(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 3 998 126 A1

(12) EUROPEAN PATENT APPLICATION
published in accordance with Art. 153(4) EPC

(43) Date of publication:
18.05.2022 Bulletin 2022/20

(21) Application number: **20836022.2**

(22) Date of filing: **06.07.2020**

(51) International Patent Classification (IPC):
B22D 11/124 *(2006.01)* ***B22D 11/22*** *(2006.01)*

(52) Cooperative Patent Classification (CPC):
B22D 11/124; B22D 11/22

(86) International application number:
PCT/JP2020/026487

(87) International publication number:
WO 2021/006253 (14.01.2021 Gazette 2021/02)

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME
Designated Validation States:
KH MA MD TN

(30) Priority: **11.07.2019 JP 2019128852**

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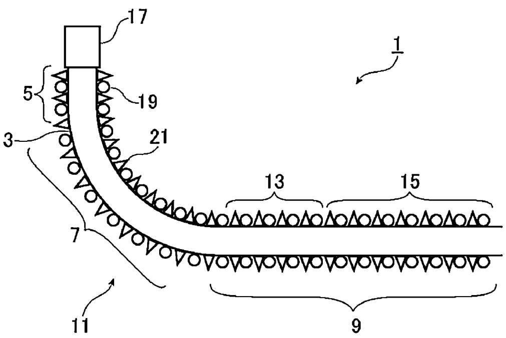
(54) SECONDARY COOLING METHOD AND SECONDARY COOLING APPARATUS FOR CONTINUOUS CASTING SLAB

(57) A secondary cooling method and a secondary cooling apparatus for a continuously cast slab by which secondary cooling can be efficiently performed without a large capital investment are provided.

A secondary cooling method for a continuously cast slab by which a cast slab 3 cast by a continuous casting machine 1 is subjected to secondary cooling in a secondary cooling zone 11 including a vertical zone 5, a curved zone 7, and a horizontal zone 9 includes a first cooling step performed in a first cooling portion 13, which is an upstream portion in the horizontal zone 9, and a second cooling step performed in a second cooling portion 15, which is a downstream portion in the horizontal zone. The first cooling step includes cooling of the cast slab with cooling water supplied at a flow density of 300 to 4000 liter/(m^2·min) so that the cooling water on a surface of the cast slab is in a nucleate boiling state in the first cooling step. The second cooling step includes cooling of the cast slab with the cooling water supplied at a flow density of 2% or more and 50% or less of the flow density of the cooling water in the first cooling step so that the nucleate boiling state of the cooling water on the surface of the cast slab is maintained in the second cooling step.

FIG. 1



Description

Technical Field

[0001] The present invention relates to a secondary cooling method and a secondary cooling apparatus for a continuously cast slab while a cast slab is subjected to secondary cooling in a secondary cooling zone of a continuous casting machine.

Background Art

[0002] In continuous casting of steel, molten steel poured into a mold is cooled by the mold and forms a solidifying shell at a contact surface that is in contact with the mold. A cast slab including the solidifying shell, which serves as an outer shell, and unsolidified molten steel in the shell is continuously pulled downward from the mold while being cooled with cooling water in a secondary cooling zone provided below the mold, and is eventually solidified entirely to the center.
[0003] The cast slab that has been solidified entirely to the center is cut to a predetermined length to produce a cast slab that serves as a rolling material.
[0004] In secondary cooling, the cast slab is generally cooled in a film boiling state. Here, film boiling is one of boiling regimes that easily occurs when an object having a high surface temperature is cooled with low-pressure cooling water supplied at a low flow rate. A layer of vapor is generated between the cooling water and the cooled object, and the cooling rate at which the object is cooled is relatively low. Although this enables reliable cooling of the object, there is a problem that the productivity is low.
[0005] In continuous casting, improvements in the quality and productivity of the cast slab are desired. This may be achieved by, for example, increasing the coefficient of heat transfer between the cooling water and the surface of the cast slab, that is, the coefficient of heat transfer during spray cooling.
[0006] Accordingly, as disclosed in Patent Literature 1, the cooling water may be sprayed against the surface of the cast slab at a high pressure, so that a larger amount of cooling water comes into contact with the surface of the cast slab per unit time. As a result, the coefficient of heat transfer is increased, and the productivity is increased accordingly.

Citation List

Patent Literature

[0007] PTL 1: Japanese Unexamined Patent Application Publication No. 2003-285147

Non Patent Literature

[0008] NPL 1: J.V. BECK, Int. J. Mass Transfer, 13 (1970), p. 703

Summary of Invention

Technical Problem

[0009] However, the method of Patent Literature 1 requires additional equipment, such as additional pumps and high pressure resistant pipes, and the cost is increased.
[0010] In addition, a very large amount of water is required to increase the coefficient of heat transfer, and the required amount of water greatly exceeds an amount of water usable in an existing continuous casting machine. Therefore, the method requires a large capital investment.
[0011] The present invention has been made to solve the above-described problem, and an object of the present invention is to provide a secondary cooling method and a secondary cooling apparatus for a continuously cast slab by which secondary cooling can be efficiently performed without a large capital investment.

Solution to Problem

[0012]

(1) A secondary cooling method for a continuously cast slab according to the present invention is a method by which a cast slab cast in a continuous casting machine is subjected to secondary cooling in a secondary cooling zone including a vertical zone, a curved zone, and a horizontal zone, and includes a first cooling step performed in an

upstream portion in the horizontal zone in a casting direction and a second cooling step performed in a downstream portion in the horizontal zone in the casting direction. The first cooling step includes cooling of the cast slab with cooling water supplied at a flow density per unit time of 300 to 4000 liter/(m^2·min) (where min means minute as a unit of time) so that the cooling water on a surface of the cast slab is in a nucleate boiling state in the first cooling step. The second cooling step includes cooling of the cast slab with the cooling water supplied at a flow density per unit time of 2% or more and 50% or less of the flow density of the cooling water in the first cooling step so that the nucleate boiling state of the cooling water on the surface of the cast slab is maintained in the second cooling step.
(2) In the secondary cooling method for a continuously cast slab according to (1), the second cooling step may be performed such that a surface temperature Ts (°C) of the cast slab at a start of cooling of the cast slab and the flow density W (liter/(m^2·min)) of the cooling water in the second cooling step satisfy a relationship of Expression (1) .

$$Ts < 10\hat{}[0.08 \times \ln(W) + 2] \qquad (1)$$

where ln is a natural logarithm and ^ is an exponentiation operator in Expression (1).
[0013] (3) In the secondary cooling method for a continuously cast slab according to (2), the second cooling step may be performed such that when a thickness of the cast slab is t (m), an average thermal conductivity of the cast slab in a thickness direction in a region excluding an unsolidified portion of the cast slab is λ (kcal/(m·hour·°C)), and a solidification temperature of the cast slab is Tc (°C), a heat flux q (kcal/(m^2·hour)) of the cooling water satisfies a relationship of Expression (2).

$$q \geq \lambda[4(Tc - Ts)/t] \qquad (2)$$

[0014] (4) In the secondary cooling method for a continuously cast slab according to any one of (1) to (3), the second cooling step may be performed such that the flow density W of the cooling water satisfies a relationship of Expression (3) .

$$W > e\hat{}[(\log(\lambda[4(Tc - Ts)/t]) - 5.2)/0.17] \qquad (3)$$

where e is a base of a natural logarithm, log is a common logarithm, and ^ is an exponentiation operator in Expression (3).
[0015] (5) In the secondary cooling method for a continuously cast slab according to any one of (1) to (4), a plurality of rollers and a plurality of spray nozzles may be provided in the horizontal zone, the rollers being arranged in the casting direction and oriented so that axial directions thereof are perpendicular to the casting direction, the spray nozzles which discharge the cooling water toward the surface of the cast slab being arranged in a cast slab width direction between the rollers that are adjacent to each other in the casting direction. A cooling surface formed when the cooling water discharged from each of the spray nozzles strikes the surface of the cast slab has a round cornered rectangular shape or an elliptical shape. At least in the first cooling step, the cooling water is discharged such that a major axis of the cooling surface is inclined at an angle in a range of 5 to 45 degrees relative to a direction perpendicular to the casting direction.
[0016] (6) A secondary cooling apparatus for a continuously cast slab according to the present invention is an apparatus by which a cast slab cast in a continuous casting machine is subjected to secondary cooling in a secondary cooling zone including a vertical zone, a curved zone, and a horizontal zone, and the horizontal zone includes a first cooling portion and a second cooling portion. In the first cooling portion, the cast slab is able to be cooled with cooling water supplied at a flow density per unit time of 300 to 4000 liter/(m^2·min) (where min means minute as a unit of time) so that the cooling water on a surface of the cast slab is in a nucleate boiling state in the first cooling portion. In the second cooling portion, the cast slab is cooled with the cooling water supplied at a flow density per unit time of 2% or more and 50% or less of the flow density of the cooling water in the first cooling portion so that the nucleate boiling state of the cooling water on the surface of the cast slab is maintained in the second cooling portion.
[0017] (7) In the secondary cooling apparatus for the continuously cast slab according to (6), a plurality of rollers and a plurality of spray nozzles are provided in the horizontal zone, the rollers being arranged in the casting direction and oriented so that axial directions thereof are perpendicular to the casting direction, the spray nozzles which discharge the cooling water toward the surface of the cast slab being arranged in a cast slab width direction between the rollers that are adjacent to each other in the casting direction. The spray nozzles are able to discharge the cooling water so that a cooling surface formed when the cooling water discharged from each of the spray nozzles strikes the surface of the cast slab has a round cornered rectangular shape or an elliptical shape. At least in the first cooling portion, the spray nozzles are arranged such that a major axis of the cooling surface is inclined at an angle in a range of 5 to 45 degrees relative to a direction perpendicular to the casting direction.

Advantageous Effects of Invention

[0018] According to the present invention, in the horizontal zone, the first cooling step is performed such that a flow density per unit time of the cooling water is 300 to 4000 liter/(m^2·min) so that the cooling water on the surface of the cast slab is in the nucleate boiling state in the first cooling portion. In addition, the second cooling step is performed such that the flow density is 2% or more and 50% or less of that in the first cooling step so that the nucleate boiling state of the cooling water on the surface of the cast slab is maintained. Thus, the amount of cooling water can be reduced, and secondary cooling can be efficiently performed without a large capital investment.

Brief Description of Drawings

[0019]

[Fig. 1] Fig. 1 illustrates the general structure of a continuous casting machine.
[Fig. 2] Fig. 2 illustrates a cooling spray included in a secondary cooling apparatus according to the present embodiment.
[Fig. 3] Fig. 3 illustrates another form of a cooling spray included in the secondary cooling apparatus according to the present embodiment.
[Fig. 4] Fig. 4 is a graph showing the relationship between the flow rate of cooling water, the surface temperature of a cast slab, and the cooling capability. Description of Embodiments

[0020] Referring to Fig. 1, a secondary cooling method for a continuously cast slab according to the present embodiment is a method by which a cast slab 3 cast by a continuous casting machine 1 is subjected to secondary cooling in a secondary cooling zone 11 including a vertical zone 5, a curved zone 7, and a horizontal zone 9. The horizontal zone 9 includes a first cooling portion 13 in which a first cooling step is performed and a second cooling portion 15 in which a second cooling step is performed.
[0021] Each item of the secondary cooling method will now be described in detail.

<Continuous casting machine>

[0022] As illustrated in Fig. 1, the continuous casting machine 1 is an apparatus in which molten steel poured into a mold 17 from a tundish (not illustrated) is supported by rollers 19 and pulled out in the form of the cast slab 3 while being subjected to secondary cooling by cooling sprays 21 disposed between the rollers 19.
[0023] As illustrated in Fig. 1, the secondary cooling zone 11, in which the cast slab 3 is subjected to secondary cooling, is sectioned into the vertical zone 5, the curved zone 7, and the horizontal zone 9. The secondary cooling method of the present invention relates to a method for cooling the cast slab 3 in the horizontal zone 9.

<First Cooling Step>

[0024] In the first cooling step performed in the first cooling portion 13 of the horizontal zone 9 in the secondary cooling zone 11, the cast slab 3 is cooled with cooling water supplied by the cooling sprays 21 at a flow density per unit time of 300 to 4000 liter/(m^2·min) (where min means minute as a unit of time) so that the cooling water on the surface of the cast slab 3 is in a nucleate boiling state in the first cooling portion 13.
[0025] The flow density per unit time of the cooling water in the first cooling portion 13 is a value calculated by dividing the total amount of cooling water (liter/min) in the first cooling portion 13 by the area (m^2) of the first cooling portion 13.
[0026] The cooling sprays 21 are devices that spray liquid or a mixture of liquid and gas over the surface of the cast slab 3. An example of liquid is water, and an example of gas is air.
[0027] As illustrated in Fig. 1, the cooling sprays 21 are disposed between the rollers 19 that convey the cast slab 3 in a casting direction.
[0028] In addition, as illustrated in Fig. 2, each cooling spray 21 includes a plurality of spray nozzles 23 arranged in a width direction of the cast slab 3 in a region between the rollers 19. The spray nozzles 23 illustrated in Fig. 2 are flat spray nozzles. Each flat spray nozzle discharges refrigerant 25, which serves as the cooling water, in the form of a fan that spreads in the cast slab width direction with the spray nozzle 23 at the center. Therefore, a striking surface in which the cooling water strikes the surface of the cast slab has an elongated linear shape with a small width in the casting direction and a large width in the cast slab width direction. In this specification, the elongated linear shape of the striking surface in which the cooling water discharged from each flat spray nozzle strikes the surface of the cast slab is referred to as a "round cornered rectangular shape".
[0029] The type of the spray nozzles 23 is not particularly limited, and sprays having nozzles similar to the flat spray

nozzles may instead be used. Examples of such sprays include oval spray nozzles (elliptical sprays or oval sprays), full cone spray nozzles (cone sprays or round sprays), which are nozzles that discharge cone-shaped jets, or nozzles that discharge quadrangular-pyramid-shaped jets, such as square sprays (quadrangular sprays, square sprays, or rectangular sprays), which are quadrangular full cone sprays.

[0030] When the flat spray nozzles or the oval spray nozzles are used as the spray nozzles 23, each nozzle is typically disposed such that the major axis of the cooling surface (striking surface in which the cooling water strikes the surface of the cast slab), which has a round cornered rectangular shape or an elliptical shape, is perpendicular to the casting direction. However, as illustrated in Fig. 3, assuming that an angle of the above-described major axis that is perpendicular to the casting direction is 0 degrees, the cooling water is preferably discharged from nozzles that are each disposed such that the major axis is inclined at an angle in the range of 5 to 45 degrees (θ = 5 to 45 degrees in Fig. 3).

[0031] The reason for this will now be described.

[0032] As described above, the spray nozzles 23 are arranged in the width direction of the cast slab 3 in each of the regions between the rollers 19. When the spray nozzles 23 are flat sprays, the cooling water discharged from the spray nozzles 23 flows along the surface of the cast slab 3 at a high velocity in the direction of the major axis of the striking surface in which the cooling water strikes the surface of the cast slab 3 (hereinafter referred to as a spray width direction) and at a relatively low velocity in the direction of the minor axis of the striking surface (hereinafter referred to as a spray thickness direction). Therefore, after striking the surface of the cast slab, the cooling water relatively gently spreads in the spray thickness direction, that is, in the casting direction. In the spray width direction, jets of cooling water discharged from adjacent sprays strike each other at velocities in the opposite directions at the ends thereof, and then change the directions thereof so as to spread in the casting direction. As a result, the cooling water flows in the casting direction along the surface of the cast slab at a relatively slow velocity after striking the surface of the cast slab.

[0033] When the major axis of the cooling surface is inclined relative to the direction perpendicular to the casting direction, interference between the jets of cooling water discharged from the adjacent sprays occur in the spray thickness direction, in which the velocity is relatively low, and does not occur in the spray width direction, in which the velocity is high. Therefore, the cooling water flows along the surface of the slab at a high velocity. As a result of the studies conducted by the present inventors, it has been found that when the cooling water flows along the surface of the cast slab, the cooling capability is increased as the velocity of the cooling water is increased. Therefore, the cooling capability is increased when each spray nozzle 23 is disposed such that the major axis of the cooling surface is inclined relative to the direction perpendicular to the casting direction. Assuming that the angle of the direction perpendicular to the casting direction is 0 degrees, the major axis of the cooling surface is preferably inclined at an angle in the range of 5 to 45 degrees.

[0034] As described above, in the first cooling step performed by the cooling sprays 21, cooling is performed at a flow density per unit time of 300 to 4000 liter/($m^2 \cdot$min) so that the cooling water is in a nucleate boiling state on the entirety or at least a portion of the surface of the cast slab 3.

[0035] When the cast slab is cooled at a high coefficient of heat transfer (hereinafter referred to as strong cooling) before the cast slab enters the horizontal zone 9, there is a high risk that cracking will occur, in particular, in a corner portion of the cast slab 3. Therefore, strong cooling may be performed in the horizontal zone 9.

[0036] However, as described above, the flow rate of the cooling water used during strong cooling needs to be reduced to reduce the capital investment. Accordingly, a method of supplying the cooling water at a high flow rate only in the first cooling step and supplying the cooling water at a low flow rate in the second cooling portion 15 has been studied.

[0037] Fig. 4 is a graph showing the relationship between the flow rate of the cooling water, the surface temperature of the cast slab 3, and the cooling capability. The vertical axis represents the cooling capability, and the horizontal axis represents the surface temperature of the cast slab. The graph shows three cases in which the flow rate of the cooling water is high, middle, and low.

[0038] In the graph of Fig. 4, the temperature region at or below the local maximum point of the cooling capability is a nucleate boiling region, and the temperature region at or above the local minimum point of the cooling capability is a film boiling region. Nucleate boiling is a boiling state in which bubbles are generated from bubble formation points serving as nucleuses and in which the cooling water is capable of extracting a very large amount of heat from a cooling object. Film boiling is a boiling state in which a film of vapor is formed at the boundary between the cooling water and the cooling object and serves as a thermal barrier that reduces the amount of heat that can be extracted from the cooling object by the cooling water.

[0039] As is clear from the graph of Fig. 4, when the temperature of the cast slab 3 is low, that is, in the nucleate boiling region, the influence of the flow rate of the cooling water on the cooling capability is small. Therefore, high cooling capability can be achieved at a low flow rate by performing cooling at a high flow rate in the first cooling step to reduce the surface temperature of the cast slab 3 so that nucleate boiling occurs, and then maintaining nucleate boiling at a low flow rate in the second cooling portion 15.

[0040] The concept of the method for cooling the cast slab according to the present invention will now be described with reference to the graph of Fig. 4. When casting proceeds from an upstream location toward a downstream location of the continuous casting machine, as for the surface temperature history of the cast slab, the temperature generally changes from right (high-temperature side) to left (low-temperature side) in the graph of Fig. 4. Although the temperature of the cast slab 3 is still high in the curved zone 7, excessive cooling is not performed and the cooling water is supplied at a low flow rate (see the region on the right of point O in Fig. 4) to prevent cracking or the like of the cast slab 3. When the cast slab 3 leaves the curved zone 7 and enters the horizontal zone 9 (point A in Fig. 4), there is less risk of cracking of the cast slab 3. Therefore, strong cooling can be performed, and the flow rate of the cooling water can be greatly increased (point A' in Fig. 4). Thus, cooling at a high flow rate is started in the first cooling step according to the present invention. The cast slab 3 is subjected to strong cooling at a high flow rate, and the surface temperature is greatly reduced. In the fastest case, the state of the cooling water changes to nucleate boiling (point B in Fig. 4) in a region downstream in the casting direction from the position at which the surface of the cast slab is cooled by the cooling water discharged from the nozzles set in the first one of the regions between the rollers in the horizontal zone. When the cast slab 3 is continuously cooled, the surface temperature thereof is further reduced and reaches point C in Fig. 4. When the surface temperature of the cast slab 3 is reduced to point C, nucleate boiling can be maintained even when the flow rate of the cooling water is low. Therefore, the flow rate of the cooling water is reduced, that is, the second cooling step is started to continuously perform strong cooling at a low flow rate (point C' in Fig. 4).

[0041] In the present invention, the flow rate of the cooling water generally changes as shown by the empty arrows in Fig. 4.

[0042] In the present embodiment, cooling at a high flow rate in the first cooling step is performed such that the flow density per unit time is 300 to 4000 liter/(m^2·min). The reason for this will now be described.

[0043] In Fig. 4, the local minimum value of the cooling capability varies depending on the flow rate. Studies conducted by the present inventors have shown that when the flow density per unit time is 300 liter/(m^2·min), a temperature giving a local minimum value of the cooling capability is about 1000°C.

[0044] Generally, the surface temperature of the cast slab 3 in the horizontal zone 9 is 1000°C or less, which is in a temperature region lower than the temperature at which the cooling capability is at the local minimum. Therefore, when the flow density per unit time is 300 liter/(m^2·min), cooling of the cast slab 3 in the horizontal zone 9 can be started with cooling capability higher than the cooling capability at the local minimum.

[0045] In addition, as illustrated in Fig. 4, when the cooling capability is between the local minimum and the local maximum, the cooling capability is increased as the flow rate of the cooling water is increased. Therefore, it is advantageous to increase the flow density per unit time in the first cooling portion 13 of the horizontal zone 9.

[0046] However, the inventors have found that when the flow density is greater than or equal to 4000 liter/(m^2·min), the cooling capability hardly changes in response to an increase in the flow density per unit time, and the cooling water cannot be effectively used.

[0047] For the above-described reason, cooling at the high flow rate in the first cooling portion 13 is performed such that the flow density per unit time is 300 to 4000 liter/(m^2·min). A more preferred range of the flow rate is 300 to 2000 liter/(m^2·min).

[0048] According to the present embodiment, cooling is performed at a high flow rate in the first cooling step so that the surface temperature of the cast slab 3 is reduced and that nucleate boiling is achieved during the first cooling step, and nucleate boiling is maintained at a low flow rate in the subsequent second cooling step. Conditions for achieving such performance in these steps will now be discussed.

[0049] The present inventors have carried out various experiments in which the cast slab 3 was cooled with water in a laboratory. As a result, it has been found that the cooling capability is at a local maximum when the surface temperature Ts (°C) of the cast slab 3 is Ts = 10^[0.08 × ln(W) + 2].

[0050] Here, W is the flow density per unit time (liter/(m^2·min)) and ln is a natural logarithm.

[0051] Therefore, in the first cooling step, cooling may be performed at a high flow rate so that the temperature is reduced to a temperature lower than Ts given above depending on the flow density per unit time in the second cooling step. In other words, cooling in the first cooling step may be performed so that the surface temperature Ts (°C) of the cast slab 3 at the time when cooling in the second cooling step is started satisfies Expression (1).

$$Ts < 10^{[0.08 \times \ln(W) + 2]} \qquad (1)$$

<Second Cooling Step>

[0052] In the second cooling step performed in the second cooling portion 15 of the horizontal zone 9, the cast slab 3 is cooled with cooling water at a flow density per unit time of 2% or more and 50% or less of that in the first cooling step so that the nucleate boiling state of the cooling water on the surface of the cast slab 3 is maintained.

[0053] The flow density per unit time of the cooling water in the second cooling portion 15 is a value calculated by dividing the total amount of cooling water (liter/min) used in the second cooling portion 15 by the area (m^2) of the second cooling portion 15.

[0054] As described above, when the first cooling step is performed such that the surface temperature of the cast slab 3 at the start of the second cooling step satisfies Expression (1) given above, cooling can be performed in the second cooling step while nucleate boiling is maintained at a low flow density, that is, the flow density per unit time W given in Expression (1). The flow density per unit time may be set to 2% or more and 50% or less of that in the first cooling step. A more preferred range of the flow density per unit time is 5% to 20% of that in the first cooling step.

[0055] The surface temperature of the cast slab increases due to a heat flux generated by the heat capacity of the inner part of the cast slab 3. The temperature increase needs to be reduced to maintain the surface temperature of the cast slab at the above-described temperature. This is because if the surface temperature exceeds the temperature at which the cooling capability is at a local maximum, the dependency of the cooling capability on the flow rate increases, and high cooling capability cannot be achieved at a low flow rate.

[0056] The temperature increase can be reduced to maintain the surface temperature of the cast slab at the above-described temperature when a heat flux of the jets of cooling water from the outside of the cast slab 3 is greater than the heat flux generated by the heat capacity of the inner part of the cast slab 3.

[0057] Ideally, the temperature distribution of the cast slab 3 has the maximum temperature at the center in the thickness direction and can be approximated by a parabola. Therefore, the recuperated heat flux q' (kcal/(m^2·hour)) can be expressed by Expression (4).

$$q' = \lambda[4(Tc - Ts)/t] \qquad (4)$$

[0058] In Expression (4), t is the thickness (m) of the cast slab, λ is the average thermal conductivity (kcal/(m·hour·°C)) in the thickness direction in a region excluding an unsolidified portion of the cast slab, and Tc is the solidification temperature (°C) of the cast slab.

[0059] Therefore, to perform cooling in the second cooling portion 15 at a low flow rate, the heat flux q (kcal/(m^2·hour)) during cooling may be set to satisfy $q \geq q'$, that is, Expression (2).

$$q \geq \lambda[4(Tc - Ts)/t] \qquad (2)$$

The temperature at the center of the cast slab in the thickness direction is difficult to measure, and is generally around the solidification temperature of the cast slab 3. Therefore, the solidification temperature is used.

[0060] The inventors have studied the flow density per unit time required to achieve cooling with the heat flux that satisfies Expression (2) given above.

[0061] The inventors have carried out an experiment of cooling a steel plate in a laboratory, and obtained a condition under which the heat flux (cooling capability) is at a local maximum in Fig. 4 in the form an empirical formula given below showing the relationship between the local maximum of the heat flux and the flow density per unit time.

$$q'' = 10\verb|^|[0.17\ln(W) + 5.2] \qquad (5)$$

According to the two expressions, Expression (5) and Expression (4) given above, that is, $q' = \lambda[4(Tc - Ts)/t]$, the condition to be satisfied in the second cooling step is $q'' > q'$, which may be changed into Expression (3) regarding the flow density per unit time W.

$$W > e\verb|^|[(\log\{\lambda[4(Tc - Ts)/t]\} - 5.2)/0.17] \qquad (3)$$

In Expression (3), e is the base of a natural logarithm and log is a common logarithm.

[0062] When the flow density per unit time in the second cooling portion 15 is set to satisfy Expression (3) given above, cooling can be performed while nucleate boiling is maintained with a small amount of water in the second cooling portion 15.

[0063] As described above, according to the secondary cooling method of the present embodiment, in the horizontal zone 9 of the secondary cooling zone 11, the first cooling step is performed at a high flow density so that the cooling water on the surface of the cast slab 3 is in a nucleate boiling state. In addition, the second cooling step is performed at a flow density per unit time of 2% or more and 50% or less of that in the first cooling step so that the nucleate boiling state of the cooling water on the surface of the cast slab 3 is maintained. Thus, the amount of cooling water used in the horizontal zone 9 can be reduced, and secondary cooling can be efficiently performed without a large capital investment.

[0064] The above-described secondary cooling method for a continuously cast slab may be implemented by a secondary cooling apparatus in which the horizontal zone 9 includes the first cooling portion 13 and the second cooling portion 15. In the first cooling portion 13, the flow density per unit time is set to 300 to 4000 liter/(m^2·min) so that the cooling water on the surface of the cast slab 3 is in a nucleate boiling state. In the second cooling portion 15, the flow rate is set to 2% or more and 50% or less of that in the first cooling portion 13 so that the nucleate boiling state of the cooling water on the surface of the cast slab 3 is maintained.

[0065] The nucleate boiling state of the cooling water may be maintained by, for example, measuring the temperature of the cooling water before and after cooling of the cast slab 3, estimating the boiling mode of the cooling water by using the value of the temperature increase of the cooling water, and adjusting the amount of cooling water so that the estimated boiling mode continues to be nucleate boiling. Comparing nucleate boiling and film boiling, the heat flux is greater in nucleate boiling. Therefore, the temperature increase of the cooling water during nucleate boiling is greater than the temperature increase of the cooling water during film boiling.

[0066] The temperature increase of the cooling water can be estimated by Expression (6). Since a portion of heat is consumed as heat of vaporization, the temperature increase of the cooling water obtained by Expression (6) is an approximate value.

$$\Delta T = q/(\rho c W) \qquad (6)$$

where ΔT is the temperature increase (°C) of the cooling water, q is the heat flux (W·m^2) from the cast slab to the cooling water, ρ is the density (kg/m^3) of the cooling water, c is the specific heat (J/(kg·K)) of the cooling water, and W is the flow density per unit time (m^3/(m^2·s)) of the cooling water.

[0067] As described above, the value of the heat flux q differs between nucleate boiling and film boiling. Therefore, the value of the temperature increase ΔT of the cooling water estimated by Expression (6) given above also differs between nucleate boiling and film boiling. Accordingly, the boiling mode of the cooling water can be estimated depending on whether the actual temperature increase, which is determined from the measured temperature values of the cooling water obtained before and after cooling of the cast slab 3, is closer to the estimated value of the temperature increase for nucleate boiling or that for film boiling based on Expression (6) given above. The nucleate boiling state of the cooling water may be maintained by adjusting the amount of cooling water so that the estimated boiling mode may be kept nucleate boiling state.

Example 1

[0068] Casting of low-carbon steel was performed by using the continuous casting machine 1 to verify the effects of the present invention, which will now be described. In the example described below, numerical values, for example, are provided to facilitate understanding of the present invention, and the present invention is not limited to the example in any respect.

[0069] The length of the continuous casting machine 1 was 45 m, and the horizontal zone 9 was constituted by fifteen segments, each having a length of 2 m. Regarding the casting conditions, the casting speed was 2 mpm, the thickness of the cast slab was 250 mm, and the width of the cast slab was 1500 mm. Water used as the cooling water was mixed with air and was discharged from the cooling sprays 21. The temperature of the water and air was 30°C.

[0070] The surface temperature of the cast slab 3 was 850°C at the time when the cast slab 3 reached the horizontal zone 9.

[0071] The solidification temperature, or the solidus temperature, was 1500°C, and the average thermal conductivity was 39.4 kcal/(m·hour·°C).

[0072] A radiation thermometer was used to measure the temperature.

[0073] The solidification position was determined from a rivet driving test.

[0074] Cooling conditions in the horizontal zone 9 were changed in various ways under the above-described conditions. The first cooling portion 13 and the second cooling portion 15 were partitioned based on the segments, and the flow density per unit time was set for each segment. The heat flux was determined by calculation based on the result of an experiment corresponding to actual operation conditions performed by using an experimental apparatus assembled simulating the actual apparatus. More specifically, in the above-described experiment, the surface temperature of the cast slab was measured by using the radiation thermometer, and the position of the solidification interface was measured by using an ultrasonic wave measurement device. Then, the results of the measurements were used to calculate the heat flux by an inverse heat flux calculation method described in Non Patent Literature 1.

[0075] As Comparative Example 1, the flow density per unit time in the horizontal zone 9 was set to a constant value of 180 liter/ (m^2·min).

[0076] As Comparative Examples 2 and 3, the horizontal zone 9 was set so that five segments at an upstream side thereof constituted the first cooling portion 13 and that the remaining ten segments constituted the second cooling portion

15, and cooling was performed by setting the flow density per unit time individually. For example, in Comparative Example 2, cooling at a flow density per unit time of 250 liter/(m^2·min) was performed in the five segments in the first cooling portion 13, and the flow density per unit time was reduced to 140 liter/(m^2·min) for cooling in the remaining ten segments in the second cooling portion 15. At the start of second cooling, that is, at the time when the flow density per unit time was reduced from 250 liter/(m^2·min) to 140 liter/(m^2·min), the surface temperature of the cast slab 3 was 763°C.

[0077] As invention examples, the numbers of segments and the flow density per unit time in the first cooling portion 13 and the second cooling portion 15 were set individually, and cooling was performed. For example, in Invention Example 1, cooling was performed at a flow density per unit time of 300 liter/(m^2·min) in five segments in the first cooling portion 13, and at a flow density per unit time of 150 liter/(m^2·min) in the remaining ten segments in the second cooling portion 15. The surface temperature of the cast slab 3 at the start of second cooling was 140°C.

[0078] Numerical values are shown in Table 1 specifically.

[0079] In Example 1, each spray nozzle is oriented so that the major axis of the cooling surface extends in a direction perpendicular to the casting direction, as illustrated in Fig. 2.

[Table 1]

	First Cooling Portion		Start of Second Cooling	Second Cooling Portion		Calculation Value of Right Side of Expression (1)	Set Value of Left Side of Expression (2)	Calculation Value of Right Side of Expression (2)	Calculation Value of Right Side of Expression (3)	Solidification Position (from End of Caster)
	Flow Density	Number of Segments	Surface Temperature	Flow Density	Ratio to First Cooling					
	L/ (m^2·min)		°C	L/ (m^2·min)	%	°C	10^5 kcal/ (m^2·h)	10^5 kcal/ (m^2·h)	L/(m^2·min)	m
Comparative Example 1	180	(5)	(791)	180	100%	260	2.68	5.05	19.3	1.0
Comparative Example 2	250	5	763	140	56%	249	3.40	5.23	21.1	1.5
Comparative Example 3	700	5	95	90	13%	229	4.81	9.44	95.4	3.8
Invention Example 1	300	5	140	150	50%	252	9.97	9.15	88.2	10.0
Invention Example 2	500	5	131	100	20%	234	9.89	9.21	89.6	10.5
Invention Example 3	1000	3	123	100	10%	234	9.71	9.26	90.9	10.8
Invention Example 4	600	7	124	120	20%	242	9.48	9.25	90.7	10.9
Invention Example 5	4000	1	105	95	2%	231	12.4	9.37	93.7	10.9

[0080] In Comparative Examples 1 and 2, Expressions (1) and (2) were not satisfied, and cooling in a film boiling region was performed over the entirety of the horizontal zone 9. Therefore, cooling was insufficient, and the temperature was high at the exit of the cooling portion.

[0081] In Comparative Example 3, Expression (1) was satisfied, so that cooling in a nucleate boiling region was performed and that the temperature was sufficiently reduced in the first cooling portion 13. However, since Expression (2) was not satisfied, nucleate boiling was not maintained and cooling in a film boiling region was performed in the second cooling portion 15. Therefore, the cooling capability was insufficient, and the temperature was high at the exit of the cooling portion.

[0082] In Invention Examples 1 to 5, cooling in the nucleate boiling region was performed and the temperature was sufficiently reduced in the first cooling portion 13. In addition, in the second cooling portion 15, nucleate boiling was maintained, so that sufficient cooling capability was achieved and the temperature was maintained low at the exit of the cooling portion. As a result, the time required to complete the solidification was reduced. This means that the casting speed can be increased and that the productivity can be increased accordingly.

Example 2

[0083] Experiments performed to verify the effect of spray nozzle inclination will now be described. The continuous casting machine and operation conditions are the same as those in Example 1.

[0084] The flat spray nozzles installed in the horizontal zone 9 were oriented so that the major axis of the cooling surface having a round cornered rectangular shape formed on the surface of the cast slab by the cooling water discharged from each spray nozzle was inclined relative to the direction perpendicular to the casting direction.

[0085] In Invention Example 6, the major axis of the cooling surface having a round cornered rectangular shape formed on the surface of the cast slab by the cooling water discharged from each of the spray nozzles in the horizontal zone 9 was inclined at an angle of 20° relative to the direction perpendicular to the casting direction. Cooling was performed at a flow density per unit time of 300 liter/(m^2·min) in five segments in the first cooling portion 13, and at a flow density per unit time of 150 liter/(m^2·min) in the remaining ten segments in the second cooling portion 15. The surface temperature of the cast slab 3 at the start of second cooling was 128°C.

[0086] In Invention Example 7, the flow densities per unit time in the first cooling portion 13 and the second cooling portion 15 were the same as those in Invention Example 6, and the major axis was inclined at an angle of 60°.

[0087] In Invention Example 8, the flow density per unit time was 1000 liter/(m^2·min) in the first cooling portion 13, and was 100 liter/(m^2·min) in the second cooling portion 15. The major axis was inclined at an angle of 20°.

[0088] In Invention Example 9, the flow densities per unit time in the first cooling portion 13 and the second cooling portion 15 were the same as those in Invention Example 8, and the major axis was inclined at an angle of 60°.

[Table 2]

	First Cooling Portion			Start of Second Cooling	Second Cooling Portion			Calculation Value of Right Side of Expression (1)	Solidification Position (from End of Caster)
	Flow Density	Number of Segments	Nozzle Inclination	Surface Temperature	Flow Density	Ratio to First Cooling	Nozzle Inclination		
	L/ (m^2·min)			°C	L/ (m^2·min)	%		°C	m
Invention Example 6	300	5	20	128	150	50%	20	286	10.3
Invention Example 7	300	5	60	137	150	50%	60	286	9.9
Invention Example 8	1000	3	20	110	100	10%	20	357	11.3
Invention Example 9	1000	3	60	121	100	10%	60	357	10.6

[0089] In Invention Examples 6 and 8, in which the inclination angle of the major axis was 20°, the cooling water flowed along the surface of the cast slab at a higher velocity than in Invention Examples 1 and 3 (see Table 1), in which the inclination angle of the major axis was 0° and in Invention Examples 7 and 9, in which the inclination angle of the major axis was 60°. As a result, the cooling capability was increased and the time required to complete the solidification was further reduced. This means that the casting speed can be increased and that the productivity can be increased accordingly.

[0090] Thus, it is suggested that the cooling capability may be increased when the major axis of the cooling surface having a round cornered rectangular shape formed on the surface of the cast slab by the cooling water discharged from each spray nozzle is inclined at an angle in a certain range (5 to 45 degrees) relative to the direction perpendicular to the casting direction.

[0091] The preferred range of the inclination angle is set to 5 to 45 degrees because the effect is small when the inclination angle is less than 5 degrees and the cooling capability is reduced when the angle exceeds 45 degrees, as suggested in the above-described case in which the angle is 60 degrees.

Reference Signs List

[0092]

1	continuous casting machine
3	cast slab
5	vertical zone
7	curved zone
9	horizontal zone
11	secondary cooling zone
13	first cooling portion
15	second cooling portion
17	mold
19	roller
21	cooling spray
23	spray nozzle
25	refrigerant

Claims

1. A secondary cooling method for a continuously cast slab by which a cast slab cast in a continuous casting machine is subjected to secondary cooling in a secondary cooling zone including a vertical zone, a curved zone, and a horizontal zone, the secondary cooling method comprising:

a first cooling step performed in an upstream portion in the horizontal zone in a casting direction and a second cooling step performed in a downstream portion in the horizontal zone in the casting direction,
wherein the first cooling step includes cooling of the cast slab with cooling water supplied at a flow density per unit time of 300 to 4000 liter/(m^2·min) (where min means minute as a unit of time) so that the cooling water on a surface of the cast slab is in a nucleate boiling state in the first cooling step, and
wherein the second cooling step includes cooling of the cast slab with the cooling water supplied at a flow density per unit time of 2% or more and 50% or less of the flow density of the cooling water in the first cooling step so that the nucleate boiling state of the cooling water on the surface of the cast slab is maintained in the second cooling step.

2. The secondary cooling method for a continuously cast slab according to Claim 1, wherein the second cooling step is performed such that a surface temperature Ts (°C) of the cast slab at a start of cooling of the cast slab and the flow density W (liter/(m^2·min)) of the cooling water in the second cooling step satisfy a relationship of Expression (1) :

$$Ts < 10\text{^}[0.08 \times \ln(W) + 2] \qquad (1)$$

where ln is a natural logarithm and ^ is an exponentiation operator in Expression (1).

3. The secondary cooling method for a continuously cast slab according to Claim 2, wherein the second cooling step is performed such that when a thickness of the cast slab is t (m), an average thermal conductivity of the cast slab in a thickness direction in a region excluding an unsolidified portion of the cast slab is λ (kcal/(m·hour·°C)), and a solidification temperature of the cast slab is Tc (°C), a heat flux q (kcal/(m^2·hour)) of the cooling water satisfies a relationship of Expression (2):

$$q \geq \lambda[4(Tc - Ts)/t] \qquad (2)$$

4. The secondary cooling method for a continuously cast slab according to any one of Claims 1 to 3, wherein the second cooling step is performed such that the flow density W of the cooling water satisfies a relationship of Expression (3):

$$W > e\hat{}[(\log(\lambda[4(Tc - Ts)/t]) - 5.2)/0.17] \qquad (3)$$

where e is a base of a natural logarithm, log is a common logarithm, and ^ is an exponentiation operator in Expression (3).

5. The secondary cooling method for a continuously cast slab according to any one of Claims 1 to 4, wherein a plurality of rollers and a plurality of spray nozzles are provided in the horizontal zone, the rollers being arranged in the casting direction and oriented so that axial directions thereof are perpendicular to the casting direction, the spray nozzles which discharge the cooling water toward the surface of the cast slab being arranged in the cast slab width direction between the rollers that are adjacent to each other in the casting direction,

wherein a cooling surface formed when the cooling water discharged from each of the spray nozzles strikes the surface of the cast slab has a round cornered rectangular shape or an elliptical shape, and
wherein, at least in the first cooling step, the cooling water is discharged such that a major axis of the cooling surface is inclined at an angle in a range of 5 to 45 degrees relative to a direction perpendicular to the casting direction.

6. A secondary cooling apparatus for a continuously cast slab by which a cast slab cast in a continuous casting machine is subjected to secondary cooling in a secondary cooling zone including a vertical zone, a curved zone, and a horizontal zone,

wherein the horizontal zone includes a first cooling portion and a second cooling portion,
wherein, in the first cooling portion, the cast slab is able to be cooled with cooling water supplied at a flow density per unit time of 300 to 4000 liter/(m^2·min) (where min means minute as a unit of time) so that the cooling water on a surface of the cast slab is in a nucleate boiling state in the first cooling portion, and
wherein, in the second cooling portion, the cast slab is able to be cooled with the cooling water supplied at a flow density per unit time of 2% or more and 50% or less of the flow density of the cooling water in the first cooling portion so that the nucleate boiling state of the cooling water on the surface of the cast slab is maintained in the second cooling portion.

7. The secondary cooling apparatus for a continuously cast slab according to Claim 6, wherein a plurality of rollers and a plurality of spray nozzles are provided in the horizontal zone, the rollers being arranged in the casting direction and oriented so that axial directions thereof are perpendicular to the casting direction, the spray nozzles which discharge the cooling water toward the surface of the cast slab being arranged in a cast slab width direction between the rollers that are adjacent to each other in the casting direction,

wherein the spray nozzles are able to discharge the cooling water so that a cooling surface formed when the cooling water discharged from each of the spray nozzles strikes the surface of the cast slab has a round cornered rectangular shape or an elliptical shape, and
wherein, at least in the first cooling portion, the spray nozzles are arranged such that a major axis of the cooling surface is inclined at an angle in a range of 5 to 45 degrees relative to a direction perpendicular to the casting direction.

FIG. 1

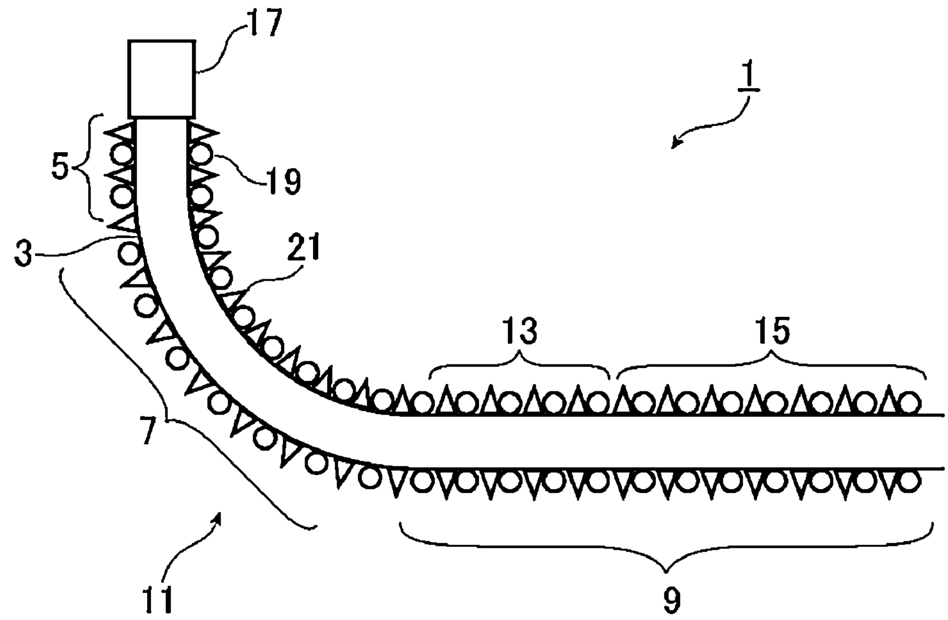

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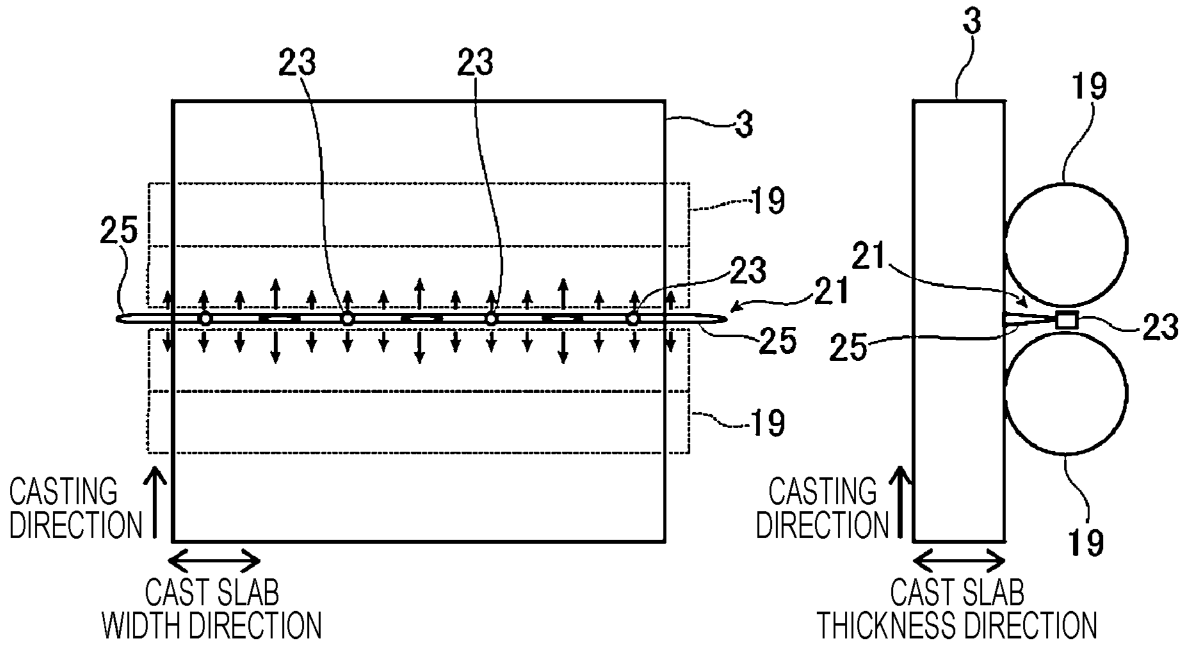
FIG. 2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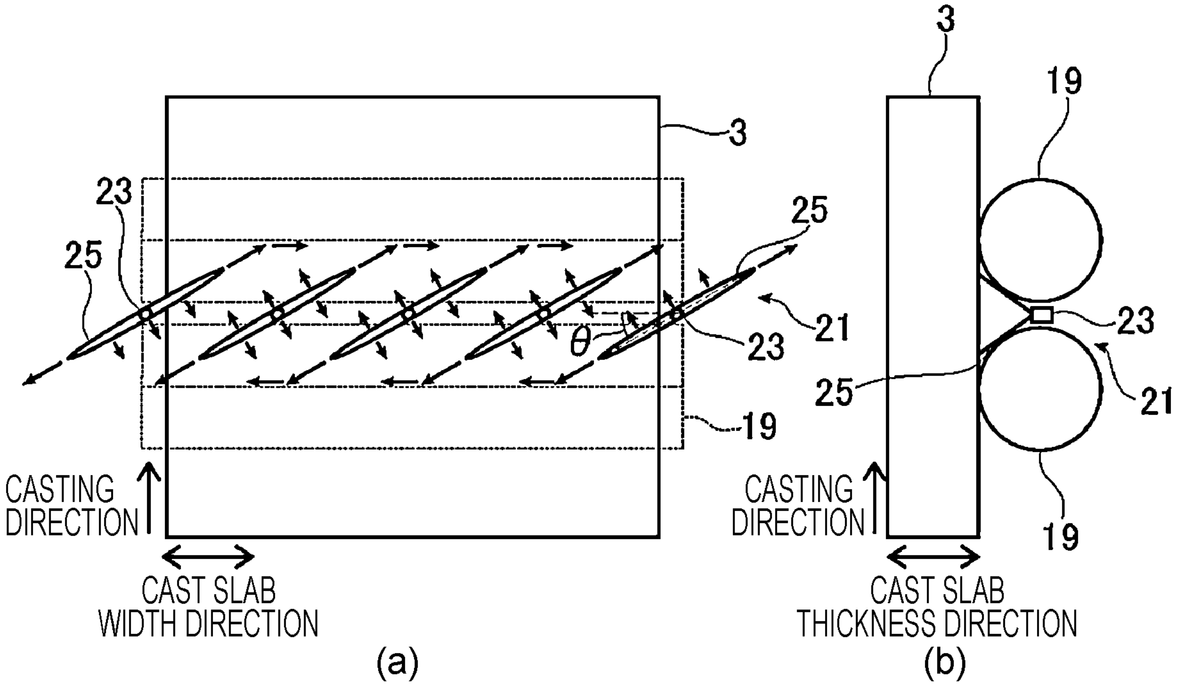
CASTING DIRECTION
CAST SLAB THICKNESS DIRECTION
(b)

FIG. 3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CASTING DIRECTION
CAST SLAB WIDTH DIRECTION
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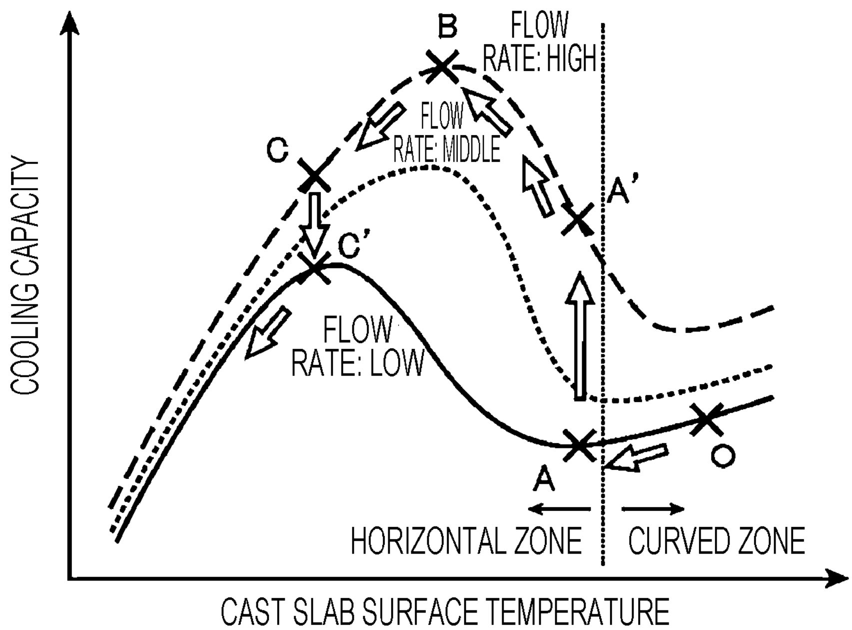
CAST SLAB THICKNESS DIRECTION
(b)

FIG. 4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FLOW RATE: MIDDLE
C
A'
C'
FLOW RATE: LOW
COOLING CAPACITY
A
O
HORIZONTAL ZONE
CURVED ZONE
CAST SLAB SURFACE TEMPERATURE

INTERNATIONAL SEARCH REPORT

International application No. PCT/JP2020/026487

A. CLASSIFICATION OF SUBJECT MATTER
B22D 11/124(2006.01)i; B22D 11/22(2006.01)i
FI: B22D11/22 B; B22D11/124 N; B22D11/124 L

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

Published examined utility model applications of Japan	1922-1996
Published unexamined utility model applications of Japan	1971-2020
Registered utility model specifications of Japan	1996-2020
Published registered utility model applications of Japan	1994-2020

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 2018-15781 A (NIPPON STEEL & SUMITOMO METAL CORPORATION) 01.02.2018 (2018-02-01) entire text, fig. 1-11	1-7
A	JP 2014-200803 A (NIPPON STEEL & SUMITOMO METAL CORPORATION) 27.10.2014 (2014-10-27) entire text, fig. 1-7	1-7

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

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 August 2020 (27.08.2020)	08 September 2020 (08.09.2020)

Name and mailing address of the ISA/	Authorized officer
Japan Patent Office 3-4-3, Kasumigaseki, Chiyoda-ku, Tokyo 100-8915, Japan	Telephone No.

Form PCT/ISA/210 (second sheet) (January 2015)

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/JP2020/026487

Patent Documents referred in the Report	Publication Date	Patent Family	Publication Date
JP 2018-15781 A	01 Feb. 2018	(Family: none)	
JP 2014-200803 A	27 Oct. 2014	(Family: none)	

Form PCT/ISA/210 (patent family annex) (January 2015)

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- JP 2003285147 A **[0007]**

Non-patent literature cited in the description

- **J.V. BECK.** *Int. J. Mass Transfer,* 1970, vol. 13, 703 **[0008]**