Abstract
Uniform dispersion of fine particles into a molten steel bath is of essential importance for efficient desulfurization and dephosphorization in the steelmaking industry. Water model experiments were carried out to promote the dispersion of fine particles into a molten steel bath contained in a cylindrical reactor. The particles were initially placed on the bath surface. The bath was mechanically agitated by means of an impeller settled on the centerline of the vessel. The dispersion of the particles was highly promoted by immersing a cylinder slightly into the bath at an offset radial position. The effects of the size of the cylinder, rotation frequency of an impeller and others on the dispersion characteristics were investigated to reveal an optimum condition for the uniform dispersion.

1. Introduction
Uniform dispersion of fine particles of a density lower than molten steel is closely associated with the efficiency of desulfurization and dephosphorization. Fine particles are currently injected into the bath together with carrier gas. It is rather difficult to disperse them uniformly into the molten steel bath, as the particles are not wetted by molten steel.

Mechanical agitation using a propeller seems a promising method. The propeller is usually placed on the centerline of the bath. The bath surface descends after the start of impeller rotation. Some of the particles approach the impeller together with the bath surface. As soon as they arrive at the impeller, they collide to the impeller and disperse into the bath. The remaining particles however remain on the bath surface. In addition, a part of the particles dispersed in the bath rise towards the bath surface due to the buoyancy forces acting on them. Consequently, even if a steady state is established in the bath, most of the particles remain on the bath surface. The dispersion efficiency therefore is not necessarily high under this condition.

In this model study a simple but efficient method of dispersing fine particles into a molten steel bath was proposed. When a circular cylinder was slightly immersed into the bath at an offset radial position, the efficiency of the dispersion of fine particles was significantly enhanced.

2. Experiment
Figure 1 shows a schematic of the experimental apparatus. The test vessel was made of transparent acrylic resin. It was enclosed with a transparent vessel of a square cross-section. De-ionized water also was filled between the two vessels to decrease the distortion of video images. Particles of a density

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of 40kg/m$^3$ and a mean diameter of 30–50µm were placed on the bath surface. The total mass of them was 0.2g (volume: 5cm$^3$). The details of an impeller are shown in Fig.2.

Even if all particles were entrapped into the bath, a part of them returned to the bath surface due to the buoyancy forces acting on them. Accordingly, all the particles never stayed in the bath. The number of particles floating on the bath surface was much greater in the absence of the immersion cylinder than in the presence of it.

The flow establishment time, $T_{fe}$, was defined as the period from the start of mechanical agitation to the moment at which the dispersion pattern of particles reached a steady state. The flow establishment time does not mean uniform dispersion of all fine particles in the bath.

Two methods were introduced for measuring the flow establishment time. First, it was determined based on the images of particles taken by a video camera and by eye inspection. In the absence of an immersion cylinder most of the particles remained on the curved bath surface. On the other hand, in the presence of an immersion cylinder particles were almost uniformly dispersed into the whole bath. Accordingly, the flow establishment time was determined by focusing only on the particles staying in the bath.

The second method focused on the local dispersion pattern of fine particles in the bath. The flow establishment time was determined with particle image velocimetry (PIV). Particles in the bath were illuminated with a laser sheet, as shown in Fig.3. The luminosity of particle images changed with time, as shown in Fig.4. The flow establishment time was defined as the period from the start of agitation to the moment at which the luminosity finally crossed the 95% or 105% of its asymptotic value.

### 3. Experimental results and discussion

#### 3.1 Entrapment process of fine particles

Figure 5 shows the dispersion of fine particles in the baths with and without an immersion cylinder. The diameter of the cylinder, $D_c$, was 50mm and the radial offset position, $L_c$, was 50mm away from the centerline of the vessel, the immersion depth of the cylinder, $H_c$, was 20mm, and the distance from the bath surface to the impeller, $H_l$, was 150mm. In the absence of the cylinder, most of the particles gathered around the supporting rod of the impeller, and accordingly, the amount of particles in the bath is limited, as shown in Fig. 5(a). On the other hand, a large-scale helical vortex was generated below the cylinder and most particles dispersed into the bath at $t=20$ s, as shown in Fig. 5(b). Although the evidence is not shown, almost all the particles dispersed into the bath at around $t=35$ s. The flow pattern in the bath with the immersion cylinder was schematically shown in Fig.6.

#### 3.2 PIV measurements of flow in the bath.

Figure 7 shows the instantaneous velocity vectors obtained with particle image velocimetry (PIV). It is evident that the flow in the bath is more violent in the presence of the immersion cylinder than in the absence of it.

#### 3.3 Effect of immersion depth of cylinder on flow establishment time

The two methods of determining the flow establishment time gave nearly the same results, and hence, the results obtained by the former video method will be presented. Figure 8 shows the effect of the immersion depth of a cylinder, $H_c$, on the flow establishment time, $T_{fe}$, where $D=200mm$, $H_l=300mm$, $D_c=50mm$, $H_c=20mm$, and $H_l=150mm$. The flow establishment time, $T_{fe}$, decreased as the immersion depth, $H_c$, decreased.

#### 3.4 Effect of radial offset position of immersion cylinder on flow establishment time

The flow establishment time had a minimum value when a cylinder was immersed at a radial position around $r = R/2$, where $r$ is the radial distance measured from the centerline of the vessel and $R$ is the vessel radius.

#### 3.5 Effect of immersion cylinder diameter on flow establishment time

Three cylinders of different diameters were used; $D_c= 25mm$, $35mm$, and $50mm$. The flow
establishment time, $T_{fe}$, had a minimum value when the cylinder of $D_c=50\text{mm}$ was used. However, the difference between the measured values for $D_c=50\text{mm}$ and $35\text{mm}$ was very small.

3.6 Effect of the immersion depth of impeller on flow establishment time

The flow establishment time became minimum when the impeller was placed between $H_I/D=0.5$ and $0.7$, although the evidence was not shown in this paper.

4. Conclusions

Uniform dispersion of fine particles in a bath agitated mechanically by an impeller was highly promoted by immersing a circular cylinder into the bath at an offset radial position. The flow establishment time was introduced to quantitatively describe the uniform dispersion of particles.

Nomenclature

$D \quad R$

$D_c$

$H_C$

$H_L$

$H_I$

$L_C$

$N$

$T$

$T_{fe}$

References

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Fig. 2 Details of impeller

Fig. 3 Laser sheet position

Fig. 4 Change in luminosity with time and definition of flow establishment time

Fig. 5 Photographs of particle dispersion

N = 400rpm, Position1, D = 50mm, H_C = 20mm
EFFECTIVE DISPERSION METHOD OF FINE PARTICLES INTO A MECHANICALLY AGITATED BATH

Fig. 6 Schematic illustration of vortex motion

Fig. 7 Velocity vectors in the presence of spiral vortex

Fig. 8 Effect of immersion depth of circular cylinder on flow establishment time