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Introduction

To produce high-quality steel products with high pro- ctivity, effective technologies for cleanliness in olten steel have been desired in the steelmaking ocess. Inclusion separation and slag removal are nportant for molten steel cleanliness. Therefore, the llowing technologies have been proposed and intro- iced to promote inclusion floatation in a tundish and to duce contamination in the tundish: (1) Use of a large- ıpacity tundish to obtain a residence time long enough r inclusions to float,1) (2) improvement of the dam ıape to the control molten steel flow,2) (3) promotion of clusion separation by heating the molten steel in the ndish,3) (4) use of Ar gas blowing into the molten steel the tundish,4) (5) development of a process in which olten steel can be fed from two ladles to a tundish dur- g ladle exchanges,5) and (6) sealing of the tundish to event oxidation by the air.6)

Recently, consumer requirements have become higher id the necessity of cost reduction has increased, high- ghting the need for more effective technology for clusion separation. In particular, reducing inclusions ithout the extra cost of a secondary refining process for gh-quality steel has become an important problem. uality improvement of the slab cast during the unsteady state in continuous casting, for example during ladle exchanges, has also become important.

In response to these needs, a new tundish in which the molten steel is horizontally rotated by electromagnetic force has been developed. This tundish is referred to as the CF tundish (centrifugal flow tundish). The effect of the rotating electromagnetic force on inclusion separation in a batch system7) and a pilot plant experiment using a 500 kg capacity tundish8) have already been reported by the authors.

In this work, experiments were carried out at Chiba No. 1 continuous casting machine, and the deoxidation performance and mechanism of inclusion separation in an industrial plant were studied.

2 Principle and Mechanism of Inclusion Separation in CF Tundish

The general concept of the CF tundish is shown in **Fig. 1**. A moving electromagnetic field is imposed from outside a cylindrical tundish. Molten steel is horizontally rotated and centripetal force acts on the inclusions due to their lower density relative to that of the molten steel.

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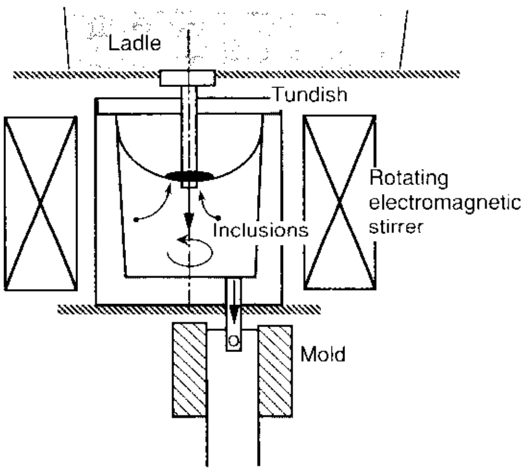

Fig. 1 Concept of centrifugal flow tundish

Inclusions are separated from the molten steel, and clean steel flows out from the bottom corner of the tundish into a mold.

Three mechanisms for inclusion separation and slag removal in the CF tundish were anticipated, as follows: (1) Concentration of inclusions by the centripetal force, (2) promotion of inclusion collision and agglomeration,$^{7)}$ and (3) improvement of the residence time distribution by the rotational flow.$^{9)}$

3 Plant Experiments Using the CF Tundish

3.1 Experimental Equipment and Conditions

To clarify the effectiveness of the CF tundish in an industrial plant, experiments were carried out at Chiba No. 1 continuous casting machine. **Figure 2** shows the general concept of the equipment. The tundish has two chambers. One is a 3 t rotation chamber, which is shown as A in Fig. 2, and the other is a 7 t rectangular chamber, which is shown as B in Fig. 2. The reason for this structure is as follows. To ensure the height of the molten steel in the tundish during the ladle exchange, a tundish must contain a certain amount of molten steel. Further, a small rotating electromagnetic stirrer is used to reduce the cost. The tundish therefore has two chambers, and molten steel is rotated only in the rotation chamber, which is connected to another chamber at its bottom.

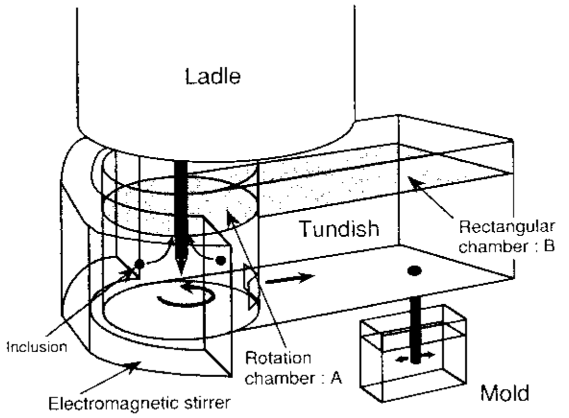

Fig. 2 Equipment of the centrifugal flow tundish in continuous casting

Table 1 Experimental conditions (No. 1 CC, Chiba Works)

Capacity of tundish	(t)	10
Ladle capacity	(t)	100
Feeding rate	(t/min)	1.5
Rotational speed	(rpm)	40~50

Table 2 Composition of molten steel

Steel	C	Si	Mn	Al	Cr
Low Al	0.05	0.4	0.6	0.02	16.3
High Al	0.05	0.4	0.6	0.07	16.3

Table 1 shows the experimental conditions: 100 t of molten ferritic stainless steel in a ladle were used, and the molten steel in three ladles was cast continuously.

The chemical composition of the molten steel is shown in **Table 2**. A submerged nozzle was employed to pour the molten steel from the ladle into the tundish.

The molten steel height was kept steady at 670 mm. During the ladle exchange, the height was decreased to 350–500 mm as the ladle emptied and increased after the next ladle began to supply molten steel at the rate of 3.5–6.5 t/min.

3.2 Deoxidation Behavior in Steady State

Figure 3 shows the total oxygen content, $[O_t]$, in a tundish with molten steel rotation and without molten steel rotation. O_{free} in Fig. 3 is the equilibrium content of solute oxygen in which the interaction between Cr and O is taken into account. The oxygen content as inclusions is calculated to deduct O_{free} from $[O_t]$. Molten steel rotation can reduce the oxygen content as inclusions in a tundish to 50% less than that without rotation.

Figure 4 shows the specific oxide area measured by the electron beam method. The amount of inclusions in the tundish without rotation is almost the same as that in the ladle. Molten steel rotation reduces the amount of inclusions to 26% of that in the ladle.

A large amount of deoxidation and inclusion separation are achieved in the CF tundish.

3.3 Deoxidation Behavior During the Ladle Exchanges

To evaluate the effect of the CF tundish on deoxida-

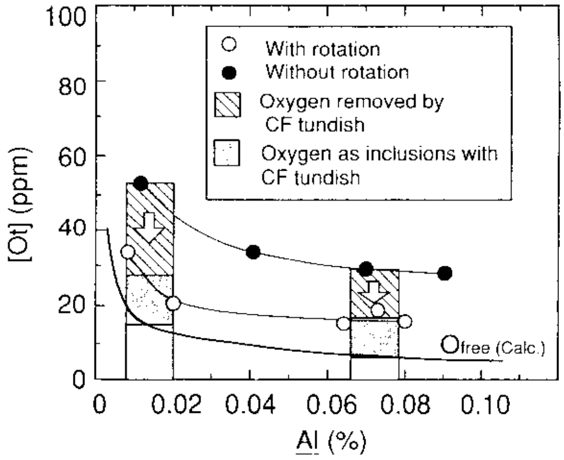

Fig. 3 Comparison of oxygen content of samples from tundish with rotation and without rotation

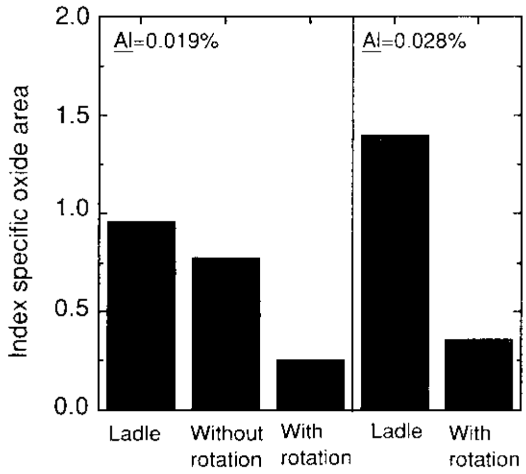

Fig. 4 Comparison of specific oxide area measured by EB method

tion, the oxygen contents of slabs were examined. **Figure 5** shows the $[O_t]$ distribution along the thickness direction in slabs cast in a steady state and during a ladle exchange. The $[O_t]$ of slabs cast with molten steel rotation is reduced to approximately half that without rotation. Even during a ladle exchange, the $[O_t]$ is as low as that in slabs cast in the steady state without rotation.

In general, $[O_t]$ increases during a ladle exchange because the slag and sand from the ladle flow into the tundish. These contaminants often cause defects in products.$^{5)}$ **Figure 6** shows the average value of $[O_t]$ from the surface to 30 mm thickness. $[O_t]$ decreases with increased rotation speed, and the $[O_t]$ of slabs during ladle exchanges with rotation is almost the same as that of slabs in the steady state without rotation.

Furthermore, slag separation during the ladle exchange is discussed in Section 3.5.2 to clarify the mechanism of this large deoxidation effect.

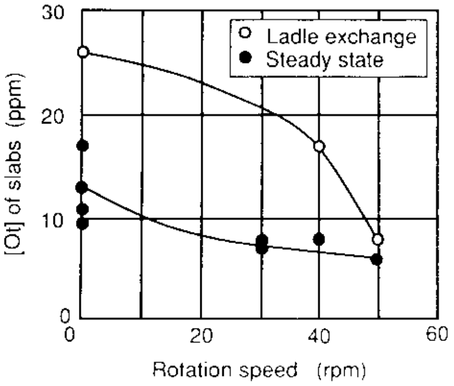

Fig. 6 Total oxygen content of slabs by CF tundish and conventional tundish during ladle exchange and steady state

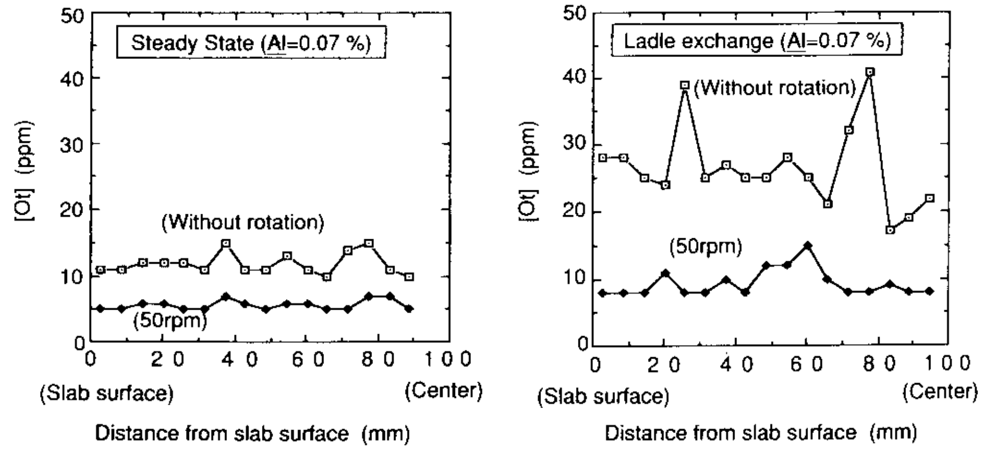

Fig. 5 Comparison of total oxygen contents of cast slabs with rotation and without rotation

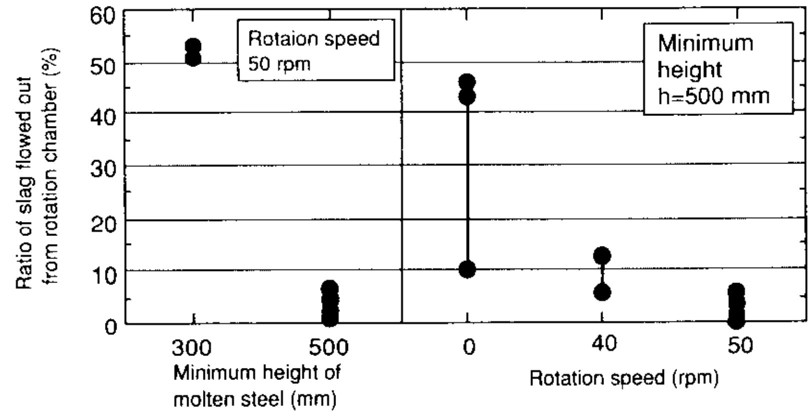

Fig. 8 Measurement of ratio of slag flowing out of rotation chamber during ladle exchange

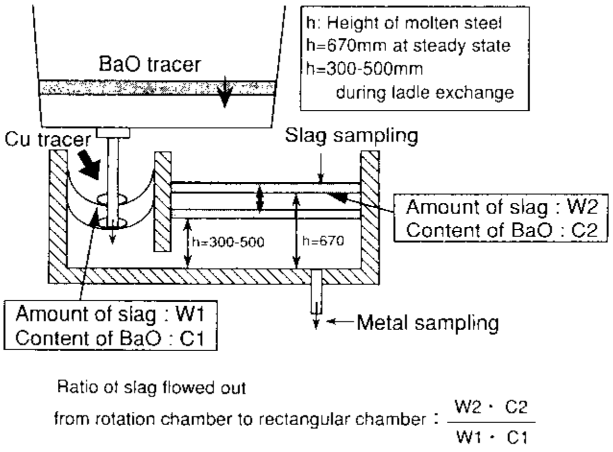

Fig. 7 Method of Cu and BaO tracer experiments

3.4 Ladle Slag Separation

To evaluate the performance of the slag separation in the CF tundish, BaO of 5 wt% relative to the whole ladle slag was put into a ladle slag as a slag tracer. The contents of BaO in the flux in the rotation chamber and the rectangular chamber were examined to estimate the amount of slag flowing from the rotation chamber into the rectangular chamber, as shown in **Fig. 7**. The results are shown in **Fig. 8**. When the lowest height of molten steel was over 500 mm, the slag separation was greatly improved with increased rotation speed.

3.5 Discussion

3.5.1 Deoxidation rate constant in CF tundish

The deoxidation rate constant is calculated by Eq. (1) when the deoxidation rate is a first order reaction.

$$-\frac{d[\mathrm{O}]}{dt} = k([\mathrm{O}] - [\mathrm{O}]_\infty) \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where, k: the deoxidation rate constant, $[\mathrm{O}]_\infty$: the oxygen content in the final stage.

$[\mathrm{O}]_\infty$ is the oxygen content when the inclusion separation is balanced with the inclusion generation and is a constant independent of the stirring time.

In a chamber with an inlet and an outlet, such as a tundish, Eq. (1) is represented as Eq. (2) when the chamber is a continuous stirred tank reactor which has several perfect mixing reactors.[10]

$$\frac{[\mathrm{O}_{\mathrm{out}}] - [\mathrm{O}]_\infty}{[\mathrm{O}_{\mathrm{in}}] - [\mathrm{O}]_\infty} = \frac{n^n}{\bar{\tau}^n\left(k + \frac{n}{\bar{\tau}}\right)^n} \cdots\cdots\cdots\cdots (2)$$

where, $\bar{\tau}$: the mean residence time, $[\mathrm{O}_{\mathrm{out}}]$: the oxygen content at the outlet, $[\mathrm{O}_{\mathrm{in}}]$: the oxygen content at the inlet, n: number of perfect mixing reactors.

The deoxidation rate in each chamber of the tundish, i.e. the rotation chamber and the rectangular chamber, was considered. That is, Eq. (3) is used assuming that both the rotation chamber and the rectangular chamber are the continuous stirred tank reactors.

$$\frac{[\mathrm{O}_{\mathrm{out}}] - [\mathrm{O}]_\infty}{[\mathrm{O}_{\mathrm{in}}] - [\mathrm{O}]_\infty} = \frac{a^a}{\bar{\tau}^a\left(k + \frac{a}{\bar{\tau}}\right)^a} = \frac{b^b}{\bar{\tau}_1^b\left(k_1 + \frac{b}{\bar{\tau}_1}\right)^b} \times \frac{c^c}{\bar{\tau}_2^c\left(k_2 + \frac{c}{\bar{\tau}_2}\right)^c} \cdots (3)$$

where, a, b, c: number of perfect mixing reactors in the whole tundish, that in the rotation chamber and that in the rectangular chamber, k, k_1, k_2: deoxidation rate constant of the whole tundish, that of the rotation chamber, and that of the rectangular chamber, respectively, τ, $\bar{\tau}_1$, τ_2: mean residence time of the whole tundish, that of the rotation chamber and that of the rectangular chamber, respectively.

The calculated results of the deoxidation rate constants are shown in **Table 3**. The deoxidation rate constants in whole tundish with rotation for low aluminum stainless steel and high aluminum stainless steel were

Table 3 Deoxidation rate constants

Al content (%)		Total oxygen content (ppm)			Deoxidation rate constants (min^{-1})		
		in ladle	in tundish	free O in tundish	k (whole tundish)	k_1 (rotation chamber)	k_2 (rectangular chamber)
0.02	without rotation	68	53	15	0.02	0.02	0.02
	with rotation	68	28		0.25	0.74	0.02
0.07	without rotation	31	28	6	0.02	0.02	0.02
	with rotation	68	16		0.17	0.51	0.02

estimated to be 0.25 min^{-1} and 0.17 min^{-1}, respectively, and those in the rotation chamber were calculated to be 0.51 min^{-1} and 0.74 min^{-1}. On the other hand, the deoxidation rate constant in whole tundish without rotation was estimated to be 0.02 min^{-1}. It was confirmed that the high deoxidation capability can be obtained by CF tundish.

The stirring energy density $\dot{\varepsilon}$ in the rotation chamber is estimated using Eq. (4).[11]

$$\dot{\varepsilon} = 2\pi NT/W \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where, N: rotation speed, T: torque, W: weight of the molten steel.

The torque can be determined by simulated calculation of the electromagnetic field and hydrodynamic flow, and is estimated at 24 kg·m when the rotation speed is 50 rpm. In this case, $\dot{\varepsilon}$ is determined to be 2.5 kw/t.

Figure 9 shows the relationship between the stirring energy density and the deoxidation rate constant in the rotation chamber of the CF tundish. Ar gas bubbling process,[12] ASEA-SKF,[13] Flux Injection process[12] and ladle refining process with a rotating electromagnetic stirrer.[12] The deoxidation rate constant increases with the stirring energy density. The stirring energy density and the deoxidation rate constant of the CF tundish are large compared with those of other processes.

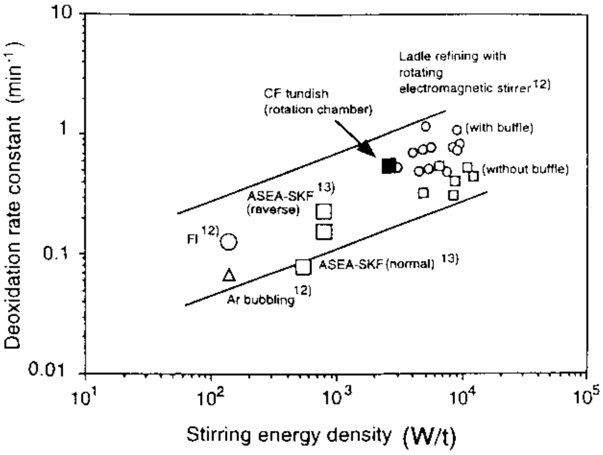

Fig. 9 Comparison of deoxidation rate constants in various processes

3.5.2 Mixing property of CF tundish

To clarify the mechanism of the slag separation, the residence time distribution of the molten steel in the tundish was investigated.

Copper grains were added to the molten steel surface near the submerged nozzle, and samples of molten steel in the outflow to the mold were taken, as shown in Fig. 7.

Figure 10 shows the change of the copper content of the samples. The same examinations were carried out at feeding rates of 3.5 t/min to 6.5 t/min and at molten steel heights from 350 mm to 500 mm.

Residence time distributions are compared by the number of perfect mixing reactors in the perfect mixing model, where the flow pattern is close to the plug flow with an increasing number of perfect mixing reactors and close to the short circuit flow with small number of perfect mixing reactors. The ratio of molten steel flowing out at time τ, $E(\tau/\bar{\tau})$ is expressed by Eq. (5).[10]

$$E(\tau/\bar{\tau}) = \frac{n^{n+1}(\tau/\bar{\tau})^{n-1}\exp(-n\tau/\bar{\tau})}{\Gamma(n)} \cdots\cdots\cdots (5)$$

where, n: the number of perfect mixing reactors, $\bar{\tau}$: mean

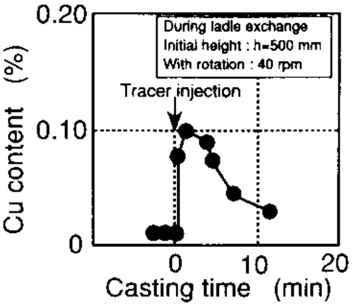

Fig. 10 Change of Cu content of outflow samples from tundish

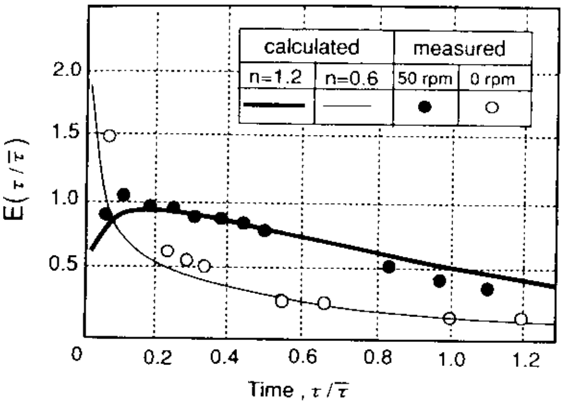

Fig. 11 Comparison between calculated and measured $E(\tau/\bar{\tau})$ during ladle exchange

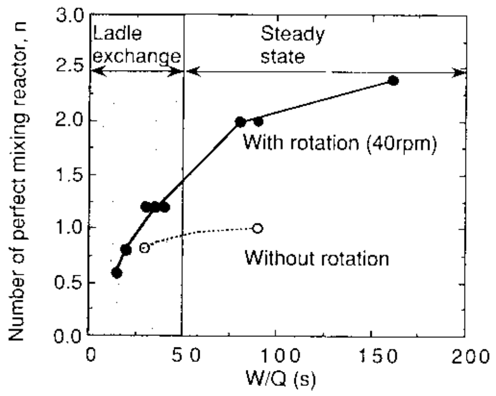

Fig. 12 Relation between W/Q and number of perfect mixing reactors

residence time, τ: residence time, $E(\tau/\bar{\tau})$: ratio of molten steel flowing out at time τ, Γ: Gamma function.

Figure 11 shows the copper content normalized on the basis of the time distribution function calculated in Eq. (5) and calculated $E(\tau/\bar{\tau})$. The number of perfect mixing reactors increases with the rotation speed of the molten steel. The relationship between W (weight of molten steel in a tundish)/Q (the rate of supplying molten steel): (s), and the number of perfect mixing reactors is shown in **Fig. 12**. W/Q is equal to the mean residence time in the steady state. During the ladle exchange, W/Q is in proportion to the amount of the molten steel when the feeding rate is constant. W/Q has a positive relationship to the number of perfect mixing reactors.

In Fig. 12, the number of perfect mixing reactors in the steady state is 2.0–2.4 with rotation and 1.0 without rotation. During the ladle exchange, the number of the perfect mixing reactors becomes 1.2 with rotation and 0.6 without rotation. Rotation of the molten steel greatly improves the residence time distribution by increasing the number of the perfect mixing reactors.

Next, the short circuit flow in the tundish is discussed

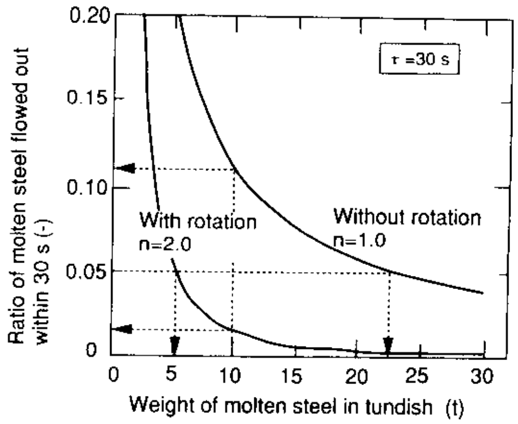

Fig. 13 Calculated results of ratio of molten steel flowing out within 30 s

using the number of the perfect mixing reactors.

The ratio of molten steel flowing out at a time t is expressed by Eq. (5), and the ratio of molten steel flowing out within a time t, $Y(t)$, is expressed by Eq. (6).

$$Y(t) = \int_0^t E(\tau/\bar{\tau})\,d\tau \quad \cdots\cdots (6)$$

The ratio of molten steel flowing out within t, $Y(t)$, can be calculated from Eqs. (5) and (6). To compare the degree of short circuit flow, the ratio of molten steel flowing out within 30 s was calculated for various tundish capacities and numbers of perfect mixing reactors. In **Fig. 13**, the ratio of molten steel flowing out within 30 s decreases as the capacity of the tundish and number of perfect mixing reactors increase. The ratio of molten steel flowing out within 30 s in a tundish with a small capacity of 5 t and 2.0 perfect mixing reactors is equal to that of a tundish with a capacity of 20 t and 1.0 perfect mixing reactor. In other words, the ratio of molten steel flowing out within 30 s from a tundish with a capacity of 10 t and 1.0 perfect mixing reactor is equal to 0.12, and that with 2.0 perfect mixing reactors is 0.05.

Short circuit flow is suppressed by increasing the number of perfect mixing reactors with the CF tundish.

4 Commercial Application at Chiba No. 4 CC

4.1 Equipmint

The CF tundish has been applied to the new Chiba

Table 4 Operational conditions of No. 4 CC

Capacity of rotation chamber	(t)	7
Capacity of rectanglar chamber	(t)	23
Ladle capacity	(t)	160
Feeding rate	(t/min)	2
Rotational speed	(rpm)	40~50

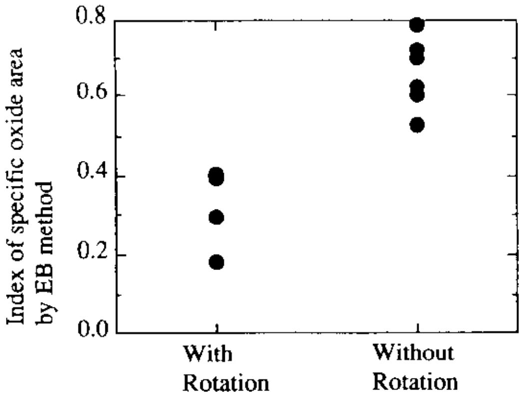

Fig. 14 Comparison of amount of inclusions in molten steel in tundish with rotation and without rotation (Al killed stainless steel)

o. 4 continuous casting machine based on the results escribed above. **Table 4** shows the main specifications f the tundish. The tundish has a capacity of 30 t and the ame mean residence time as that in the Chiba No. 1 ontinuous casting machine. The minimum molten steel eight during ladle exchanges is over 500 mm based on xperimental results at Chiba No. 1 CC.

4.2 Effect of the CF Tundish

In **Fig. 14**, the amount of inclusions measured by the lectron beam method is compared. Using the CF ındish, the amount of inclusions is reduced to half.

Figure 15 shows an index of the ratio of defects in ot and cold rolled coils. The index of defects is reduced) 60% of that without the CF tundish.

The process is being successfully used in the comercial production of high-quality stainless steel slabs.

Conclusion

A new technology for inclusion separation, the CF ındish, has been developed. The following effects were larified by experiments at an industrial plant.

1) The CF tundish has a large deoxidation performance estimated at 0.17–0.25 min^{-1} as the deoxidation rate constant in the whole tundish. In the rotation chamber, the deoxidation rate constant is calculated to be 0.51–0.74 min.$^{-1}$
2) The mechanism of inclusion separation in the CF tundish was also discussed. Centripetal force and the large amount of turbulent energy caused by rotational flow accelerate inclusion separation. Furthermore, the residence time distribution of the molten steel in the tundish is improved, promoting slag removal during ladle exchanges.
3) The amount of inclusions was reduced to half and defects of hot-rolled coils were reduced to 60% of the level without the CF tundish, demonstrating that coils of high quality can be produced using the CF tundish in the commercial process.

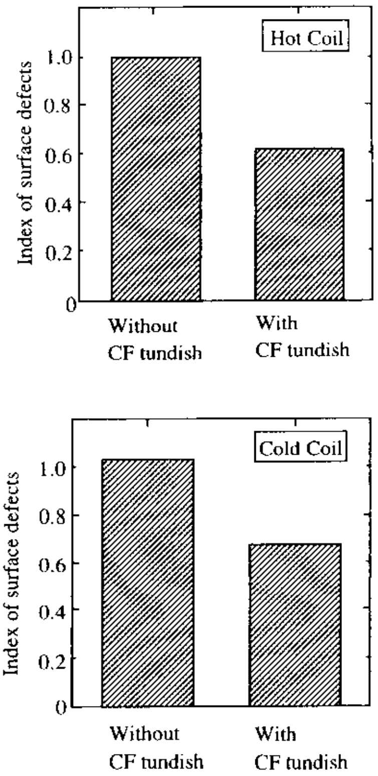

Fig. 15 Effect of the CF tundish on surface quality of stainless steel coils

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