OXYGEN TRANSFER BETWEEN FLUX AND STEEL IN CONTINUOUS CASTING TUNDISH

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Synopsis : The chemical compositions of tundish flux were studied to decrease oxygen content in molten steel in the tundish. Production scale experiments revealed that high basicity flux ($CaO/SiO_2 \geqq 11.0$) is superior in decreasing oxygen content, compared with low basicity flux ($CaO/SiO_2=0.83$). Oxidation and deoxidation rates in the tundish were evaluated quantitatively based on the experimental results. Mathematical model was developed to make clear the behavior of oxygen concentration and to predict the change in oxygen concentration during casting.

Key words: continuous casting; tundish; deoxidation; cleanliness.

1. Introduction

Continuous casting technology for the manufacturing of defect-free slab becomes more important with increase in quality requirements for steel products. The main defects of cold rolled steel sheet attributable to steelmaking conditions are sliver and blister, which originate in the entrapment, by the solidifying shell in the continuous casting mold, of alumina clusters, individually/in combination with the argon gas bubbles blown into the immersion nozzle. To suppress such defects and ensure high quality in continuously cast slab, it is necessary to improve steel cleanliness in the ladle treatment and continuous casting processes. The content of non-metallic inclusions in the steel must be decreased, and the oxidation of steel melt by the atmosphere must be prevented.

The purposes of this study were to determine the optimal chemical composition of the tundish flux which is applied to the surface of the molten steel in the tundish for preventing the oxidation of the melt and absorbing non-metallic inclusions, and secondly, to analyze the deoxidation behavior of the molten steel in the tundish.

2. Experiments

In the casting of ultra low carbon steel (C<0.0030%, Al=0.040 to 0.050%, Si<0.01%) at the No.5 continuous caster at Mizushima works, tundish flux is used to prevent the oxidation of the melt by oxygen in the atmosphere and to eliminate non-metallic inclusions by absorbing them when they float up to the surface in the tundish. The effect of the chemical composition of the tundish flux on the cleanliness of the molten steel in the tundish and continuously cast slab was studied.

The main experimental conditions are shown in Table 1. Four kinds of tundish flux were examined as shown in Table 2. Tundish flux in amounts of 80 to 160kg was added to the surface of the molten steel at each side of the tundish, and a sampling of the steel and slag at S_1 and S_2 was carried out as shown in Fig.1 to evaluate changes in chemical composition of them.

The distances of the long nozzle and S_1 point from the immersion nozzle are 2.77m and 1.92m, respectively. Metal sampling was carried out with silica tube at S_2 in the mold, which is close to the spout of the immersion nozzle, therefore the chemical composition of the metal sampled was considered to be the same as that at the tundish exit.

Table 1 Experimental conditions.

Ladle capacity	250t
Tundish capacity	50t
Caster type	2 strand Curved-type(12m in radius)
Feed rate	2.6–2.8t/min·str
Slab size	$220mm^t \times 1100-1500mm^w$
Superheat in tundish	15–30°C

Table 2 Chemical compositions of tundish fluxes.

	A	B	C	D
SiO_2(%)	47.4	7.6	5.7	2.6
Al_2O_3(%)	2.7	22.2	20.7	20.5
CaO(%)	39.5	46.2	62.5	58.2
CaO/SiO_2	0.83	6.1	11.0	22.2
Softening temperature(°C)	1280	1380	1300	1410

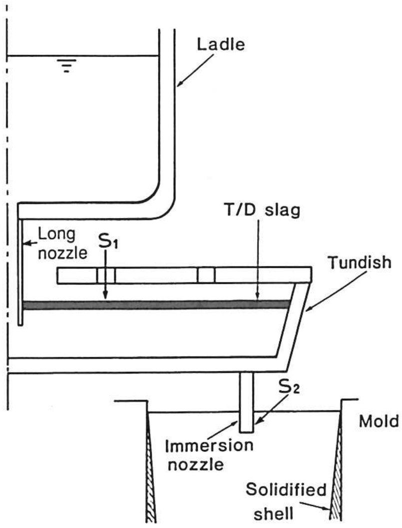

Fig. 1 Schematic drawing of sampling position of slag and metal during casting.

3. Results and Discussions

3.1 Effects of tundish flux on cleanliness of molten steel and continuously cast slab

Figure 2 shows the effect of the basicity of tundish flux on the difference, Δ[T·O], between total oxygen content at the end of RH treatment and that in the tundish. Total oxygen content, [T·O], in the tundish decreases with increase in basicity of the tundish flux, resulting in a decrease in Δ[T·O]. However, the total oxygen content at the end of RH treatment, deoxidation and contamination of the melt during ladle transfer, and the effectiveness of sealing between the ladle and tundish vary with each charge, causing the scattering of data shown in Fig.2.

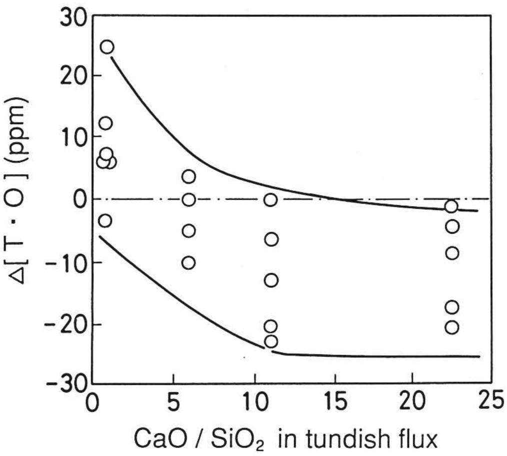

Fig. 2 Relation between Δ[T·O] and basicity of tundish flux.

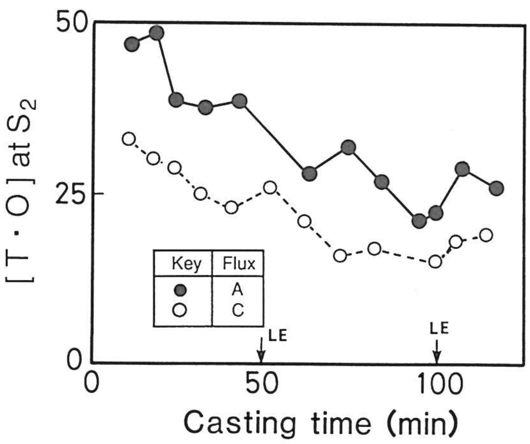

Fig. 3 Influence of tundish flux on the oxygen concentration of molten steel in tundish. (LE: Ladle Exchange)

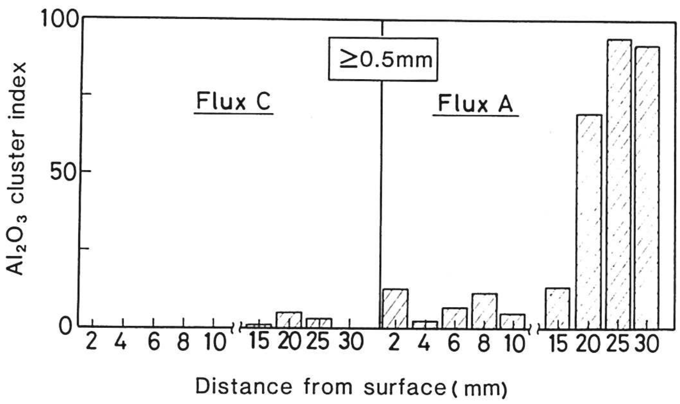

Fig. 4 Distributions of alumina cluster across thickness of cast slab.

To estimate more precisely the effect of the tundish flux on steel cleanliness, a more sophisticated experiment was subsequently carried out. Two fluxes, A and C, were used in the same tundish of a two-strand machine. Flux A was added on the surface of the molten steel at the left side of the tundish, which corresponds to Strand 1, and Flux C at the right side (Strand 2). Changes in total oxygen content at S_2 for Strands 1 and 2 are shown in Fig.3. The [T·O] at S_2, with the higher basic Flux C is 6 to 16ppm lower than that with the low basicity Flux A.

The casting was carried out under the conditions in Table 1 and, small size slabs ($220mm^t \times 1300mm^W \times 500mm^l$) were sampled for examination, which correspond to the experimental conditions shown in Fig.3. The number of large alumina spots was detected on the longitudinal cross section of the slab by machining every 2 to 5mm from the loose-side surface of the slab.

Figure 4 shows the distribution of alumina clusters with diameter of larger than 0.5mm across the thickness of slabs. A small number of alumina clusters was observed in the strand cast with Flux C, while a large number was observed in the region from the surface to 20 to 30mm thickness of the slabs cast using Flux A.

3.2 Reduction of (SiO_2) in tundish slag

Based on the results of 3.1, an effort was made to explain how the basicity of the tundish flux affects the cleanliness of molten steel and slab. Changes in the chemical composition of the tundish slag during casting are caused by the following factors: 1) Inflow of SiO_2 used as a packing material for the teeming nozzle of the ladle. 2) Reduction of (SiO_2) in tundish slag by aluminum, $\underline{Al}$, in steel melt. 3) Float up of Al_2O_3 in steel melt.

Changes in (CaO), (Al_2O_3) and (SiO_2) concentrations in tundish slag during casting are shown in Fig.5 for Flux A, C and D.

When low basicity Flux A is used, the (CaO) concentration decreases from 40% to 20% as a result of the increased silica and alumina contents caused by 1) and 2), while the (Al_2O_3) concentration increases from 3% to 25% due to 2) and 3), and the (SiO_2) concentration decreases from 46% to 30% because of the balance of factors 1) and 2).

In case of high basicity Flux C or D, (CaO) and (Al_2O_3) concentrations change in the same way for Flux A, but (SiO_2) concentration increases from 3 to 5% to 15 to 20% during casting.

Figure 6 shows changes in the mass of (SiO_2), W_{SiO_2}, in the tundish slag.

When Flux C or D is used, the rate of increase in W_{SiO_2} is 0.336kg SiO_2/min., which corresponds to the amount of SiO_2 used as a packing material for the teeming nozzle of the ladle, indicating no reduction of (SiO_2) by aluminum in the steel melt.

It is presumed that SiO_2 supplied from the ladle, melts and is absorbed into slag at a constant rate.

On the other hand, the change in SiO_2 content for Flux A is smaller than that estimated,the rate of increase in W_{SiO_2} is 0.068kg SiO_2/min., suggesting the reduction of (SiO_2) and hence contamination of the steel melt by $\underline{Al}$, which is formed by the following reaction.

$$4\underline{Al}+3SiO_2=3\underline{Si}+2(Al_2O_3) \quad (1)$$

The rate of reduction of (SiO_2), in the tundish slag by $\underline{Al}$, Q_{SiO_2}, is given by eq. (2).

$$Q_{SiO_2}=0.336-0.068=0.268kgSiO_2/min. \quad (2)$$

In this study, the dependence of Q_{SiO_2} on (SiO_2) concentration in slag with Flux A was not clear.

Umesawa and Kajioka[1] investigated the reduction of (SiO_2) in ladle furnace slag by aluminum in Al killed steel, and confirmed that silica activity in slag, a_{SiO_2}, affects the reduction rate of (SiO_2).

Changes in a_{SiO_2} in tundish slag with Flux

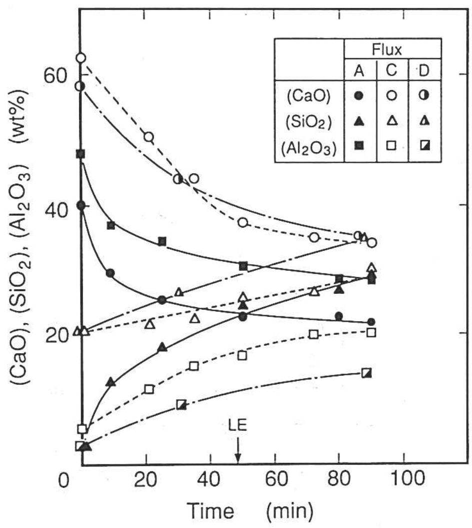

Fig. 5 Concentration changes of (CaO), (Al_2O_3) and (SiO_2) in tundish slag with time during casting.

A, C and D are shown in Fig.7[2], where concentrations of (CaO), (Al_2O_3) and (SiO_2) are normalized to the ternary $CaO-Al_2O_3-SiO_2$ system.

When Flux A is used, a_{SiO_2} varies from above 0.20 at the initial stage of casting to 0.10 at the end of casting.

On the other hand, a_{SiO_2} shows 0.008 for Flux C and 0.004 for Flux D at the end of casting, being 1/10 to 1/20 of Flux A.

The difference in reduction rate of (SiO_2) depends on a_{SiO_2} in tundish slag. Further discussion is, however, difficult because reaction mechanism and rate-determining step in the reduction of (SiO_2) by $\underline{Al}$ under the experimental conditions of this study are not clear.

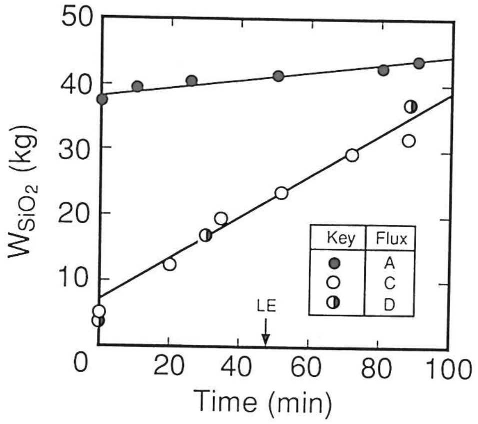

Fig. 6 Change in mass of SiO_2 in tundish slag during casting.

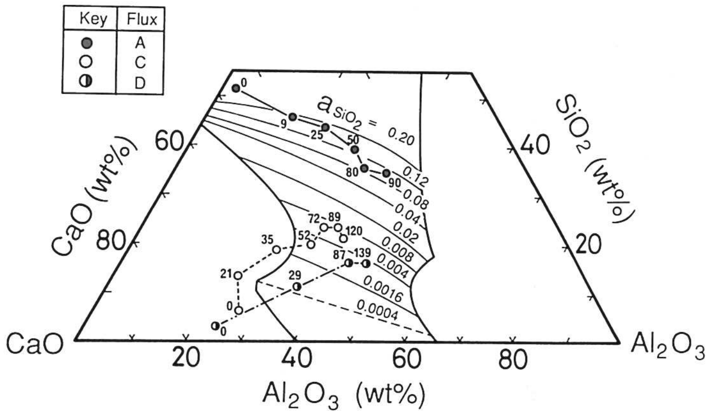

Fig. 7. Change in a_{SiO_2} in tundish slag during casting. (The figures by the plots show the casting time. (min))

3.3 Analysis of deoxidation behavior in tundish

3.3.1 Deoxidation model

To clarify the deoxidation behavior in the tundish and the effect of the tundish flux on the cleanliness of molten steel and cast slab, the deoxidation model was developed.

The tundish is considered as a steady-flow chemical reactor of length L, through which fluid flows with a constant velocity, v, and where the total oxygen is mixing in flow direction with a dispersion coefficient E.

In the tundish, the following two reactions occur.

1) Deoxidation by coagulation and floating up of inclusion,
2) Contamination caused by the reduction of (SiO_2) at the slag/metal interface.

Many studies on steel flow and inclusion removal in the tundish[3],[4] have been investigated recently with three-dimensional hydrodynamic analysis from the microscopic standpoint.

The deoxidation model in the present study has the following characteristics compared with the above analysis:

1) Deoxidation reaction proceeds as homogeneous one shown by eq.(5)[5]. This assumption eliminates complicated calculation which needs formulations of coagulation and floating up phenomena coupled with three dimensional fluid flow.
2) Contamination rate is evaluated by eq.(6), in which constant values are determined experimentally by using two kinds of flux.

The fundamental equation is as follow:

$$\partial C/\partial t=-v\partial C/\partial t+E\partial^2 C/\partial x^2+R \quad (3)$$

where C is concentration of total oxygen, t is time, E is the axial dispersion coefficient, R is a reaction term and evaluated by eq.(4) as the sum of deoxidation rate R_1 and contamination rate R_2, and R_1 and R_2 are expressed by eqs.(5) to (7).

$$R=R_1+R_2 \quad (4)$$

$$R_1=-kC \quad (5)$$
$$R_2=\alpha \cdot A \cdot qo \quad (6)$$
$$qo=Q_{SiO_2}\times 32/60\times 10^3\times 1/60/SM \quad (7)$$

where k is the deoxidation rate constant, A is constant, qo is the total oxygen flux by eq.(1), α is the contamination ratio of the molten steel due to eq.(1), SM is the area of slag/metal interface in the tundish.

In this study, E was estimated to be 22.4 $cm^2\cdot s^{-1}$[6].

3.3.2 Estimation of deoxidation rate constant, k, in tundish

Figure 8 shows the changes in total oxygen content with time measured at S_1 and S_2 during the casting with Flux C.

The deoxidation rate constant in tundish, k, in eq.(5), can be estimated from the data shown in Fig.8 as follows.

In this case, reduction of (SiO_2) by eq.(1) does not occur, and the reaction term of R_2 is negligible.

The positions of S_1 and S_2 were assumed to be the inlet and the exit of tundish, respectively. Boundary conditions are shown in eqs.(8) and (9). Initial condition is shown in eq.(10).

$$E\partial c/\partial x|at\ x=L \quad (8)$$
$$c(0,t)=g(t) \quad (9)$$
$$c(x,0)=x/L(c(L,0)-c(0,0))+c(0,0) \quad (10)$$

Equation(3) is solved numerically in the range of L from 0 to 192cm.

Total oxygen content calculated at the exit, C(L,t), was compared with observed one as shown in Fig.8 and the deoxidation rate constant, k, is estimated to be 1×10^{-3} to $3\times 10^{-3}s^{-1}$, and $2\times 10^{-3}s^{-1}$ as a mean value. Any significant difference in k value was not recognized when the value of E was changed from 11.4 to 44.8 $cm^2\cdot s^{-1}$.

Ohnishi et al.[7] have presented the relationship between deoxidation rate constant, k, and rate of dissipation of energy density, $\dot{\varepsilon}$, in ASEA-SKF and Ar bubbling processes as shown in Fig. 9.

The value $\dot{\varepsilon}$ in the tundish is estimated by eq.(11)[8], as a stirring energy density supplied by kinematic energy of teeming flow from ladle to tundish.

$$\dot{\varepsilon}=Qp\cdot w^2/2W_{ST} \quad (11)$$

where Qp is the feed rate of molten steel into tundish, w is the flow velocity of molten steel from ladle into tundish, W_{ST} is the mass of molten steel in tundish.

Substituting 93.3 $kg\cdot s^{-1}$ for Qp, 4.72 $m\cdot s^{-1}$ for w and 50 ton for W_{ST}, $\dot{\varepsilon}$ in this study is estimated to be 20.8 watt/ton.

The relation between k and $\dot{\varepsilon}$ obtained in this study agrees well with that presented by Ohnishi et al. as shown in Fig. 9.

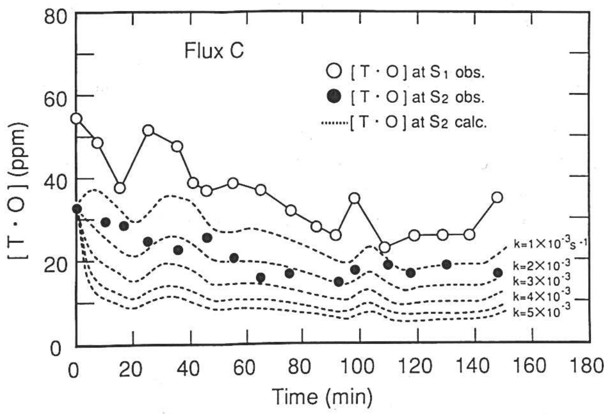

Fig. 8 Comparison between calculated and observed results on [T·O] at the exit of tundish.
($E=22.4cm^2\cdot s^{-1}$, $v=0.48cm\cdot s^{-1}$, $L=192cm$, $\alpha=0$)

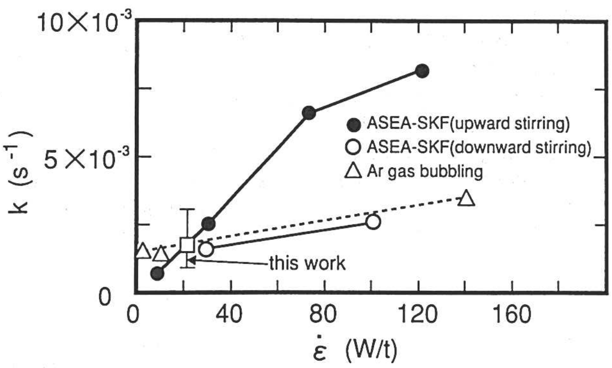

Fig. 9 Relation batween k and $\dot{\varepsilon}$ in ladle refining process presented by Ohnishi et al.

3.3.3 Estimation of contamination rate in molten steel from tundish slag.

Figure 10 shows changes in total oxygen content with time measured at S_1 and S_2 during the casting with low basicity Flux A.

The rate of contamination of molten steel due to eq.(1) can be estimated from the data shown in Fig.10 as follows:

In this case, reaction terms in eq. (4), R_1 and R_2, must be considered, the value of k is $2\times10^{-3}s^{-1}$ and qo in eq. (6) is evaluated from Q_{SiO_2} in eq.(2).

Equation(3) is solved numerically using the same calculation procedure as in 3.3.2, but where α in eq.(6) is changed as a fitting parameter. Calculated results are shown in Fig.10. The value of α can be evaluated to be 0.6 to 1.0 in this figure. This result suggests that 60 to 100% of alumina produced by eq.(1) at the slag/metal interface is trapped into molten steel and becomes the contamination source.

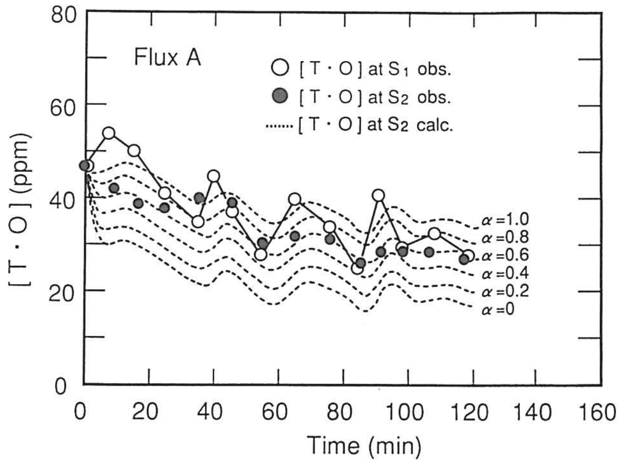

Fig. 10 Comparison between calculated and observed results on [T·O] at the exit of tundish.
($k=2\times10^{-3}s^{-1}$, $E=22.4cm^2\cdot s^{-1}$, $v=0.48cm\cdot s^{-1}$, L=192cm)

4. Conclusion

Behavior of oxygen concentration in the continuous casting tundish was investigated. The results obtained are as follows:

1) The effect of basicity of tundish flux on the oxygen concentration in the tundish was studied. High basicity flux (Flux, C or D, shown in Table 2) is recommended for improving steel cleanliness because of lowering silica activity in tundish slag.
2) The deoxidation model developed in this study on the basis of the dispersed plug flow phenomenon makes it possible to estimate the deoxidation constant, k, in the tundish. The value of k evaluated was 1×10^{-3} to $3\times10^{-3}s^{-1}$. This value is consistent with the relation between k and $\dot{\varepsilon}$ confirmed previously in ladle refining process.
3) The rate of contamination of molten steel due to the reduction of (SiO_2) in slag which occurs when a low basicity flux (Flux A) is used, was evaluated using the deoxidation model.

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