PARTICLE BEHAVIOR IN A HORIZONTAL GAS-SOLID AGITATED VESSEL WITH TWO PARALLEL AXES

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Particle behavior in a horizontal gas-solid agitated vessel with two parallel axes was investigated. The particle behavior depends on the particle holdup and flow velocity as well as their distribution in the vessel. Therefore particle holdup and three components of particle velocity were quantitatively measured at a local point in the vessel by using an electrostatic-capacity method and an image-sensor technique, respectively. A model based on the balance of the forces which act on a particle was also proposed to estimate the particle trajectory in the vessel. This model enabled us to predict the elevation of particle through the particle trajectory and velocity. The particle velocity calculated by this model was almost in agreement with the measured maximum velocity.

Introduction

With the development of high-activity catalysts, gas-phase bulk polymerization processes have attracted much interest in various polymerization processes, because the gas-phase process has the advantage that capital investment and operating costs are lower than those of competing processes. One type of reactor being used in these processes is a fluidized bed and the other is an agitated vessel. The former has already been used, but it must supply excess gas, not only for reaction but also for fluidization. On the contrary, the latter does not need excess gas for fluidization. However, the following problems should be addressed when an agitated vessel is to be used as a commercial-scale gas-phase polymerization reactor:

1) How to adequately disperse solid particles to obtain homogeneous reaction conditions in the whole of the reactor vessel.
2) How to estimate the particle holdup in continuous operation.
3) How to remove the heat of chemical reaction from the particles.
4) How to scale up a reactor vessel.

To settle these problems, the particle behavior in an agitated vessel should be investigated. However, only a few researchers have attempted to clarify the particle behavior in a vertical agitated vessel and there are no available studies related to a horizontal one. Moreover, several works have employed simple measuring techniques of particle velocity in the equipment, although these techniques are not suitable for measurement of particle velocity in an agitated vessel due to the complicated movements of the particles.

The purpose of this paper is, therefore, to investigate the particle dispersion in a horizontal gas-solid agitated vessel with two parallel axes proposed by Murakami for a gas-phase bulk polymerization reactor. Firstly, the particle holdup (void fraction) was measured at a local point in the suspension in the vessel by means of an electrostatic-capacity method. Secondly, three components of the particle velocity were measured, using an image sensor technique. This
technique, using an image fiber, was originally developed by Kamiwano et al.\textsuperscript{53} and it enabled us to measure the local velocity of an individual particle in the space above the particle bed in a vessel with opaque walls. In addition to these measurements, a model was proposed to predict the particle velocity measured in the vessel.

1. Experimental

1.1 Apparatus

The reactor vessel used is shown in Fig. 1. The vessel has two parallel axes and four paddle impellers on each axis. The diameter of an impeller was 0.14 m, and the length of the vessel was 0.28 m. The bottom of the vessel was constructed as two horizontal semi-cylindrical sections to diminish the stagnant zone between the vessel wall and the impeller. Adequate space was provided in the upper part of the vessel, i.e., above the particle bed, in order not to interrupt the movements of solid particles in the gas phase. In this study, the experiments were carried out without air flow for reaction and/or fluidization.

The rotational speed of each axis was set at 5 r.p.s. Glass beads with a diameter of 0.5 mm were used as the solid particles, and 2 kg of the particles were filled in the vessel.

1.2 Particle holdup measurement

The particle holdup in the vessel was measured by use of an electrostatic-capacity method\textsuperscript{11} based on the principle of a parallel-plate condenser. The electrostatic capacity, $C$, can be expressed as

$$ C = \frac{SD}{d} \tag{1} $$

where $D$ is the dielectric constant, $S$ the surface area of the plates and $d$ the distance between the two plates. The dielectric constant depends on the quantity of solid particles and the particle holdup between the parallel plates. Figure 2 shows a schematic diagram of the particle holdup measuring system. The electrostatic capacity was measured by a capacitance meter (MC-118, KUWANO Elec., Co., Ltd.). Figure 3 shows the major measuring positions for the particle holdup in the vessel. The height of $Z=0.19$ m corresponded to the upper-limit position which the ascending particles can reach.

1.3 Particle velocity measurement

To measure the three components of the particle velocity, a self-scanning linear image sensor technique developed by Kamiwano et al.\textsuperscript{53} was used here. The image sensor (TCD104C, TOSHIBA Co., Ltd.) consisted of a 150-bit photodiode array with CCD analog-shift registers. Figure 4 shows a schematic diagram of the velocity measuring system, which utilizes an image fiber (L.G3.3-950SC, MACHIDA Manuf., Co., Ltd.) inserted into the vessel. Light beams from halogen lamps illuminates the particles moving in front of the image fiber in the vessel. The cross-sectional area of the image fiber was 3.3 mm $\times$ 3.3 mm. The light reflected by the particle surface is transferred to the image sensors through an image fiber, a condensing lens and a half-mirror. Using the half-mirror, two image sensors are arranged perpendicularly with proper separation.
The output signals are proportional to the intensity of reflection which the image sensor receives, and the output signals have peaks when the particles cross the sensors. Thus, the two components of the particle velocity can be calculated by

\[ V_x = (n_1 - n_2) \Delta d / \Delta t \]  

\[ V_z = W_z / \Delta t \]  

where \( \Delta d \) is the width of photodiode, \( W_z \) the distance between the two image sensors, \( \Delta t \) the time required for a particle to move from one sensor to the other, and \( n_1 \) and \( n_2 \) denote the horizontal positions on photodiode arrays where a peak appears in the time records of the output signals of the two sensors.

**Figure 5** shows a block diagram of the signal processing system. Output signals from the sensors were transiently stored in the digital memories (DM-2210, IWATSU Elec. Co., Ltd.) through the differential amplifiers to remove a noise signal. Then the signals were transmitted to a 16-bit microcomputer through a GP-1B. Finally, two components of the particle velocity were calculated using Eqs. (2) and (3).

To confirm the velocity range and the accuracy of this measuring technique, the velocity of a particle which was fixed on the rotating disk was measured. The particle was set to cross the two parallel photodiode arrays at an angle of 45°. Then, measured particle velocities \( V_z \) and \( V_x \) should exactly be equal to the product of the tip speed of the rotating disk and \( 1/\sqrt{2} \), respectively. **Figure 6** shows a comparison of the measured particle velocities \( V_z \) and \( V_x \) with the velocity calculated from the product of the tip speed of the rotating disk, \( V_0 \), and \( 1/\sqrt{2} \). It is found that the error is within 5% at velocities less than 2 m/s. To avoid errors due to the presence of numerous particles in a measuring volume, only 1 wt% of the particles filled in the vessel were painted white. The rest were painted black to prevent reflection. Then, the error could be neglected.

Particle velocity measurement was conducted at the same positions as for particle holdup measurement. The measurements were repeated 100 times and averaged at every position to reduce the statistical error due to the random movement of particles. The particle velocity in Y-direction was measured by changing the direction of the image fiber in the vessel.

**2. Results and Discussion**

2.1 Particle holdup

The distributions of the particle holdup are shown by contours in Figs. 7(a) and (b). The contours were determined by interpolating or extrapolating the values of the particle holdup measured at each point described in Fig. 3. The particle holdup on the \((Z,X)\)-plane A just above the impellers is larger than that on the \((Z,X)\)-plane B between the impellers (see Fig. 3). The particle holdup in the vicinity of points A5, 6 and 10 (see Fig. 3) gives the maximum value. This region just corresponds to the region where many particles are lifted up by the impeller. As time proceeds, the particles are dispersed in the whole of the vessel. Near the side wall the particle holdup is somewhat large. This is attributed to the particles that rebound from the vessel wall.

2.2 Particle velocity

**Figures 8(a) and (b)** show the frequency distributions of vertical and horizontal particle velocities which were measured 100 times at point A4 shown in
Fig. 7. Distributions of particle holdup on (a) (Z,X)-plane A and (b) (Z,X)-plane B

Fig. 8. Frequency distributions of particle velocities in (a) vertical and (b) horizontal directions at point A4; dotted lines show the normal distribution

Fig. 9. Ensemble-averaged particle velocity vectors and particle holdup on (a) (Z,X)-plane A, (b) (Z,X)-plane B and (c) (Z,Y)-plane C

Fig. 3. It is found that the frequency distributions are approximated by the normal distributions indicated by the dotted line.

Together with the measurements of the particle holdup, the ensemble-averaged velocity vectors of the particles are shown in Figs. 9(a), (b) and (c) by the arrows. The length of each arrow indicates the magnitude of the velocity vector, its thickness the magnitude of the particle holdup. It is found that the particles are strongly lifted up in the region above the impeller (Fig. 9(a)) and they fall into the region between the impellers (Figs. 9(b) and (c)).

2.3 Model

To simulate the behavior of the particles shown in Fig. 9(a), a two-dimensional model is proposed here. We firstly calculate the movement of a single particle on the impeller, and then calculate the trajectory of the particle emitted from the impeller. The model assumes that the forces which act on a particle are the gravitational force $F_g$, the frictional force $F_f$ and the centrifugal force $F_c$ as shown in Fig. 10. The equation of motion for a single particle can be written as

$$ m \frac{d^2r}{dt^2} = mr \omega^2 - mg \{\sin(\omega t + \theta_0) + \mu \cos(\omega t + \theta_0)\} \quad (4) $$

where $m$ is the mass of a particle, $\omega = 2\pi N$ the angle velocity of impellers, $\mu = 0.17$ the coefficient of wall friction. Giving the initial conditions as

$$ r = r_0, \quad dr/dt = 0 \quad \text{at} \quad t = 0 \quad (5) $$

we can obtain the solution of Eq. (4):

$$ r = r_0 \cosh \omega t - \frac{g}{2\omega^2} \left[ \{\cos \theta_0 \sinh \omega t - \sin \theta_0 \cosh \omega t \right. \\
- \sin(\omega t + \theta_0) + \mu \{\cos \theta_0 \cosh \omega t + \sin \theta_0 \sinh \omega t \}
- \cos(\omega t + \theta_0) \left. \right] \right] \quad (6) $$
Equation (6) gives the relationship between time $t$ and particle position $r$. Here $r_0$ and $\theta_0$ are the parameters. The particle velocity in the $r$-direction can be obtained by the time-derivative of Eq. (6),

$$V_r = \frac{dr}{dt}$$

(7)

This equation gives the relationship between time $t$ and particle velocity in the $r$-direction. The particle velocity at the instant of a particle’s emission from an impeller can be calculated by

$$V_0 = \sqrt{V_t^2 + V_R^2}$$

(8)

where $V_t$ is the tip speed of the impeller, $V_R$ the velocity given by Eq. (7) at $t = t_R$. Here $t_R$ is the time obtained from Eq. (6) at $r = R$, i.e., at the impeller radius.

The behavior of the particle emitted from an impeller can be given by the following resistance law:

$$\frac{dV_z}{dt} = \frac{\rho_a - \rho_p}{\rho_p} g - \frac{3}{4} C_s \frac{\rho_a}{\rho_p D_p} \sqrt{V_z^2 + V_x^2} |V_z|$$

(9)

$$\frac{dV_x}{dt} = -\frac{3}{4} C_s \frac{\rho_a}{\rho_p D_p} \sqrt{V_z^2 + V_x^2} |V_x|$$

(10)

where $C_s$ is the drag coefficient calculated by

$$C_s = \left( \frac{8 \pi}{\rho_a D_p} \frac{\eta}{\sqrt{V_z^2 + V_x^2}} + 1 \right)^2$$

(11)

$\eta$ the viscosity of air, $D_p$ the particle diameter, and $\rho_a$ and $\rho_p$ denote the densities of air and particle, respectively. Eqs. (9) and (10) are non-linear equations and they can be solved numerically by using a Runge-Kutta method. The initial values of $V_z$ and $V_x$ are the vertical and horizontal components of $V_0$ given by Eq. (8):

$$V_z = V_0 \sin(\omega t_R + \theta_0 + \tan^{-1}(V_x/V_z))$$

(12)

$$V_x = V_0 \cos(\omega t_R + \theta_0 + \tan^{-1}(V_x/V_z))$$

(13)

The particle trajectories calculated by Eqs. (7), (8), (9) and (10) are shown in Fig. 11 against $r_0$. Here $r_0$ is related to the impeller width and ranges from 0.047 m to 0.07 m. The initial value of the inclined angle of the impeller, $\theta_0$, at which the particles begin to move on the impeller, was set to $-10^\circ$ by observation. Comparisons of the trajectories between measurements (Fig. 9(a)) and predictions (Fig. 11) show good qualitative agreement. However, only the vertical component of the predicted velocity is larger than that of the measured velocity (compare the upper-limit positions of particle movement in Figs. 9(a) and 11). This discrepancy depends on the assumption used in the model that the particles have no mutual interaction such as collision. Therefore, the predicted velocity has the larger maximum value. To confirm it, the measured maximum velocity and predicted velocity in the vertical ($Z$)-direction are compared in Fig. 12. The contours of the measured maximum velocity were drawn by interpolating or extrapolating the values of the maximum velocity measured at each point shown in Fig. 3. The predicted contours were
drawn by tracing the points with the same velocity on the trajectories (see Fig. 11) of particles with various $R_0$ values. The predicted contours are comparatively similar to the measured ones, which supports the discussion above.

**Conclusions**

The particle behavior in a horizontal gas-solid agitated vessel with two parallel axes was investigated by measuring the particle holdup and three components of particle velocity at a local point in the vessel. Furthermore, a model was proposed to simulate the particle trajectories in the vessel. The results showed how and where the particles are dispersed, and the model well predicted the maximum velocity measured in the vessel.

The rotational speed of each impeller and the dimensions of the paddle impeller were fixed in this study, but their effects on dispersion should be investigated to design an effective vessel in future.

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**Nomenclature**

- $C$ = electrostatic capacity [F]
- $C_s$ = drag coefficient [—]
- $D$ = dielectric constant [F/m]
- $D_p$ = diameter of particle [m]
- $d$ = distance between plates of capacitance probe [m]
- $\Delta d$ = width of photodiode [m]
- $F_c$ = centrifugal force acting on a particle [N]
- $F_f$ = frictional force acting on a particle [N]
- $F_g$ = gravitational force acting on a particle [N]
- $g$ = gravitational acceleration [m/s²]
- $m$ = mass of particle [kg]
- $N$ = rotational speed of impeller [s⁻¹]
- $n$ = position where output voltage of imagesensor indicates a peak [—]
- $R$ = radius of impeller [m]
- $r$ = coordinate [m]
- $r_0$ = initial position of particle [m]
- $S$ = surface area of plate of capacitance probe [m²]
- $t$ = time [s]

- $t_R$ = time obtained from Eq. (6) at $r = R$ [s]
- $\Delta t$ = time required for a particle to move from one sensor to the other [s]
- $v$ = particle velocity [m/s]
- $V_0$ = particle velocity at the instant of particle emission from impeller [m/s]
- $V$ = particle velocity obtained from Eq. (9) at $t = t_R$ [m/s]
- $V_1$ = tip speed of an impeller [m/s]
- $W$ = distance between the two sensors [m]
- $X$ = coordinate [m]
- $Y$ = coordinate [m]
- $Z$ = coordinate [m]

- $\varepsilon$ = void fraction [—]
- $\eta$ = viscosity of air [Pa⋅s]
- $\theta$ = angle of impeller [rad]
- $\theta_0$ = initial angle of impeller [rad]
- $\mu$ = coefficient of wall friction [—]
- $\rho_s$ = density of air [kg/m³]
- $\rho$ = density of particle [kg/m³]
- $\omega$ = angle velocity of impeller [rad/s]

**Subscripts**

- $r$ = refers to $r$ coordinate
- $x$ = refers to $X$ coordinate
- $y$ = refers to $Y$ coordinate
- $z$ = refers to $Z$ coordinate

**Literature Cited**


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