Model Study of Mixing Time in Top Slag Layer Agitated by Gas Injection

Manabu Iguchi*, Kei-ichi Nakamura**
and Zen-ichiro Morita***

*:Department of Materials Science and Processing,
Faculty of Engineering, Osaka University,
2-1 Yamadaoka, Suita, Osaka, 565 Japan
Tel. 81-6-879-7480
**:Graduate School, Osaka University
***:Professor Emeritus, Osaka University,
now with Sumitomo Metal Industries Ltd,
1-8 Fuso, Amagasaki, Hyogo, 660 Japan
Tel. 81-6-489-5970

ABSTRACT

In iron bath smelting reduction processes and other refining processes with a thick top slag layer, mixing in the top slag layer affects significantly the efficiency of the processes. The degree of mixing is commonly characterized by the mixing time. Concerning cold model experiments, water and silicone oil are often used as the models of molten iron (or steel) and molten slag, respectively. For the water bath, the mixing time can be measured with an electric conductivity sensor using aqueous KCl solution as tracer. Much information on the mixing time in the water bath has been accumulated.

On the other hand, little is known about the mixing time in the top slag layer because aqueous KCl solution is insoluble in the oil, and hence, the above-mentioned method cannot be applied to the silicone oil.

Considering these circumstances, we have developed an optical sensor to measure the mixing time in the top slag layer. Silicone oil was used as the model of molten slag and fine $CaCO_3$ powder was used as the tracer. In this study we examined the adequacy of the optical sensor and then investigated the mixing time in the slag layer agitated by bottom gas injection.

1.INTRODUCTION

In steelmaking processes, gas injection techniques have been extensively used to enhance chemical reaction rates, homogenize temperature and chemical compositions, and remove nonmetallic inclusions.[1] As one of indices for the degree of mixing, the concept of mixing time has been widely employed.[2][3] Numerous model investigations on the mixing time for various types of reactors with gas stirring have been carried out using a deionized water bath and an electric conductivity sensor. The water was used as the model of molten steel because its kinematic viscosity is approximately the same as that of the molten steel. Dilute aqueous KCl solution was chosen as tracer. The mixing time was determined from the history of the electric conductivity of liquid in the bath. Much information on the mixing time has been accumulated through water model experiments.[3]

In iron bath smelting reduction processes[4] and some kinds of metals refining processes[5] (for example, desulphurization process), a thick top slag layer is used. Mixing in the top slag layer plays an important role for slag/metal reactions because the reactions are controlled by the mass transfer in the top slag layer. Accordingly, the mixing in the top slag layer is closely associated with the efficiency of the processes.

Transparent oils such as silicone oil are usually used as the model of top slag.[6] It is difficult to measure the mixing time in the oils by using the conventional method based on electric conductivity measurement because aqueous KCl solution is insoluble in the oils.

Accordingly, we developed a new method for determining the mixing time in an oil bath. Fine $CaCO_3$ powder was used as the tracer. This method is based on the measurement of a temporal change in the transmittance of a laser beam crossing through a transparent vessel containing oil. The change in the transmittance is caused by the scattering of the laser beam on $CaCO_3$ particles. The transmittance of the laser beam approaches a constant value as mixing proceeds, and accordingly, the mixing time can be determined in the same manner as for the conventional method.[3]

2.EXPERIMENTS

2.1 Experimental apparatus

Figure 1 shows a schematic of the experimental apparatus. Two cylindrical vessels made of transparent acrylic resin were used. One had an inner diameter D of 20cm and a height H of 39cm, and the other had D=14cm and H=25cm. The inner diameter of the centered single-hole nozzle is 0.2cm. Fine $CaCO_3$ powder of a mean diameter of approximately 1μm and a density of ρ_p=1.77g/cm^3 was charged into a bath from the bath surface.

The Reynolds number of a particle moving in liquid is expressed by

$$Re_p = \bar{v}_r d_p / \nu_L \qquad (1)$$

$$\bar{v}_r = \bar{v}_p - \bar{v}_L \tag{2}$$

where $\bar{v}_r$ is the relative velocity between the particle and liquid, ν_L is the kinematic viscosity of the liquid, $\bar{v}_p$ is the particle velocity, and $\bar{v}_L$ is the liquid velocity.

According to preliminary measurements, it was found that each particle moved without relative velocity, $\bar{v}_r \fallingdotseq 0$ and the particle Reynolds number was much less than the unity under the present experimental conditions. Consequently, the fine $CaCO_3$ powder disperses in the bath with liquid motion, supporting that the powder is useful as tracer.

2.2 Water model experiment

In order to assess the accuracy of the new method for determining the mixing time, water model experiments were carried out and the results were compared with those obtained with the conventional method.

Deionized water was filled in each vessel to a prescribed depth, and the fine $CaCO_3$ powder was added from the bath surface. The mass of the powder for one charge was 0.2g for the smaller vessel and 0.5g for the larger vessel.

The mixing time was defined as a period for the instantaneous transmittance of a laser beam to settle within ± 5 % deviation around the final value in the bath, as shown in Fig.2. Sensor position and tracer charge position were changed as shown in Fig.3. The distance from the bottom of the bath to the sensor was denoted by H_s and the radial distance from the centerline of the bath to the sensor was denoted by R_s (see Figs.1 and 3). The tracer was charged from four different positions. Each tracer charge position is 1cm apart from the side wall.

2.3 Oil model experiment

The kinematic viscosity of the representative top slag attains up to about 100 times as large as the molten steel. Four kinds of silicone oils with different kinematic viscosity were used as the model of the top slag. The physical properties of them are listed in Table 1. The determination method of the mixing time is just the same as described for the water model experiment.

Table 1 Physical properties of liquid at 298K

Specimens	Density g/cm^3	Kinematic viscosity cSt	Surface tension dyn/cm
Silicone No.1	0.818	1.00	16.9
Silicone No.2	0.873	2.00	18.3
Silicone No.3	0.915	5.00	19.7
Silicone No.4	0.935	10.0	20.5
Water	0.996	0.857	72.0

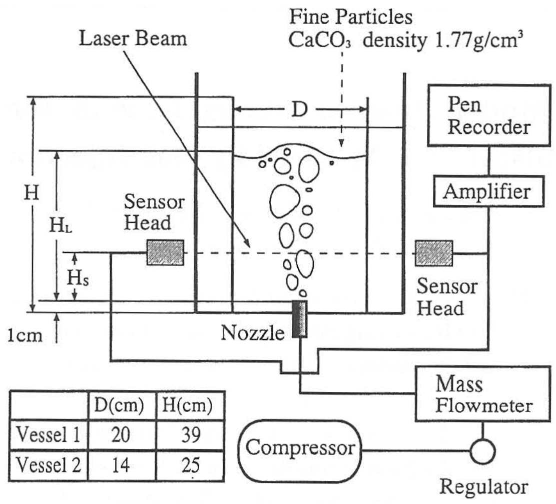
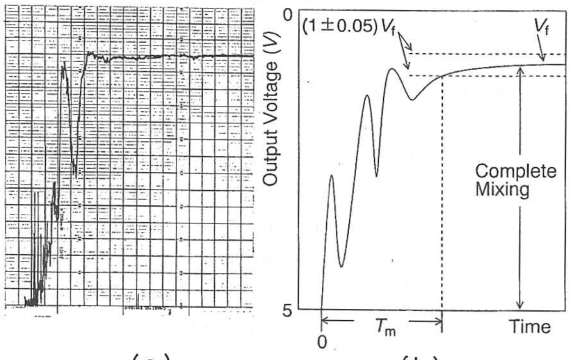


Fig.1 Experimental apparatus.



(a) (b)

Fig.2 Definition of mixing time.

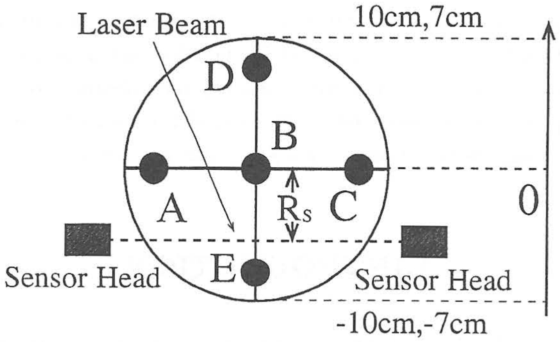


Fig.3 Sensor position and tracer charge positions.

3.RESULTS AND DISCUSSION

3.1 Water model experiments

3.1.1 Mixing time determined by conventional method

The mixing time T_m obtained by the conventional method for water baths in the aforementioned two vessels is given by[7]

$$T_m = 190\dot{\epsilon}^{-0.4} \quad (3)$$

where $\dot{\epsilon}$ is the rate of specific potential energy input to the gas stirred system described by

$$\begin{aligned}\dot{\epsilon} &= \rho_L g Q_g H_L/(\pi \rho_L H_L D^2/4) \\ &= 4gQ_g/(\pi D^2) \quad (4)\end{aligned}$$

Equation (3) is valid under the following conditions.

$$10\text{cm} < H_L \leq 30\text{cm}, 10^2\text{cm}^2/\text{s}^3 < \dot{\epsilon} < 10^3\text{cm}^2/\text{s}^3$$

For the two vessels, Eq.(3) reduces to

$$T_m = 120Q_g^{-0.4} \qquad (D = 20\text{cm}) \qquad (5)$$

$$T_m = 91Q_g^{-0.4} \qquad (D = 14\text{cm}) \qquad (6)$$

3.1.2 Mixing time determined by the present method

(1) Effect of sensor position on mixing time

The radial sensor position was fixed at position E (R_s=9cm) and the axial distance H_s was changed from 5cm to 20cm with equal intervals of 5cm. Figure 4 shows measured T_m values against the axial sensor distance H_s. Tracer was charged from the bath surface at position E. Measurements were carried out for three different gas flow rates. The measured T_m values are almost independent of the axial distance from the bottom of the vessel, H_s, and approximated satisfactorily by the empirical correlation of T_m, Eq.(5), originally derived from the conventional mixing time measurements using dilute aqueous KCl solution as tracer.

As shown in Fig.5, T_m is not influenced by the radial sensor position R_s, either. The empirical correlation, Eq.(5), is also valid in these cases. Precise T_m measurement can not be made at around the centerline of the bath because the laser beam was scattered to a great extent there by rising bubbles.

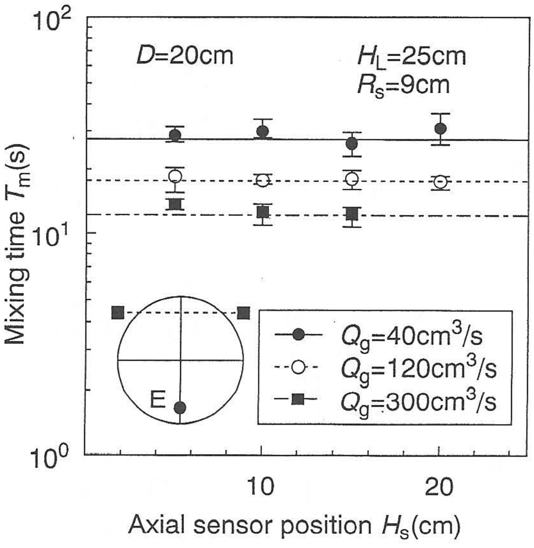


Fig.4 Relation between mixing time and axial sensor position.

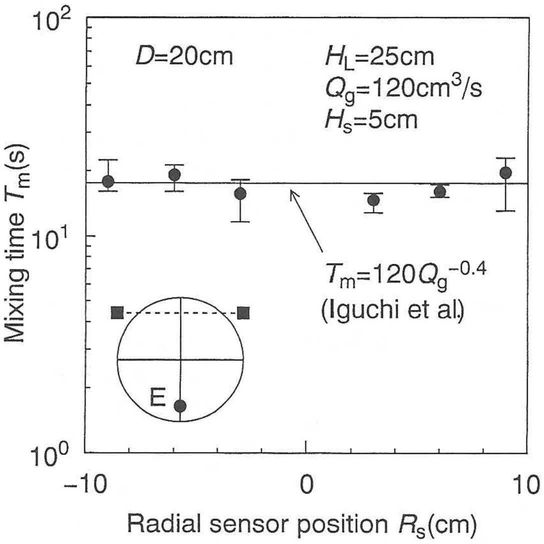


Fig.5 Relation between mixing time and radial sensor position.

(2) Effect of tracer charge position on mixing time

Figure 6 shows measured values of the mixing time for different tracer charge positions. Fine $CaCO_3$ powder was charged in turn from the bath surface at positions A through E. The measured T_m values are hardly affected by tracer charge position.

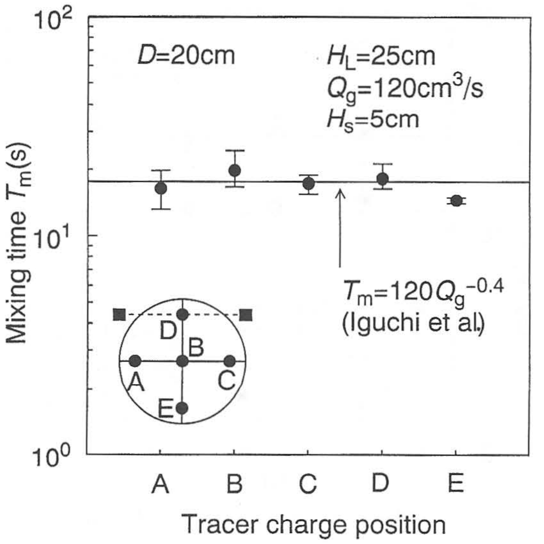


Fig.6 Mixing time as a function of tracer charge position.

(3) Effect of gas flow rate on mixing time

Measured values of the mixing time T_m for the larger and smaller vessels were plotted against gas flow rate Q_g in Figs.7 and 8, respectively. In the two figures, the measured T_m values can be approximated satisfactorily by the empirical correlation derived from the conventional method.

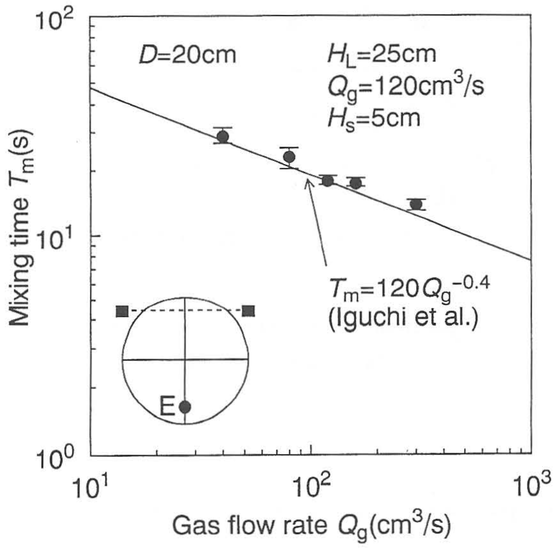


Fig.7 Relation between mixing time and gas flow rate for D=20cm.

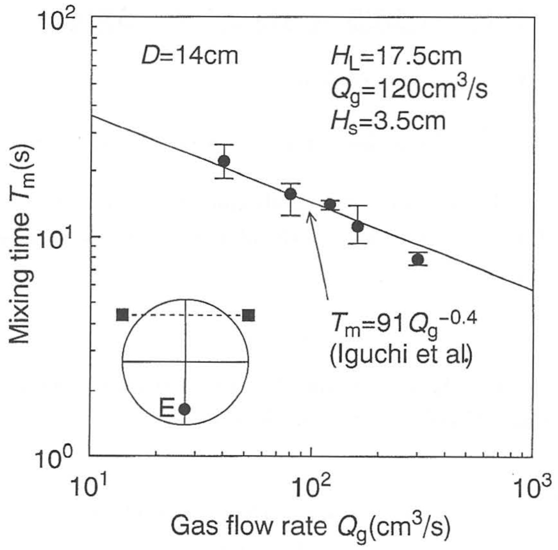


Fig.8 Relation between mixing time and gas flow rate for D=14cm.

(4) Effect of bath depth on mixing time

There occur two kinds of swirl motions in a bath agitated by bottom gas injection.[8] One is caused by vertical bath oscillations due to quasi-periodical generation of bubbles and is closely associated with the rotary sloshing which occurs when a vessel containing liquid in it is oscillated in the vertical or horizontal direction.[9] The other is caused through Coanda effect.

These two kinds of swirl motions take place for $0.3 < H_L/D < 1$ and $H_L/D \gtrsim 2$, respectively.[8] It should be noted that the above-mentioned mixing time measurements were carried out in the absence of the swirl motions.

Figure 9 shows T_m against the bath depth H_L. Only the former swirl motion was observed for H_L =10 cm, whereas the latter swirl motion did not occur. In the presence of the swirl motion, the mixing time became very short. On the other hand, in the absence of the swirl motion, T_m decreased as H_L increased.

3.2 Oil model experiments

Figure 10 shows measured values of the mixing time for silicone oil No.4 (commercial name: TSF-10) against the gas flow rate Q_g. The measured T_m value for the silicone oil became much larger than that for water, and accordingly, it cannot be predicted by Eq.(6). However, the dependence of T_m on Q_g is the same as that for water baths. This fact means that T_m depends strongly on the kinematic viscosity of the silicone oil, ν_L.

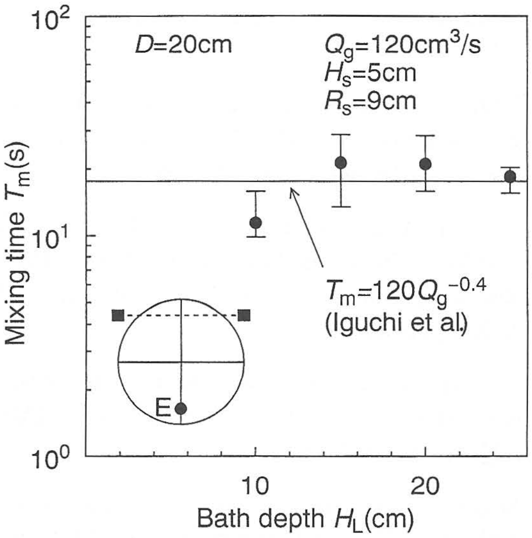


Fig.9 Mixing time as a function of bath depth.

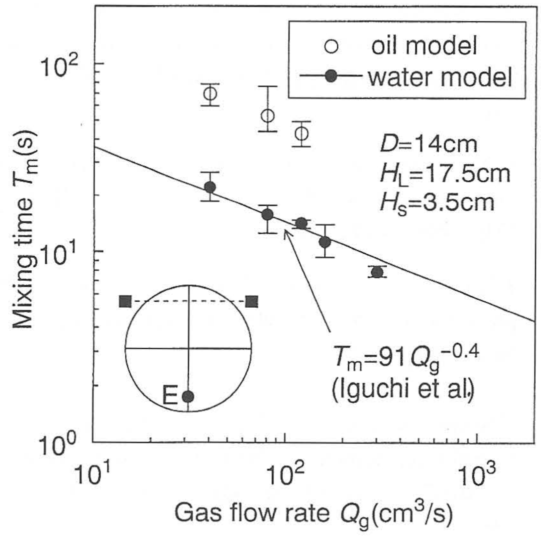


Fig.10 Mixing time for silicone oil bath (silicone oil No.4) in smaller vessel.

Considering this result and previous experimental results of T_m for water models, the following two dimensionless parameters, Π_1 and Π_2, were introduced.

$$\Pi_1 = T_m(H_L/D_{h1})[g/D_{h1}]^{1/2} \tag{7}$$

$$\Pi_2 = Re_{h1} = D_{h1}v_{sp}/\nu_L \tag{8}$$

$$D_{h1} = 6D/(4 + D/H_L) \tag{9}$$

$$v_{sp} = 4Q_g/(\pi D^2) \tag{10}$$

where D_{h1} is a newly defined hydraulic diameter, g is the acceleration due to gravity, and v_{sp} is the superficial velocity.

The present measured T_m values were replotted in Fig.11 together with previous measured values obtained for water models on the basis of ± 5 % criterion.[10]-[12] All the measured values can be correlated satisfactorily by this arrangement method. The following empirical correlation therefore was proposed.

$$T_m(H_L/D_{h1})[g/D_{h1}]^{1/2} = 3.13 \times 10^3 Re_{h1}^{-0.468} \tag{11}$$

Equation (11) reduces to

$$T_m = 89.5Q_g^{-0.468}D_{h1}^{1.033}D^{0.925}H_L^{-1}\nu_L^{0.468} \tag{12}$$

Mazumdar and Guthrie proposed the following empirical correlation for water models.[13]

$$T_m = 5.14Q_g^{-1/3}D^{7/3}H_L^{-1} \tag{13}$$

Consequently, functional relationship of Eq.(12) is very similar to Eq.(13) except for the kinematic viscosity of liquid, ν_L.

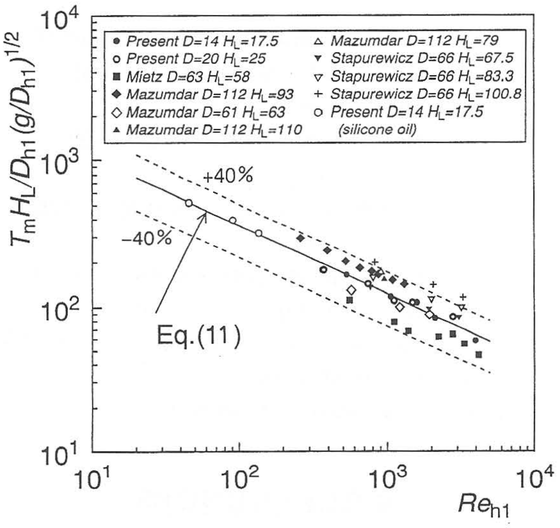


Fig.11 Correlation of mixing time as a function of Reynolds number.

4.CONCLUSIONS

A new method for measuring mixing time in a model oil bath agitated by gas injection was developed to investigate mixing phenomena in a top slag layer. The mixing time was determined from a change in the transmittance of a laser beam crossing through the bath. Fine $CaCO_3$ powder was used as tracer The adequacy of this method was confirmed by comparing the experimental results with those obtained using the conventional method. An empirical correlation of the mixing time was derived as a function of gas flow rate, bath depth, bath diameter and the kinematic viscosity of liquid in the bath.

5.NOMENCLATURE

D: bath diameter (cm)
D_{h1}: hydraulic diameter defined by Eq.(9) (cm)
d_p: particle diameter (cm)
H_L: bath depth (cm)
H_s: axial distance from the bottom of the vessel to the sensor (cm)
Q_g: gas flow rate (cm^3/s)
Re_p: particle Reynolds number defined by Eq.(1) (-)
R_s: radial distance from the centerline of the vessel to the sensor (cm)
T_m: mixing time (s)
$\bar{v}_r$: relative velocity defined by Eq.(2) (cm/s)
v_{sp}: superficial velocity defined by Eq.(10) (cm/s)
$\dot{\epsilon}$: rate of spesific potential energy input defined by Eq.(4) (cm^2/s^3)
ν_L: kinematic viscosity of liquid (cm^2/s)
ρ_L: density of liquid (g/cm^3)
Π_1, Π_2: dimensionless parameters (-)

6.REFERENCES

1. K.Mori and M.Sano, "Dynamics in injection metallurgy", Tetsu-to-Hagane, 67-6(1981), pp.672-695.
2. K.Nakanishi, T.Fujii and J.Szekely, "Possible relationship between energy dissipation and agitation in steel processing operations", Ironmaking and Steelmaking, 2-3(1975), pp.193-199.
3. D.Mazumdar and R.I.L.Guthrie, "The physical and mathematical modeling of gas stirred ladle systems", ISIJ Int., 35-1(1995), pp.1-20
4. K,Narita; Inbath Smelting Reduction Processes, (1992), Kobelco.
5. ISIJ, "Recent development in steelmaking technologies using gas injection", ISIJ, Proc.100th and 101th Nishiyama Memorial Lecture, (1984)
6. M.Iguchi, A.Kawajiri, H.Tomida and Z.Morita, "Cold model experiments on the dynamic behavior of bubbles rising in highly viscous liquid", ISIJ Int., 33-3(1993), pp.361-368.
7. M.Iguchi, N.Kawabata and Z.Morita, "Mixing time in a bottom blown bath with through flow", CAMP-ISIJ, 7(1994), p.1095.
8. M.Iguchi, S.Hosohara, T.Koga, R.Yamaguchi and Z.Morita, "The swirl motion of vertical bubbling jet in a cylindrical vessel", Tetsu-to Hagane, 78-12(1992), pp.1778-1785., ISIJ Int., 33-10(1993), pp.1037-1044.
9. H.N.Abramson, W.H.Chu and D.D.Kâna, "Some studies of nonlinear lateral sloshing in rigid containers", Trans. ASME, J. Appl. Mech., (1996), p.777-784.
10. D.Mazumdar and R.I.L.Guthric, "Mixing models for gas stirred metallurgical reactors", Metall.Trans.B, 17B(1986), pp.725-733.
11. J.Mietz and F.Oeters, "Model studies of mixing phenomena in stirred melts", Canad. Metall. Quart., 28-1(1989), pp.19-27.
12. T.Stapurewicz and N.J.Themelis, "Mixing and mass transfer phenomena in bottom-injected gas-liquid reactors", Canad. Metall. Quart., 26-2(1987), pp.123-128.
13. D.Mazumdar and R.I.L.Guthrie, "Considerations concerning the numerical computation of mixing times in steelmaking ladles", ISIJ Int., 33-4(1993), pp.513-516.