluidity estimation device
101	information processing unit
102	input unit
103	output unit
111	RAM
112	ROM
112a	estimation program
113	CPU

Claims

1. A molten steel fluidity estimation method of estimating fluidity of molten steel in a casting mold of a continuous casting machine, the method comprising:

an error calculating step of calculating, at positions of respective sensors arranged in the casting mold, an error between distribution of physical quantities measured by the respective sensors and distribution of physical quantities calculated by using a physical model;
an external force applying step of applying an external force in a vicinity of a discharge opening of a nozzle configured to discharge the molten steel into the casting mold; and
an estimating step of estimating fluidity by calculating the fluidity in a state in which the external force adjusted to compensate the error is applied.

2. The molten steel fluidity estimation method according to claim 1, wherein
the estimating step comprises:

a perturbation calculating step of calculating a difference between fluidity in a state in which the external force is applied and fluidity in a steady state in which the external force is not applied, as perturbation of the fluidity due to the external force;
a correction term calculating step of calculating a correction term by adjusting the external force and the perturbation of the fluidity so that the error is compensated; and
a fluidity calculating step of calculating the fluidity by superposing the correction term on the fluidity in the steady state.

3. The molten steel fluidity estimation method according to claim 2, wherein
at the external force applying step, the external force is applied in the vicinity of the discharge opening of the nozzle,

with a plurality of types of external forces as bases, the external forces being combined with each other depending on a degree of influence of each external force,
the perturbation calculating step calculates, corresponding to each type of the external force, a difference between the distribution of the physical quantities in the state in which the external force is applied and the distribution of the physical quantities in the steady state in which the external force is not applied, and calculates a degree of influence of each type of the external force compensating the error by performing linear regression analyses of the difference and the error, and
the correction term calculating step calculates a correction term compensating the error based on the degree of influence and the difference between the fluidity calculated corresponding to each type of external force in the state in which the external force is applied and the fluidity in the steady state in which the external force is not applied.

4. The molten steel fluidity estimation method according to any one of claims 1 to 3, wherein the sensor is a thermocouple, and the physical quantities represent a temperature of the molten steel at the position in which the thermocouple is arranged.

5. A molten steel fluidity estimation device adapted to estimate fluidity of molten steel in a casting mold of a continuous casting machine, the fluidity estimation device comprising:

an error calculation unit configured to calculate, at positions of respective sensors arranged in the casting mold, an error between distribution of physical quantities measured by the respective sensors and distribution of the physical quantities calculated by using a physical model;
an external-force application unit configured to apply an external force in a vicinity of a discharge opening of a nozzle configured to discharge the molten steel into the casting mold; and
an estimation unit configured to calculate fluidity in a state in which the external force adjusted to compensate the error is applied.

FIG.1

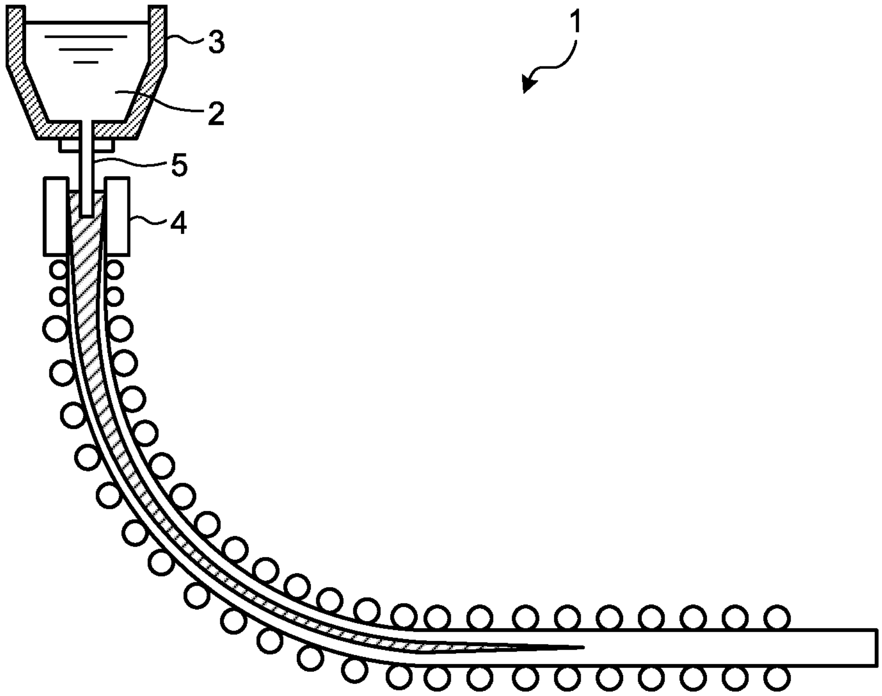


FIG.2

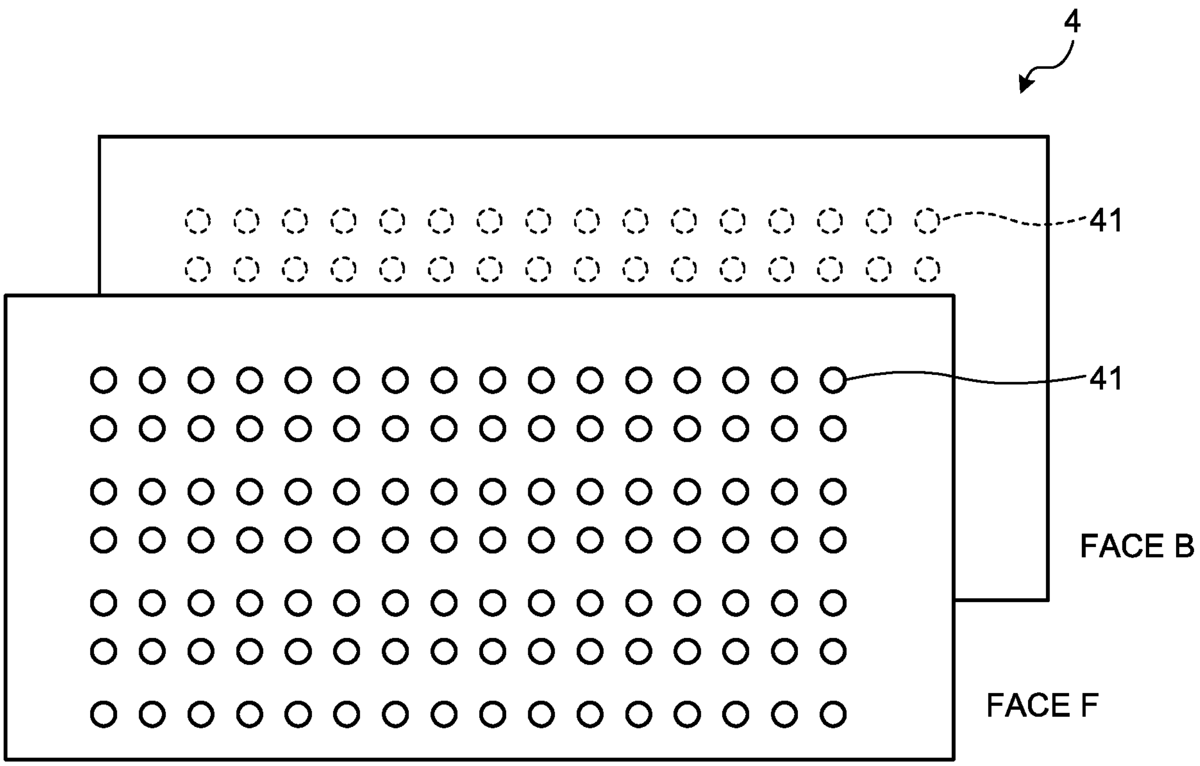


FIG.3

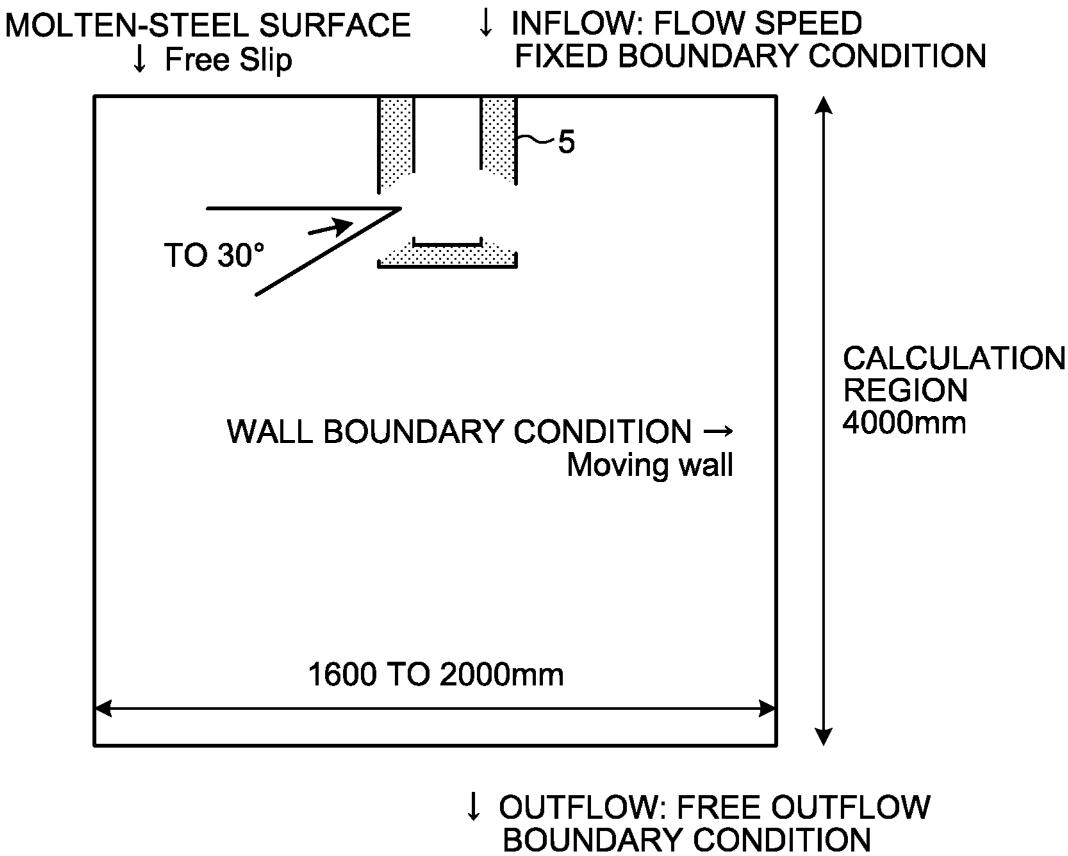

MOLTEN-STEEL SURFACE
↓ Free Slip
↓ INFLOW: FLOW SPEED
FIXED BOUNDARY CONDITION
5
TO 30°
CALCULATION
REGION
4000mm
WALL BOUNDARY CONDITION →
Moving wall
1600 TO 2000mm
↓ OUTFLOW: FREE OUTFLOW
BOUNDARY CONDITION

FIG.4

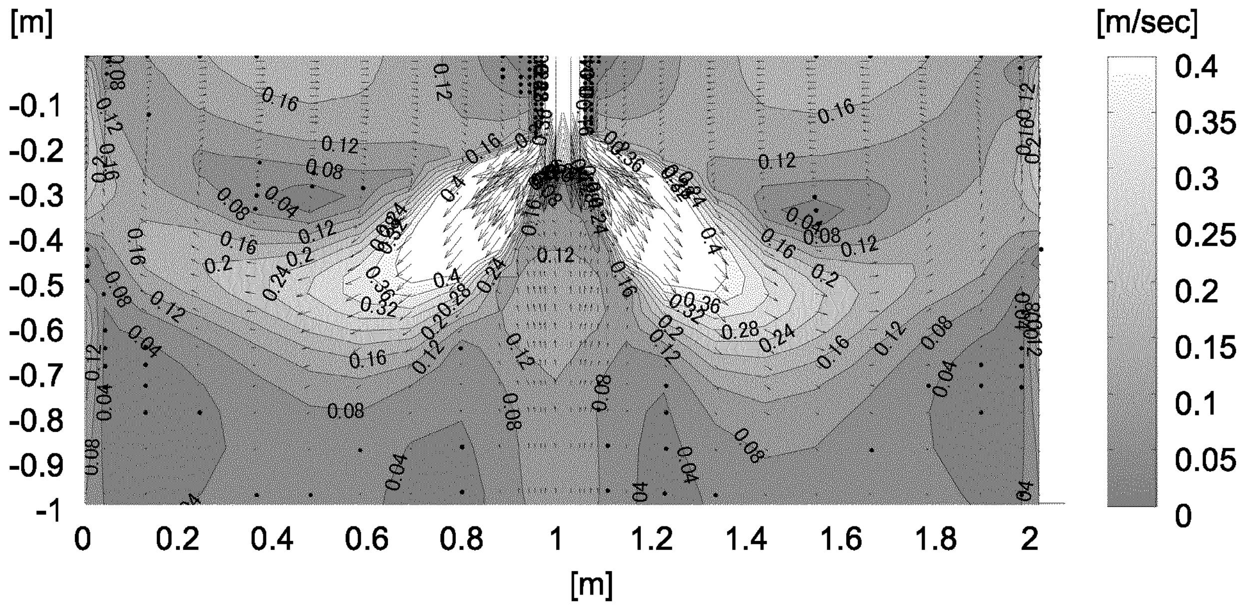

[m]
[m/sec]
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
[m]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

FIG.5

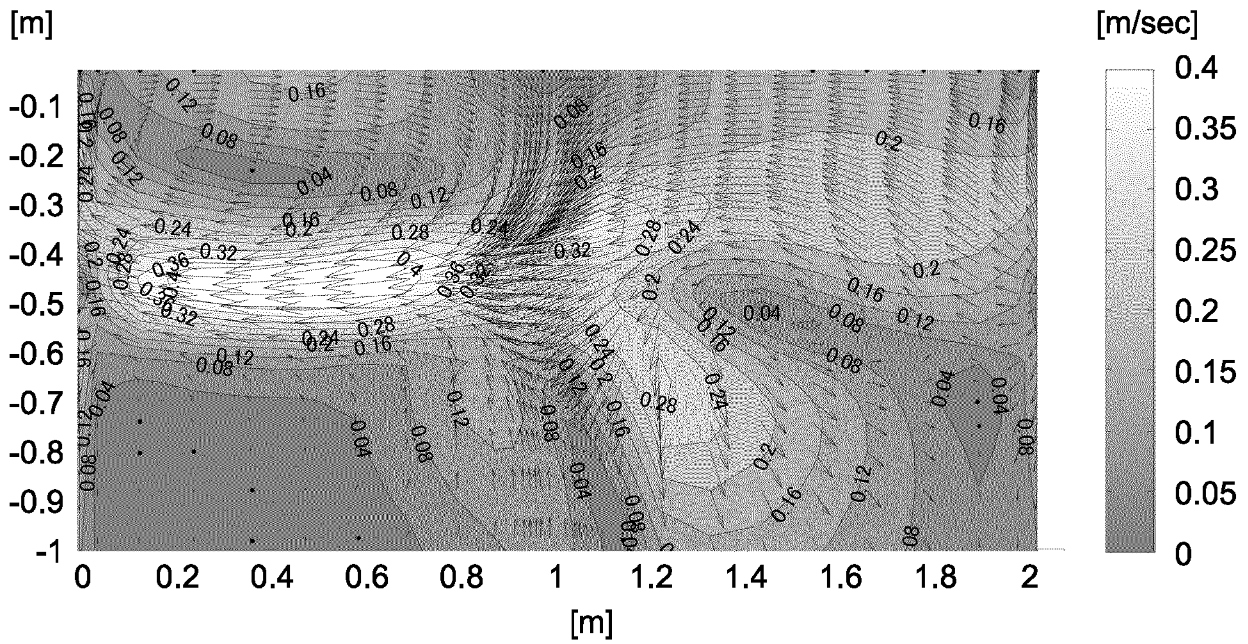
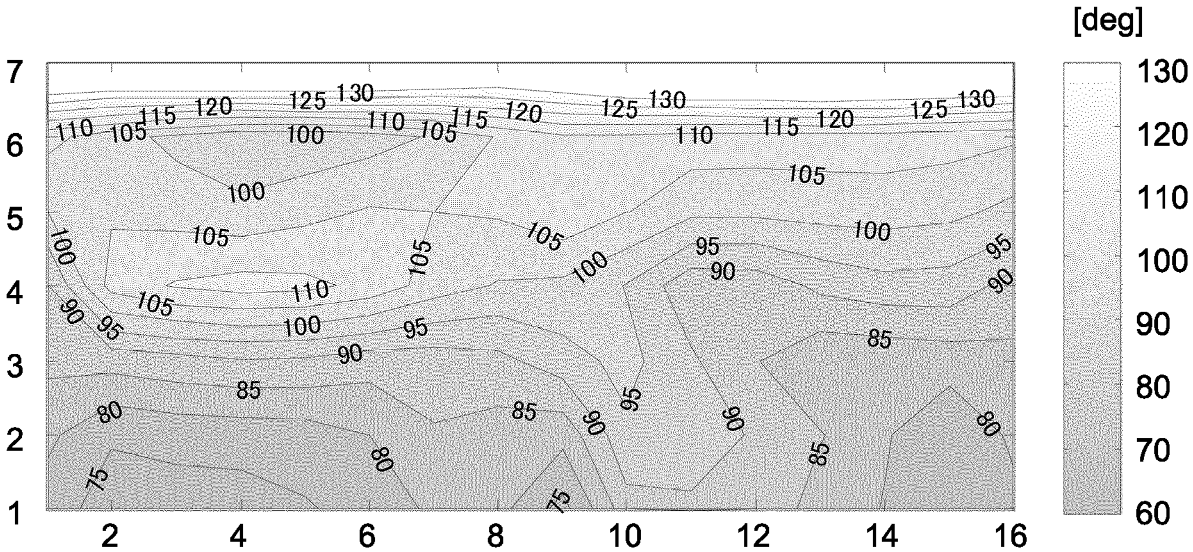

[m]
[m/sec]
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
[m]
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0

FIG.6


[deg]
130
120
110
100
90
80
70
60
7
6
5
4
3
2
1
2
4
6
8
10
12
14
16
110
105
115
120
125
130
100
110
105
115
120
125
130
110
115
120
125
130
100
105
105
100
105
100
105
100
105
95
90
110
90
95
95
90
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90
85
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80
85
90
95
90
85
80
80
75
75
80

FIG.7

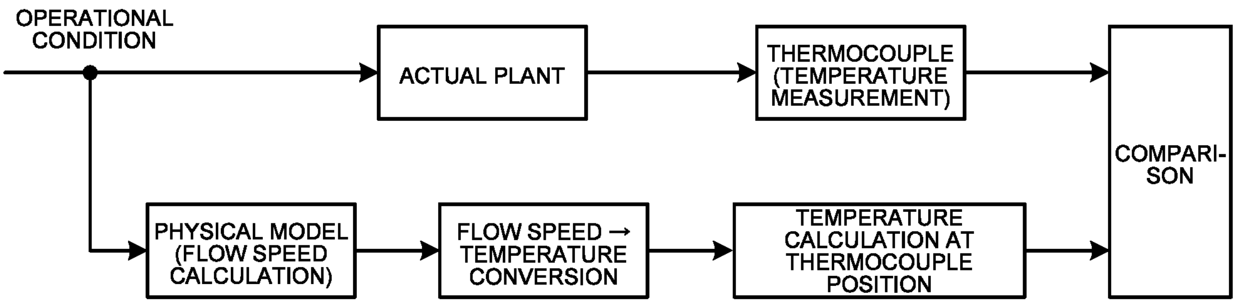

OPERATIONAL CONDITION
ACTUAL PLANT
THERMOCOUPLE (TEMPERATURE MEASUREMENT)
COMPARI-SON
PHYSICAL MODEL (FLOW SPEED CALCULATION)
FLOW SPEED → TEMPERATURE CONVERSION
TEMPERATURE CALCULATION AT THERMOCOUPLE POSITION

FIG.8

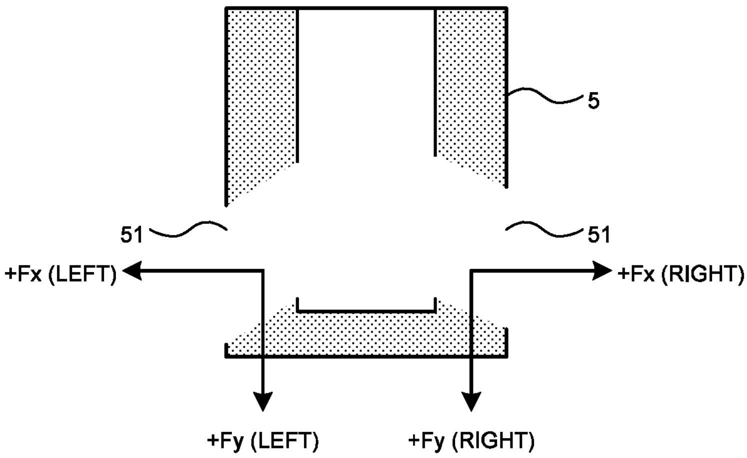

5
51
51
+Fx (LEFT)
+Fx (RIGHT)
+Fy (LEFT)
+Fy (RIGHT)

FIG.9

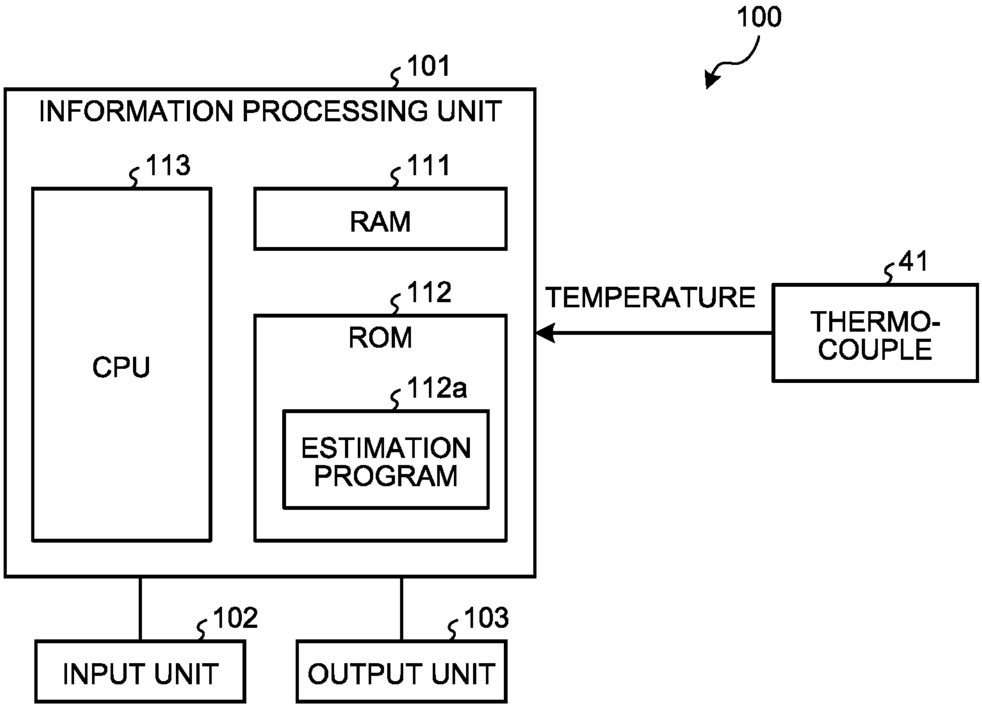

100
101
INFORMATION PROCESSING UNIT
113
CPU
111
RAM
112
ROM
112a
ESTIMATION PROGRAM
TEMPERATURE
41
THERMO-COUPLE
102
INPUT UNIT
103
OUTPUT UNIT

FIG.10

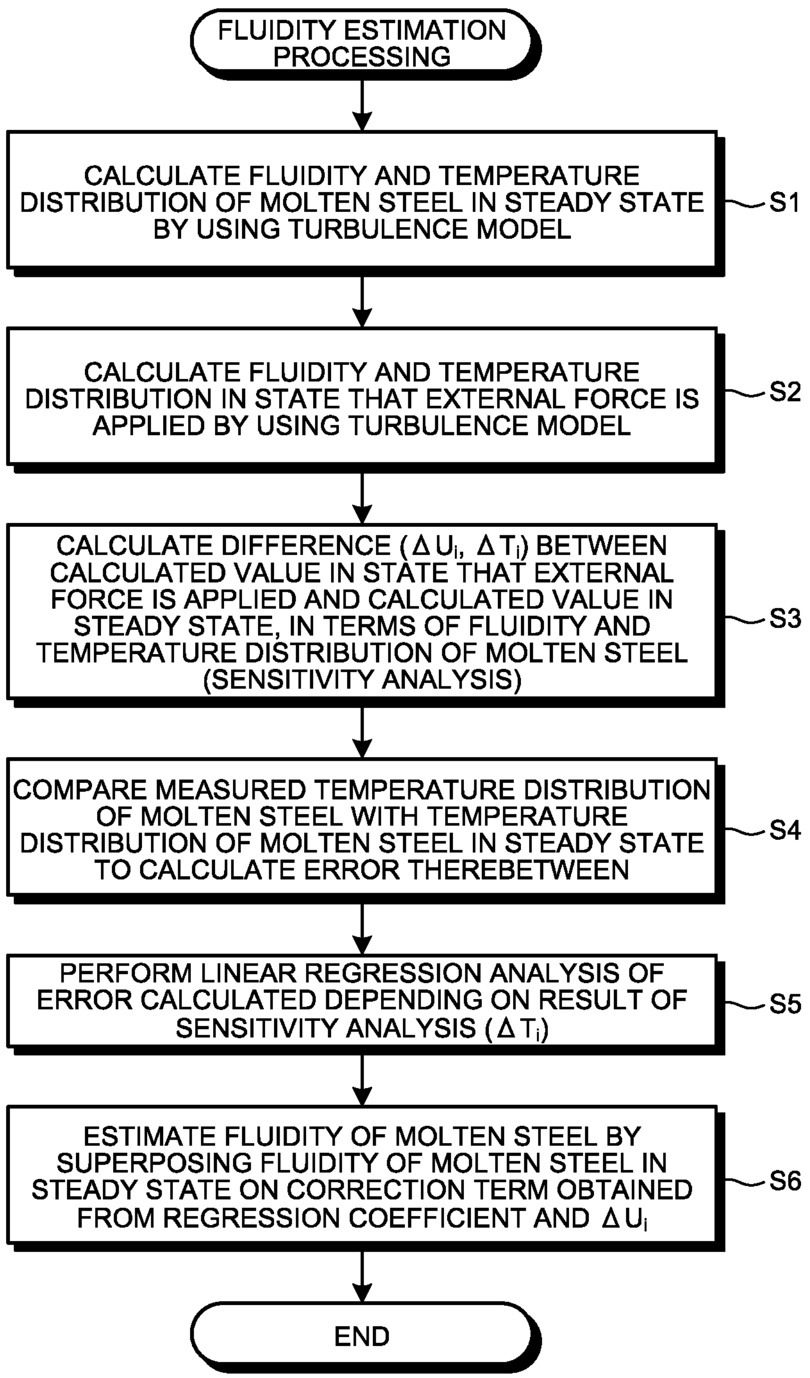

FLUIDITY ESTIMATION PROCESSING
CALCULATE FLUIDITY AND TEMPERATURE DISTRIBUTION OF MOLTEN STEEL IN STEADY STATE BY USING TURBULENCE MODEL
S1
CALCULATE FLUIDITY AND TEMPERATURE DISTRIBUTION IN STATE THAT EXTERNAL FORCE IS APPLIED BY USING TURBULENCE MODEL
S2
CALCULATE DIFFERENCE (ΔU_i, ΔT_i) BETWEEN CALCULATED VALUE IN STATE THAT EXTERNAL FORCE IS APPLIED AND CALCULATED VALUE IN STEADY STATE, IN TERMS OF FLUIDITY AND TEMPERATURE DISTRIBUTION OF MOLTEN STEEL (SENSITIVITY ANALYSIS)
S3
COMPARE MEASURED TEMPERATURE DISTRIBUTION OF MOLTEN STEEL WITH TEMPERATURE DISTRIBUTION OF MOLTEN STEEL IN STEADY STATE TO CALCULATE ERROR THEREBETWEEN
S4
PERFORM LINEAR REGRESSION ANALYSIS OF ERROR CALCULATED DEPENDING ON RESULT OF SENSITIVITY ANALYSIS (ΔT_i)
S5
ESTIMATE FLUIDITY OF MOLTEN STEEL BY SUPERPOSING FLUIDITY OF MOLTEN STEEL IN STEADY STATE ON CORRECTION TERM OBTAINED FROM REGRESSION COEFFICIENT AND ΔU_i
S6
END

FIG.11A

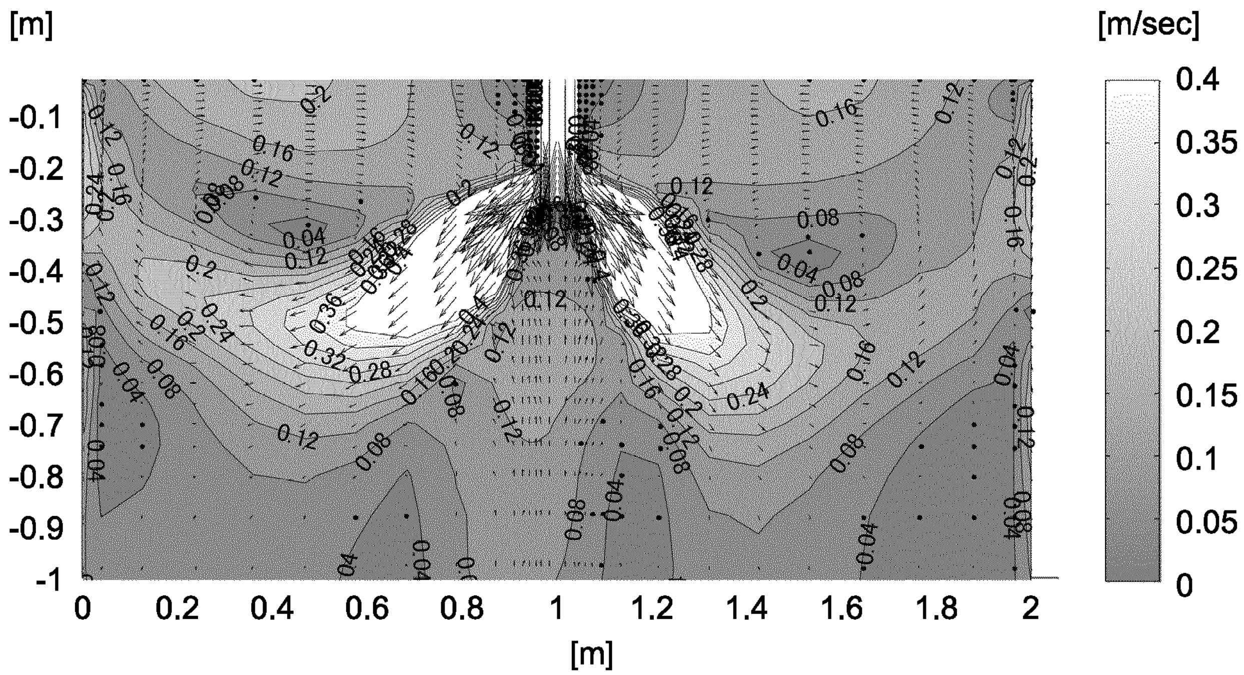


FIG.11B

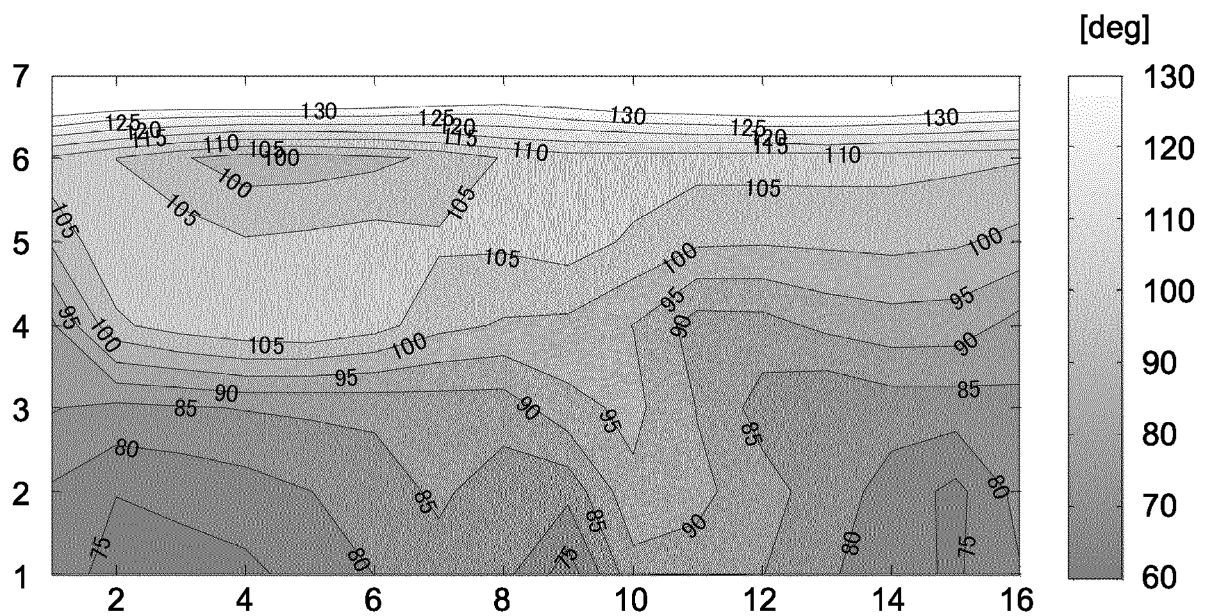


FIG.12A

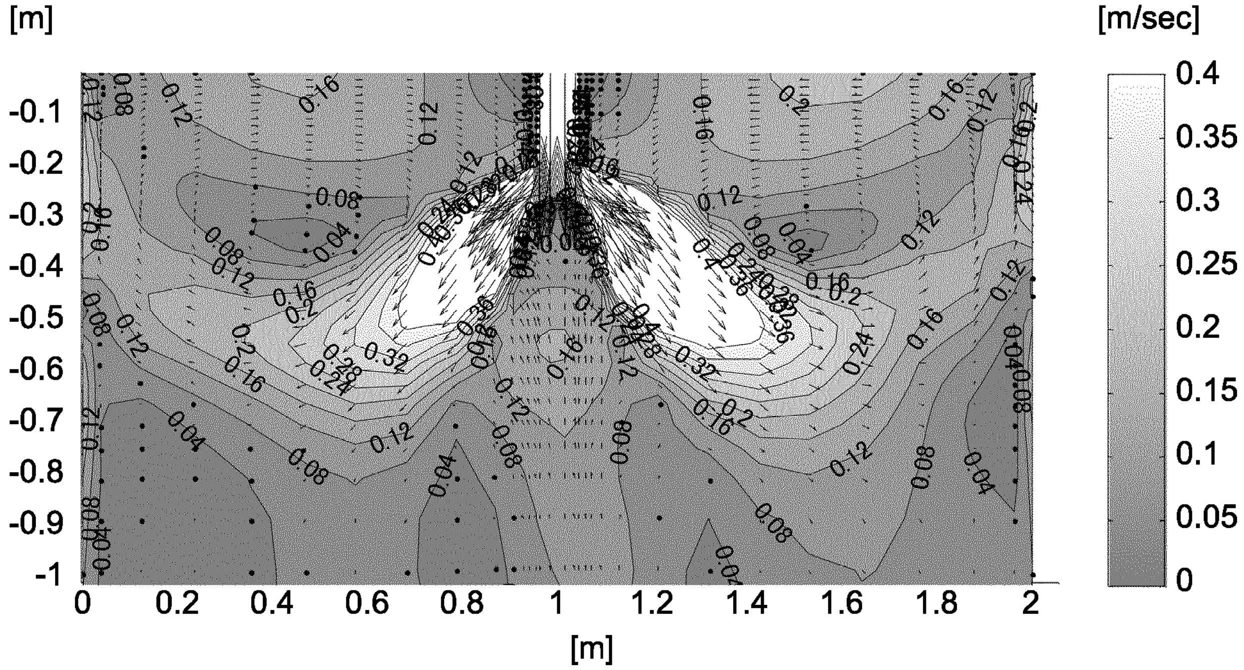


FIG.12B

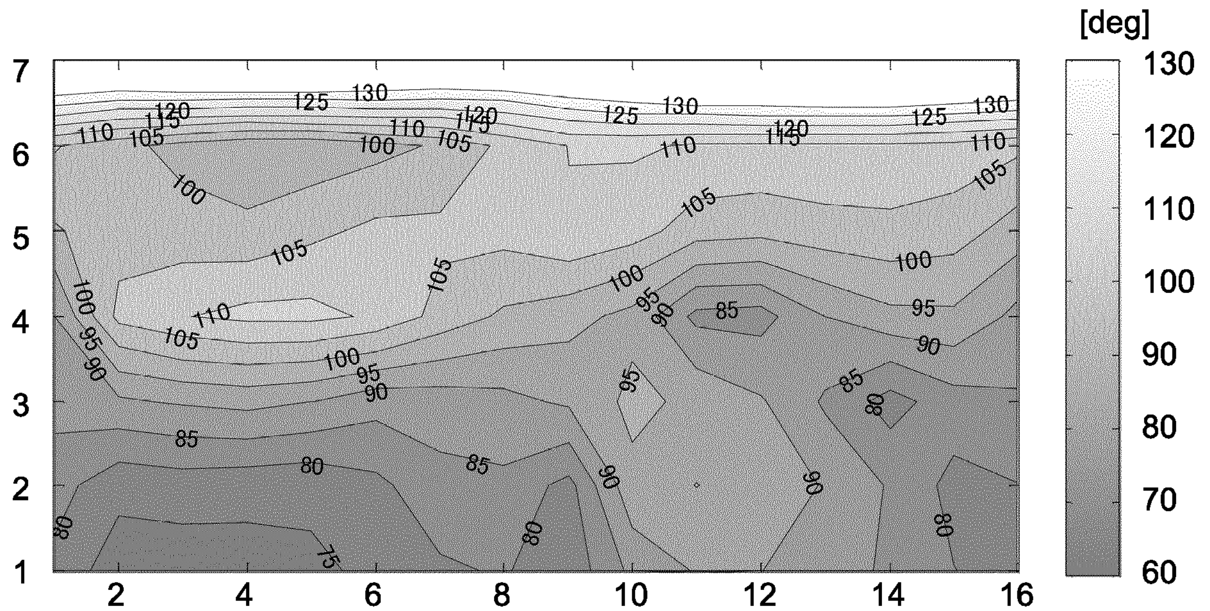


FIG.13A

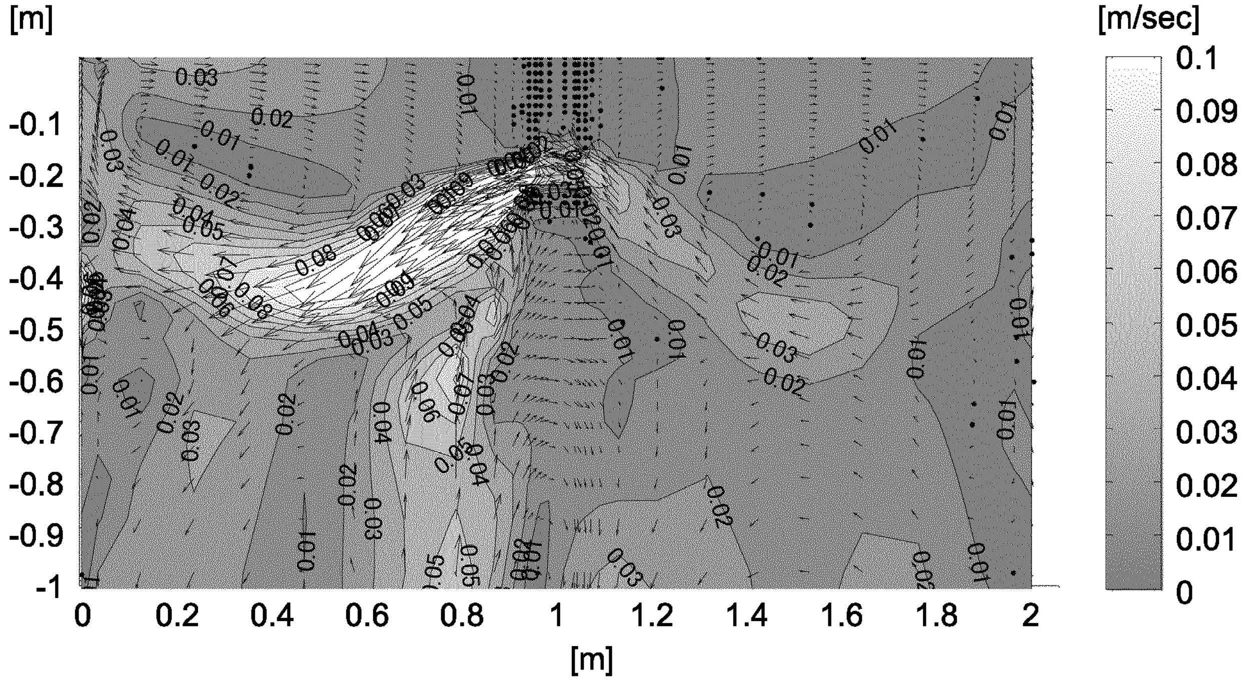


FIG.13B

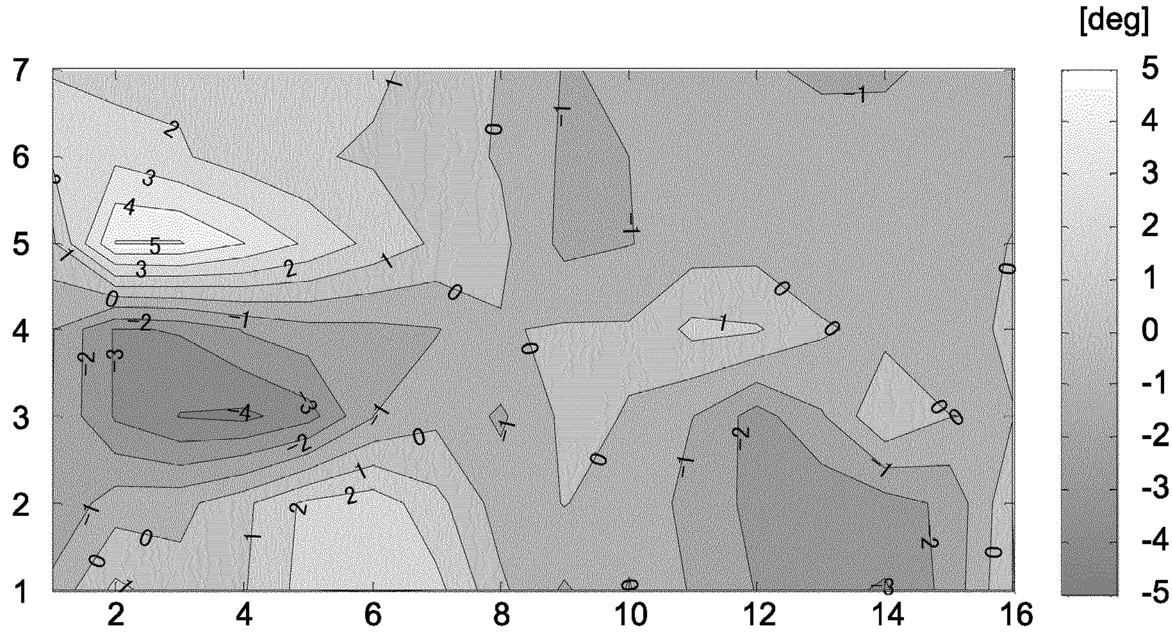


FIG.14A

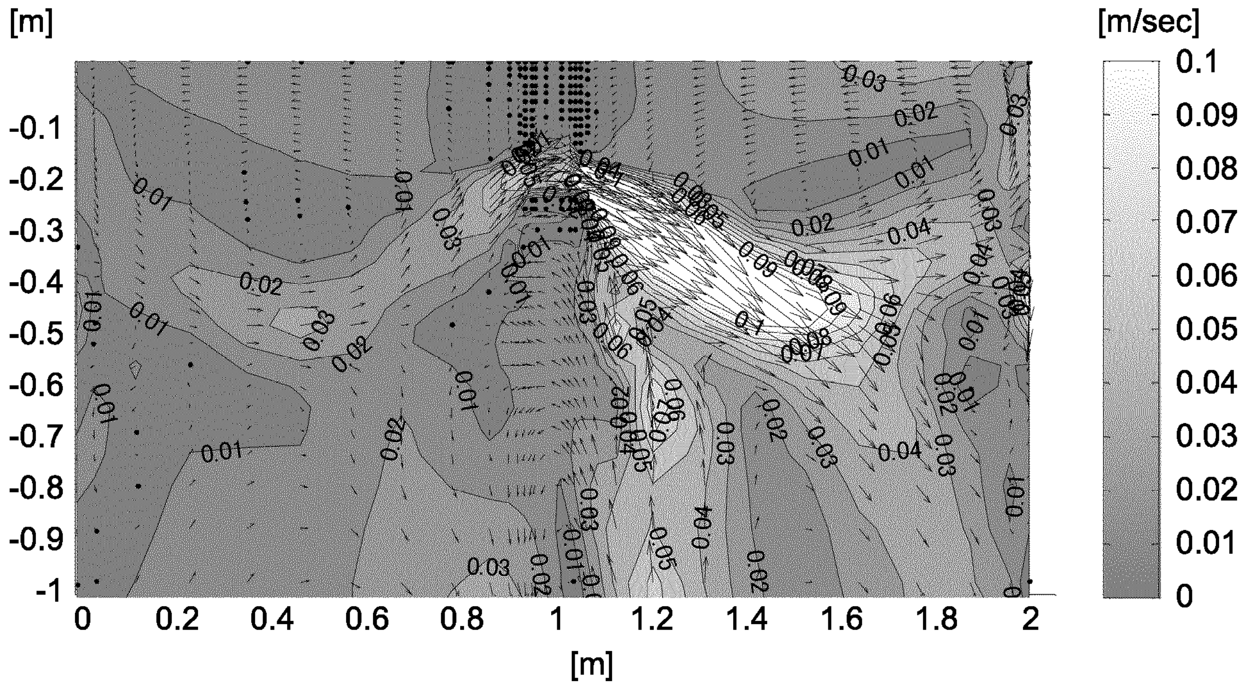


FIG.14B

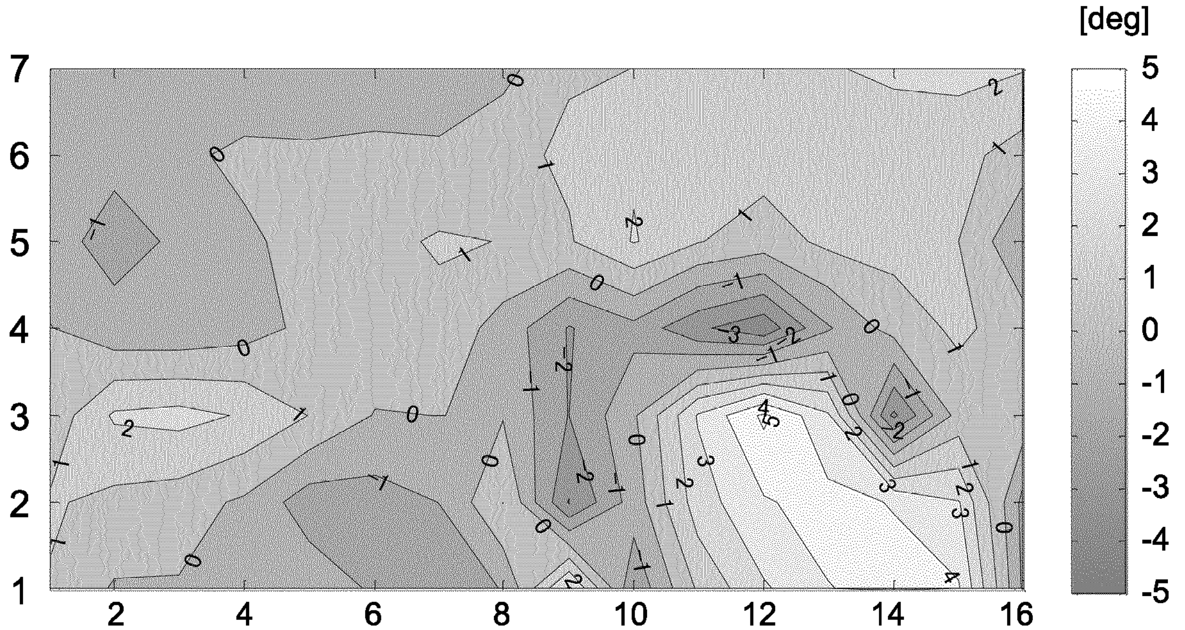


FIG.15A

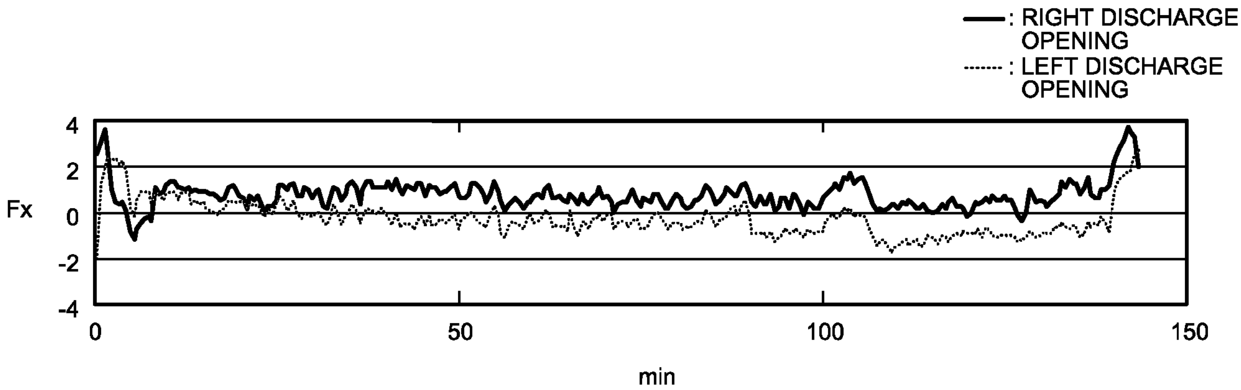


FIG.15B

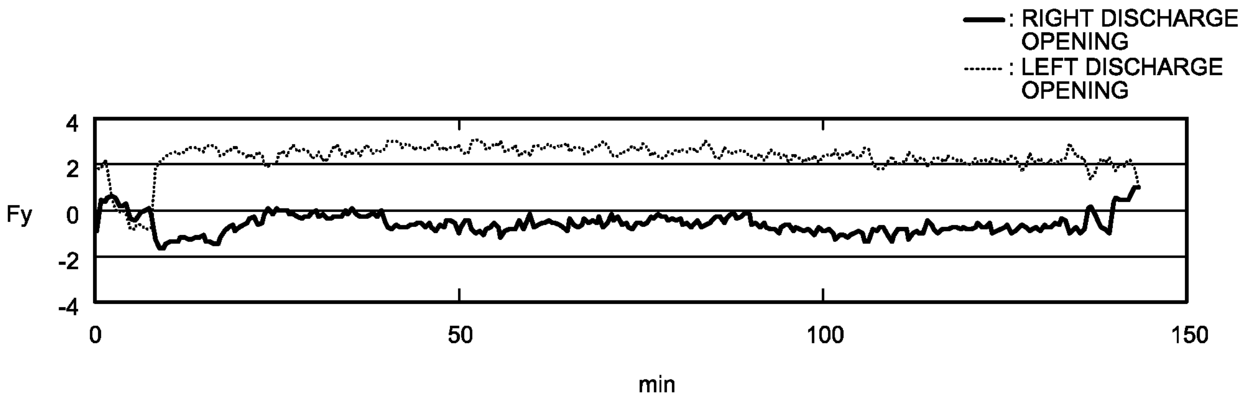


FIG.16A

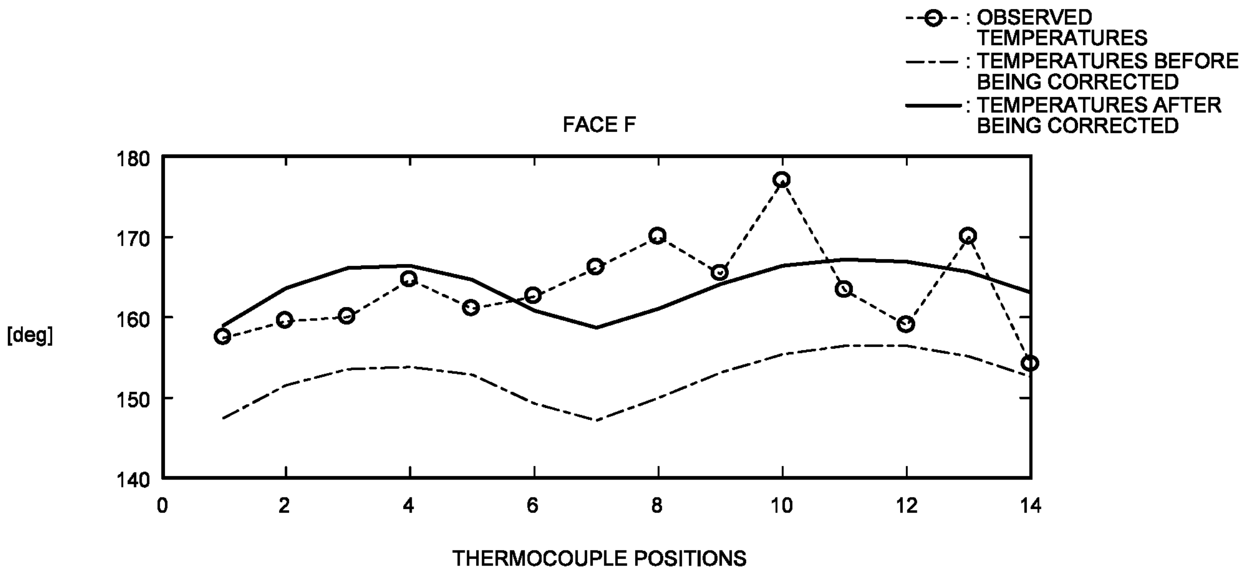


FIG.16B

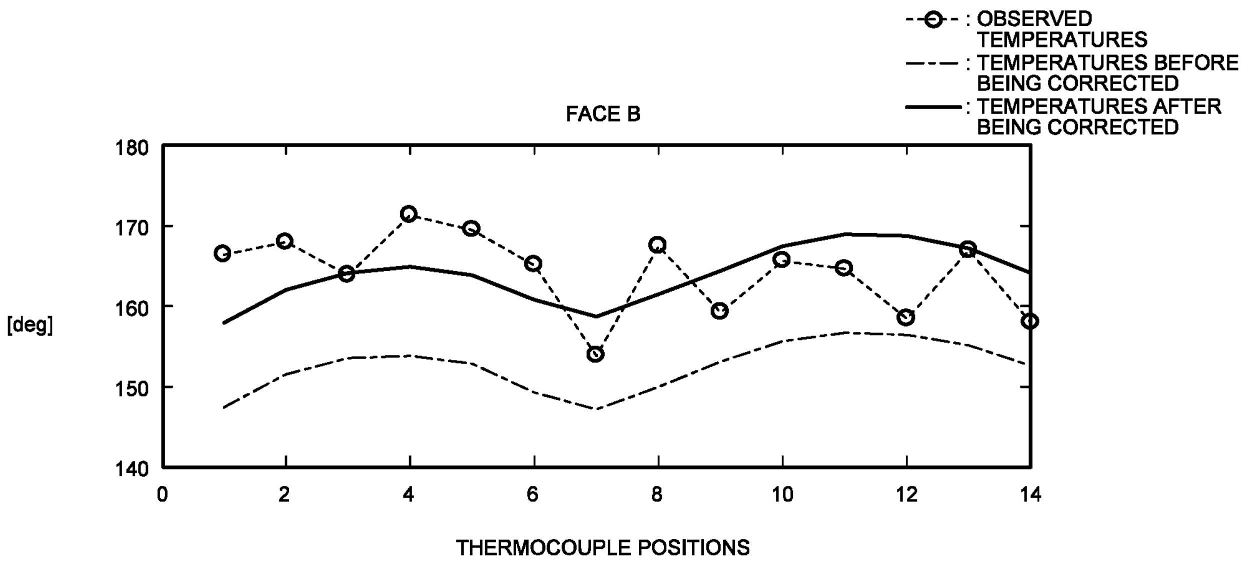


FIG.17A

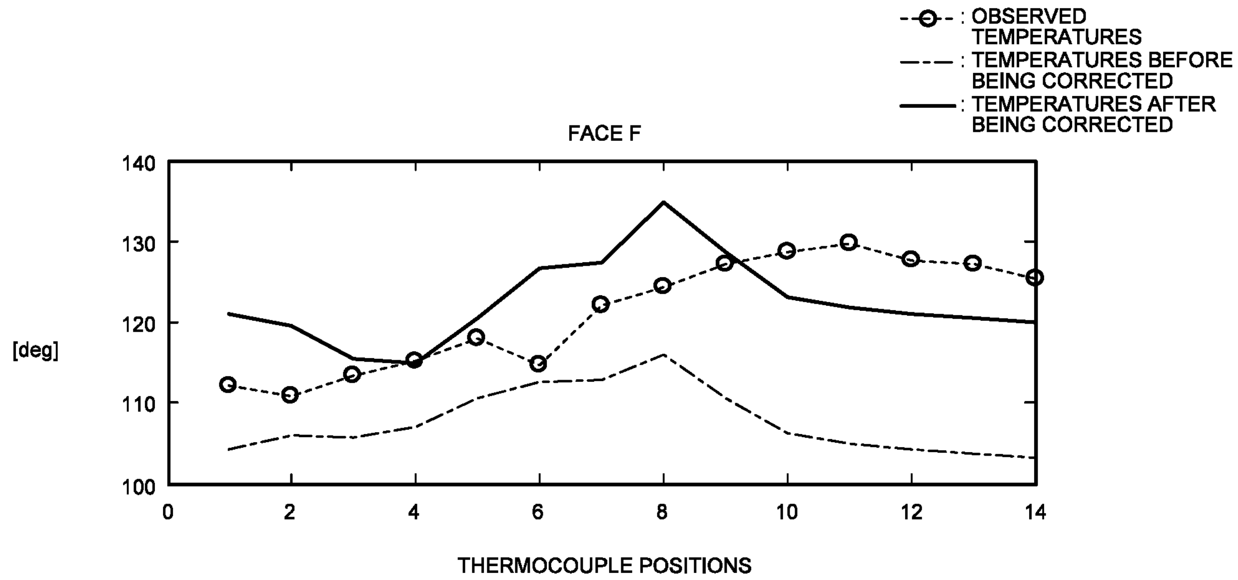


FIG.17B

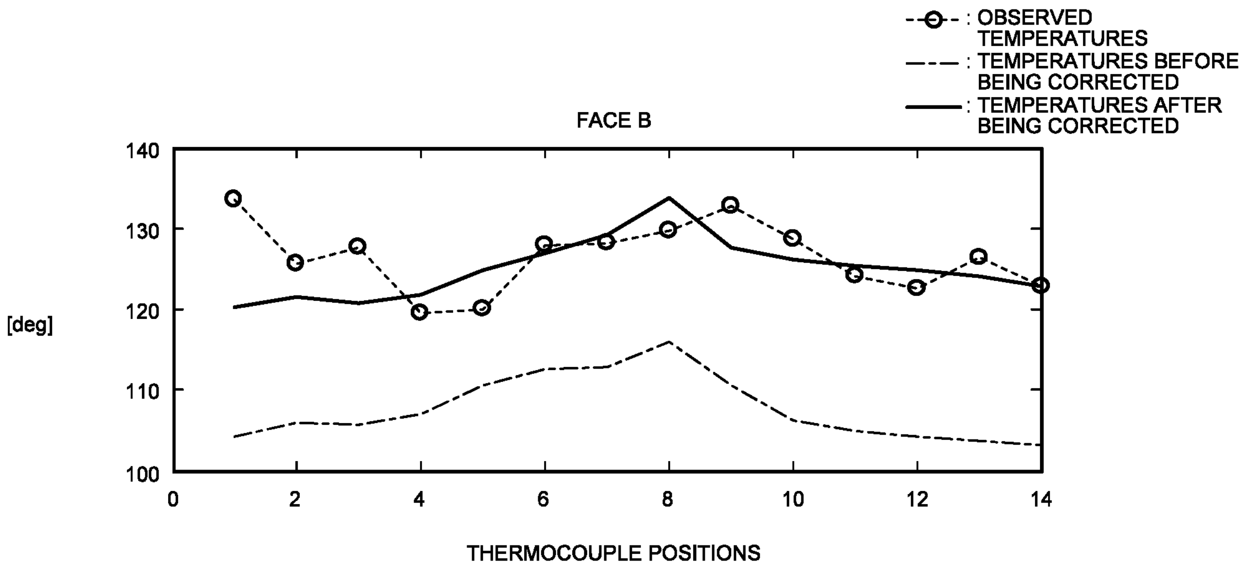


FIG.18A

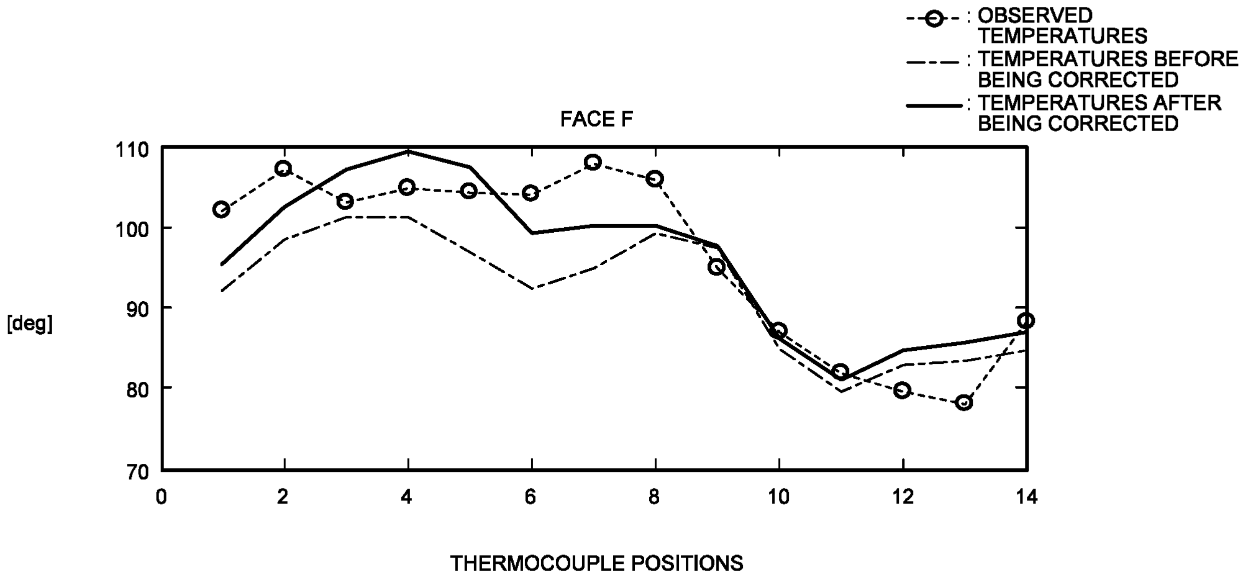


FIG.18B

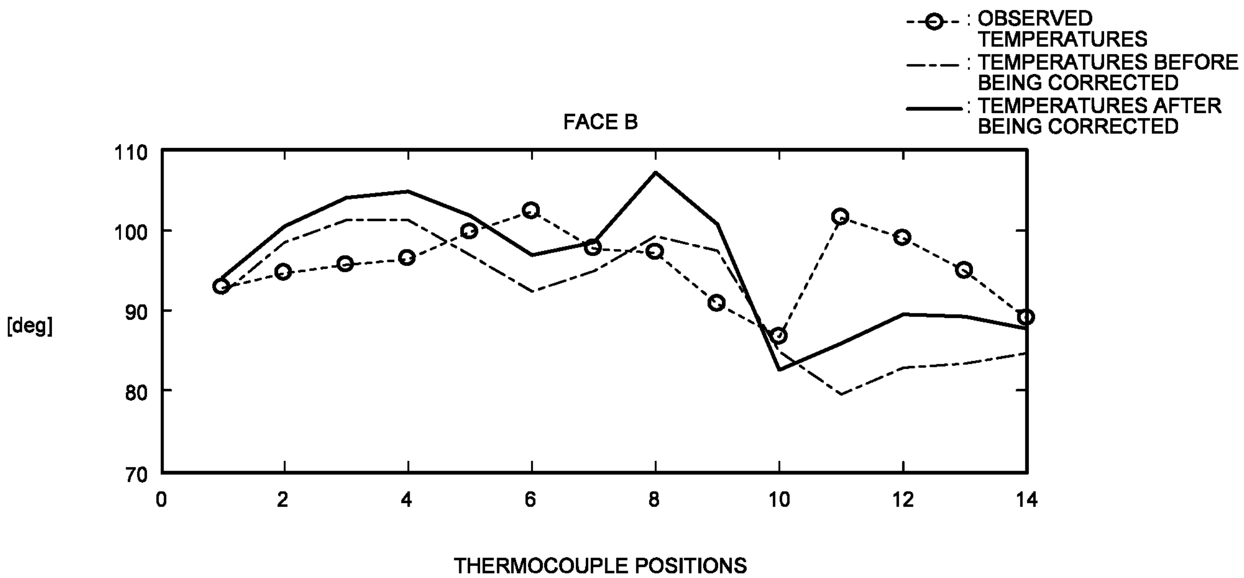


FIG.19A

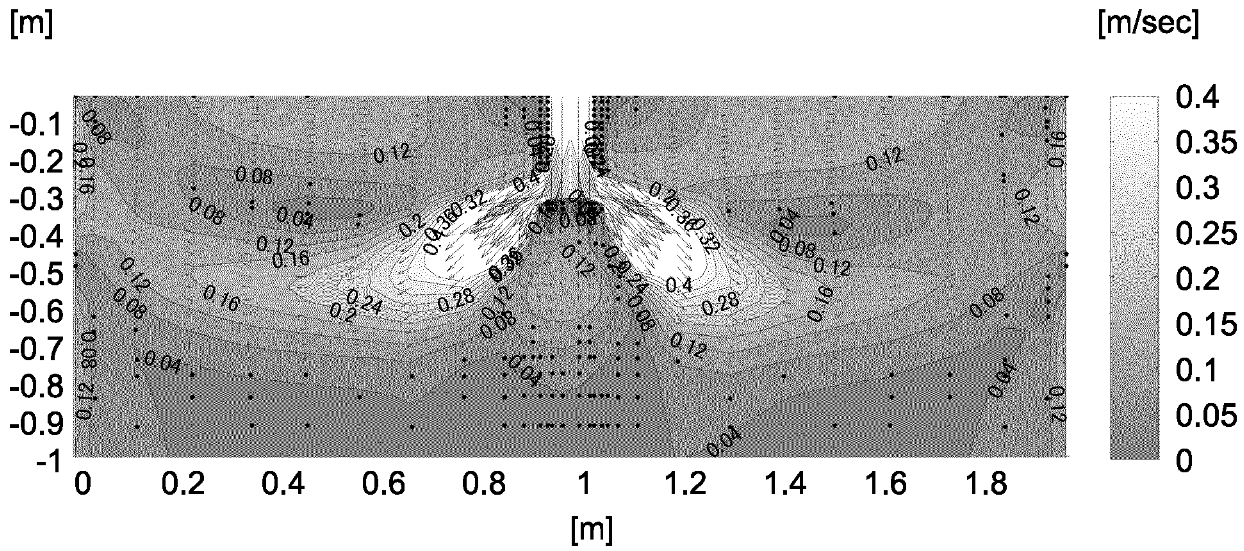
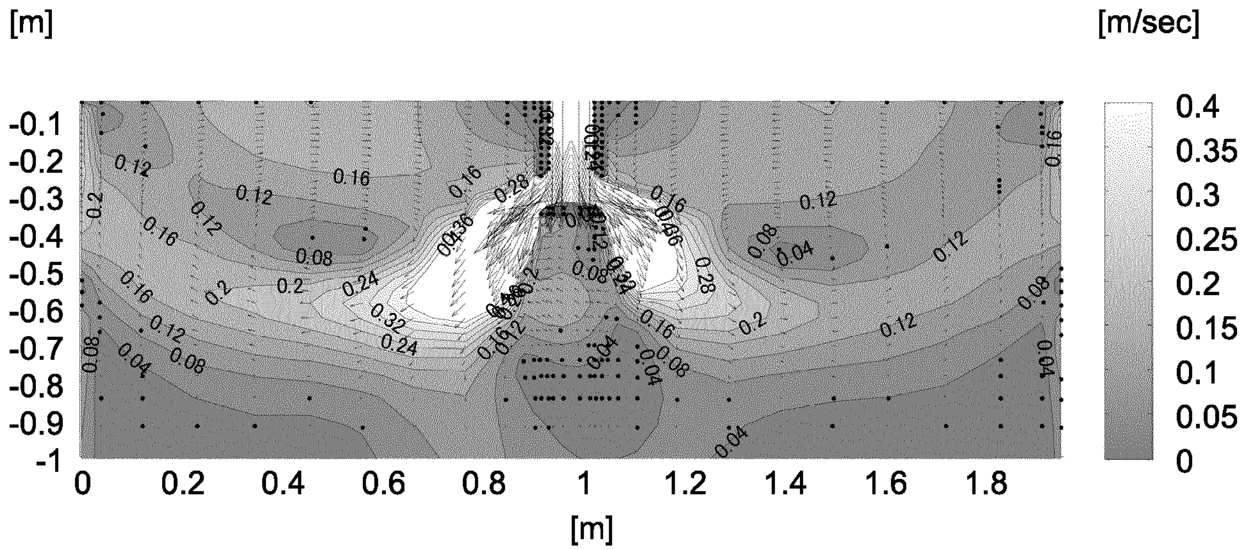


FIG.19B



INTERNATIONAL SEARCH REPORT

International application No.
PCT/JP2015/069338

A. CLASSIFICATION OF SUBJECT MATTER
B22D11/16(2006.01)i, *B22D11/115*(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)
B22D11/00-B22D11/22

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	1996-2015
Kokai Jitsuyo Shinan Koho	1971-2015	Toroku Jitsuyo Shinan Koho	1994-2015

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 2003-1386 A (Nippon Steel Corp.), 07 January 2003 (07.01.2003), entire text; fig. 1 to 10 (Family: none)	1-5
A	JP 7-47453 A (Nippon Steel Corp.), 21 February 1995 (21.02.1995), entire text; fig. 1 to 2 (Family: none)	1-5

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

* Special categories of cited documents:
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"O" document referring to an oral disclosure, use, exhibition or other means
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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search
07 September 2015 (07.09.15)

Date of mailing of the international search report
29 September 2015 (29.09.15)

Name and mailing address of the ISA/
Japan Patent Office
3-4-3,Kasumigaseki,Chiyoda-ku,
Tokyo 100-8915,Japan

Authorized officer

Telephone No.

Form PCT/ISA/210 (second sheet) (July 2009)

REFERENCES CITED IN THE DESCRIPTION

Patent documents cited in the description

- JP 10005957 A **[0005]**
- JP 2003001386 A **[0005]**
- JP 2003181609 A **[0005]**
- JP 3386051 B **[0005]**