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Fluidization of fine powder assisted by vertical vibration in fluidized bed reactor

Jae-Rang Lee*,, Naim Hasolli*, Kang-San Lee*, Kwan-Young Lee**, and Young-Ok Park*,†**

*Climate Change Research Division, Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 34129, Korea
**Department of Chemical and Biological Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Korea
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Abstract−This study examined the fluidization phenomenon using vertical vibration for fine powder in a mechanical vertical vibration for fluidized bed reactor. The fine powder used belongs to the Geldart group C with a mean powder size of 2.25 μm. It was verified that channeling and agglomeration phenomena appeared with a fluidization method without vibration of fine powders belonging to the group C. To keep fluidization phenomenon of the agglomerating fine powder superior, a smooth fluidization condition was made by giving vertical vibration function and removing cohesion between particles. To verify the smooth fluidization condition of the fine powder, changes in the bed height to diameter (H/D) ratio of the fluidized bed reactor, pressure drop due to changes of vibration frequency with superficial gas velocity, minimum fluidization velocity, and changing characteristics of bed expansion ratio were investigated experimentally. This study examined pressure drops from H/D variable of values 1 and 2, minimum fluidization velocity, and bed expansion ratios at 0 to 60 Hz of vibration frequency. There is a trend that as vibration frequency increases, the pressure drop is stabilized, minimum fluidization velocity decreases, and the bed expansion ratio increases.

Keywords: Vertical Vibration, Fine Powder, Channeling, Agglomeration, Fluidization Phenomenon

INTRODUCTION

Fluidized bed reactors have made a significant contribution to chemical, material, energy, environmental, and powder industries [1,2]. It is expected that future industries employing the fluidized bed reactor will increasingly use fine powders [3-5]. Fine powders have been proven to have better catalytic, electronic, optical, physical, and chemical characteristics than coarse powders. As fine powders have larger surface areas and better reaction rates than coarse powders, allowing the charging in more copious amounts in a limited capacity than coarse powders, it is possible to increase the production rate [6-8]. Geldart classified powders in groups A, B, C, and D according to powder size, density, and categorized fluidization forms. Group C, belonging to fine powders, possess a strong force between particles, and are more difficult to undergo fluidization [9]. To understand the fluidization of powders with strong agglomeration, research on fluidization is required to relieve force between particles with external force [10,11]. To create a smooth fluidization state for powders with strong agglomeration, research on the acoustic, magnetic force, mechanical vibration wascarried out [12]. Fluidization method using acoustic was successful at activating fluidization by relieving agglomeration of the fine powder by increasing sound pressure level [13-15]. It has been verified that the fluidization method using magnetic force aids fluidization of the magnetic powder belonging to Geldart group C [16,17]. Fluidization method of fine powder using acoustic or magnetic force, except for mechanical vibration, can be conducted on a laboratory scale, but it is difficult to apply this technology in the industrial field due to quantity and characteristics of the material [18-20]. Fluidization technology can relieve van der Waals forces of the fine powders with the help of mechanical vibration, which has been carried out many times until now, but it still requires more research [21-23]. It is required to analyze visual characteristics of the fluidization method using mechanical vibration, to understand whether it is a technology applicable in industrial fields [24].

This research examined fluidization characteristics of the fine powder, belonging to Geldart group C, in a fluidized bed reactor to allow vertical vibration. It examined behaviors, pressure drop, bed expansion, and minimum fluidization velocity of the fine powder on 0 to 60 Hz vibration frequency with variable bed height to diameter (H/D) ratio.

EXPERIMENTAL

1. Experimental Procedure

A schematic diagram of the experimental setup and apparatus used in this study is shown in Fig. 1 and experimental conditions are summarized in Table 1. Nitrogen was used as a gas required for fluidization, and an electric inductance vibrator (Hyosung Inc., Korea) was used for mechanical vibration that allows vibration frequency up to 60 Hz. The ratio of bed expansion was confirmed by tape measure. Vibration cycles were adjusted using a piezoelectric accelerometer fixed on one side of the fluidized bed reactor. To measure the pressure drop, electronic remote sensor differential pressure drop (Differential pressure transmitter, Rosemount, Inc., USA) ports were installed on the distributor of mesh type and above maximum bubbling height.

Fine powders can be fluidized with the assistance of mechanical vibration. Studies on fluidization by vibration were carried out on fine powders with mechanical vibration. Vibration intensity by

†To whom correspondence should be addressed.
E-mail: yopark@kier.re.kr

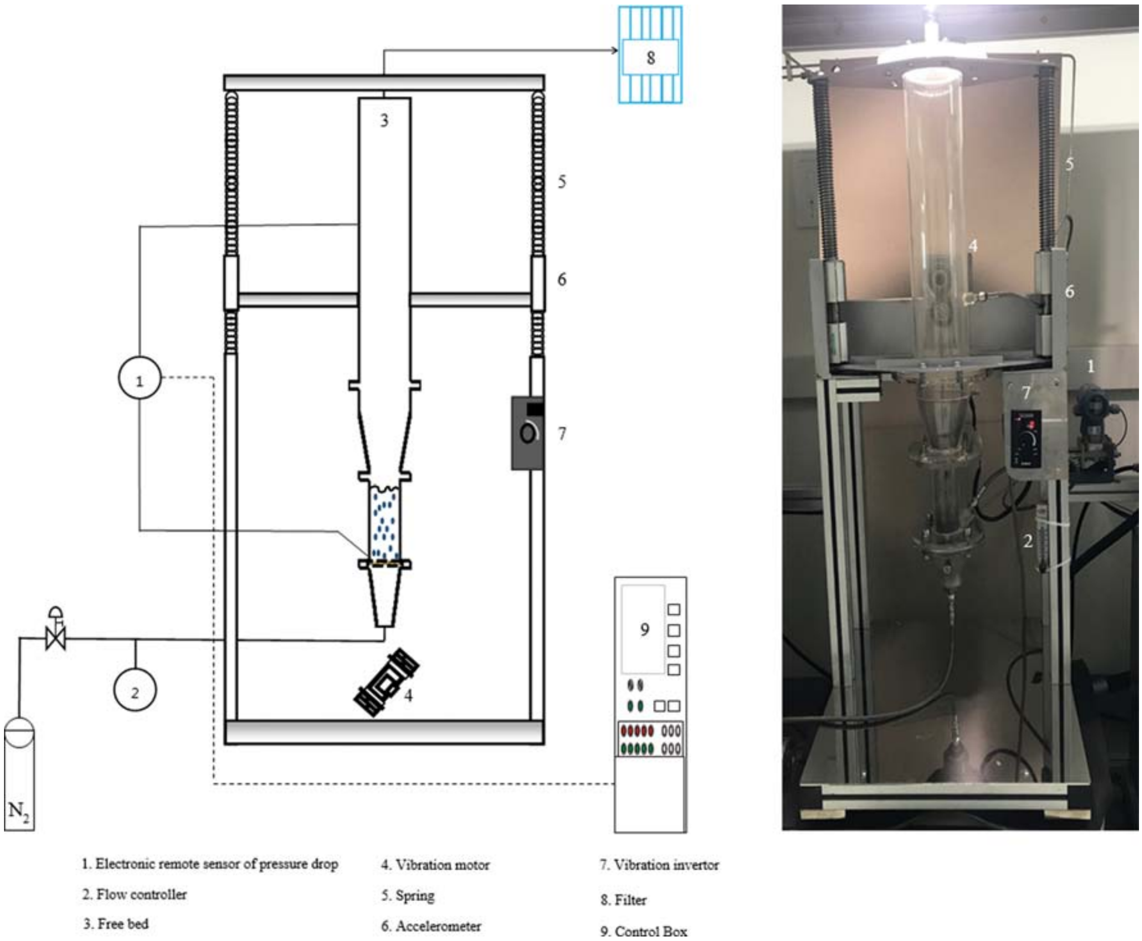

Fig. 1. Schematic diagram and photo of the apparatus.

Table 1. Experimental conditions

Parameter	Value
Fluidization gas [-]	Nitrogen
Superficial gas velocity [m/s]	0 to 0.45
Bed height per bed diameter ratios [-]	1, 2
Charging amount of powder [g]	200, 400±20
Initial bed height [cm]	5, 10
Bed diameter [cm]	5
Frequency of vibration [Hz]	0 to 60
Amplitude of vibration [mm]	0.4
Vibration direction [-]	Vertical
Temperature [°C]	20±2

gravitation is a nonlinear function of vibration frequency, as shown in Eq. (1) [25,26].

$$\text{Vibration intensity} = A\frac{(2\pi f)^2}{g} \tag{1}$$

In Eq. (1), A is the amplitude of vibration, f is the vibration frequency, g is the acceleration due to gravity.

2. Materials

Images of the fine powder, magnified 50 to 200 times, using a scanning electron microscope (SEM) show a spherical shape, as shown in Fig. 2. Analysis of powder size using a powder size distribution analyzer (TSI, model 3603, USA) shows that a mean powder size is 2.25 μm; the results of powder size analysis are depicted in Fig. 3. Powder density, indicated by Eq. (2), was verified to be 8,200 kg/m^3 [27]. Table 2 summarizes the physical properties of the fine powders that are included in the Geldart group C according to powder size and density.

$$\text{Powder density} = \frac{\text{Mass of the particle}}{\text{Volume that the particle would displace if its surface were nonporous}} \tag{2}$$

RESULTS AND DISCUSSION

1. Pressure Drop

Fluidization is defined as a process which causes the injected solids to behave as a fluid in a fluidized bed reactor filled with powder, by blowing gas upwards. As gases are injected into a fluidized bed reactor, powders undergo bed expansion, and the drag force between them maintains a balance, defined as homogeneous fluidization. Due to channeling and cracks, no reaction between gases and powders occurs in the fluidized bed reactor, without affecting powder distance of the powder layer in the bed, which is defined

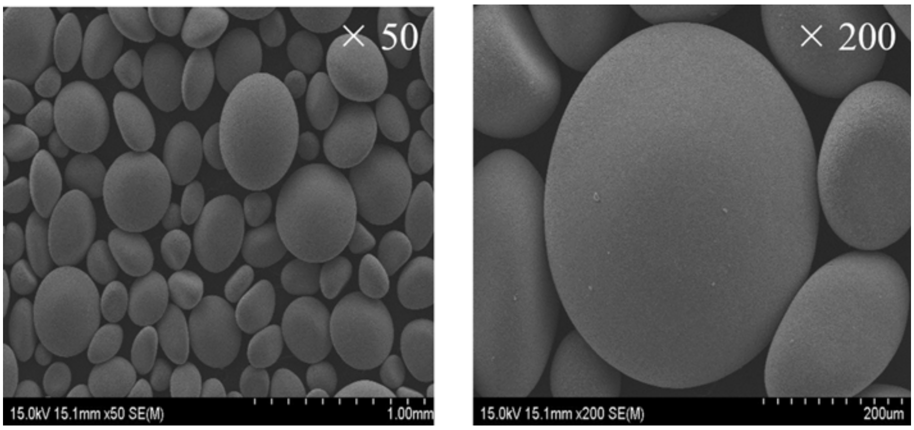

Fig. 2. SEM micrographs of the fine powder.

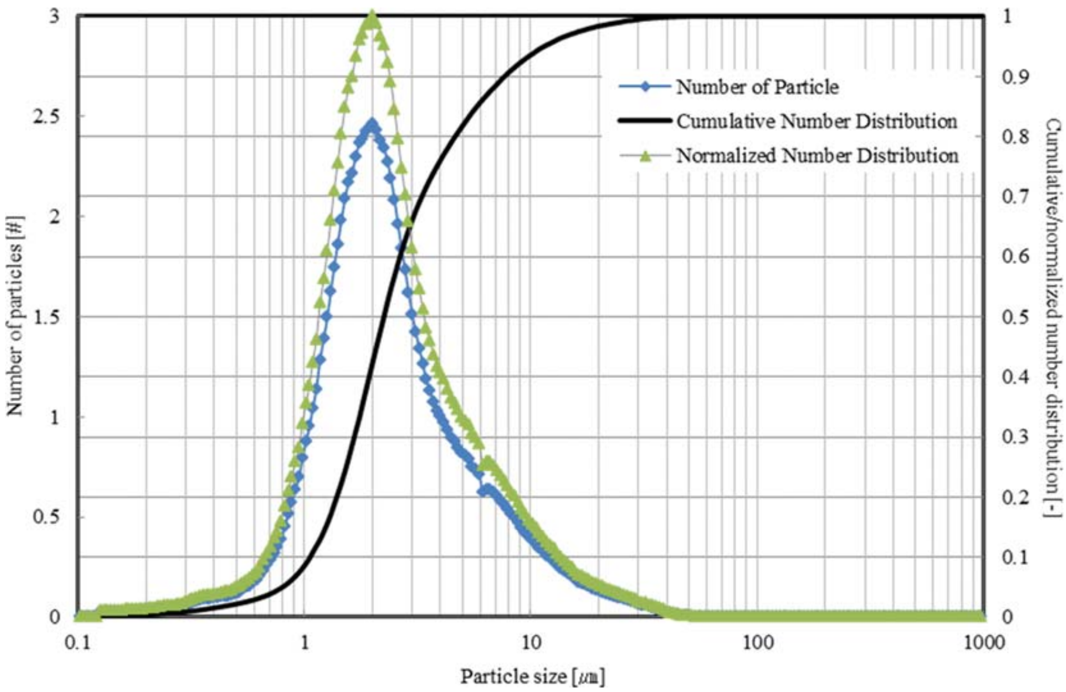

Fig. 3. Powder size distribution of fine powder.

Table 2. Physical properties of fine powder

Parameter	Value
Powder type [-]	NiO
Mean powder size [μm]	2.25
Powder density [kg/m^3]	8,200
Shape [-]	Spherical
Geldart classification [-]	Group C

as heterogeneous fluidization [28,29]. Pressure drop in the fluidization system is a measure for determining whether the fluidization is homogeneous or heterogeneous [30].

Pressure drop with respect to bed diameter and powder injection height for the fluidized bed reactor with mechanical vibration, is an element to measure the fluidization of a system [31,32]. Fig. 4 shows trends of a pressure drop for H/D of 1 and 2, with respect to vibration frequency. The number of vibration cycles per minute as per the vibration frequency is 28 rpm at 1 Hz, and 1,680 rpm at 60 Hz. The correct pressure drop was measured using the increasing method from minimum to maximum flow speed and the decreasing method from maximum to minimum flow speed. Channeling and agglomeration phenomena were deemed to exist at superficial gas velocity 0 to 0.45 m/s without vibration. It was determined that fluidization occurs after 0.07 m/s at 15 Hz vibration frequency. Homogeneous fluidization was verified at a 30 to 60 Hz vibration frequency. A pressure drop for H/D of 1 with a decreasing method at 0.45 m/s superficial gas velocity under 60 Hz and 15 Hz was measured as 1,660 and 1,100 Pa, and those for H/D of 2 under 60 Hz and 15 Hz as 2,820 and 1,950 Pa. A pressure drop

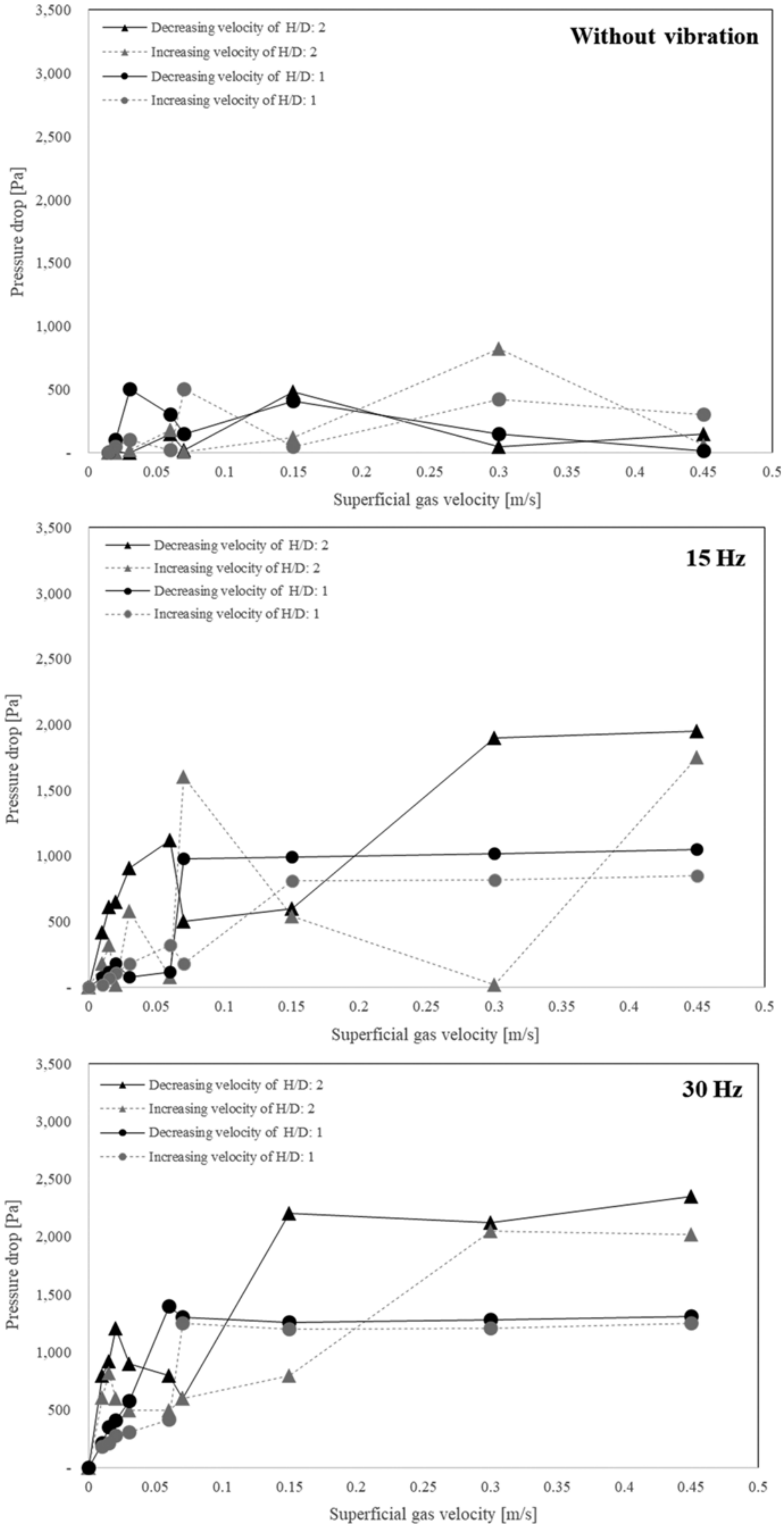

Fig. 4. Pressure drop trend for H/D of 1 and 2 at vibration frequency 0 to 60 Hz with superficial gas velocity using increasing and decreasing methods.

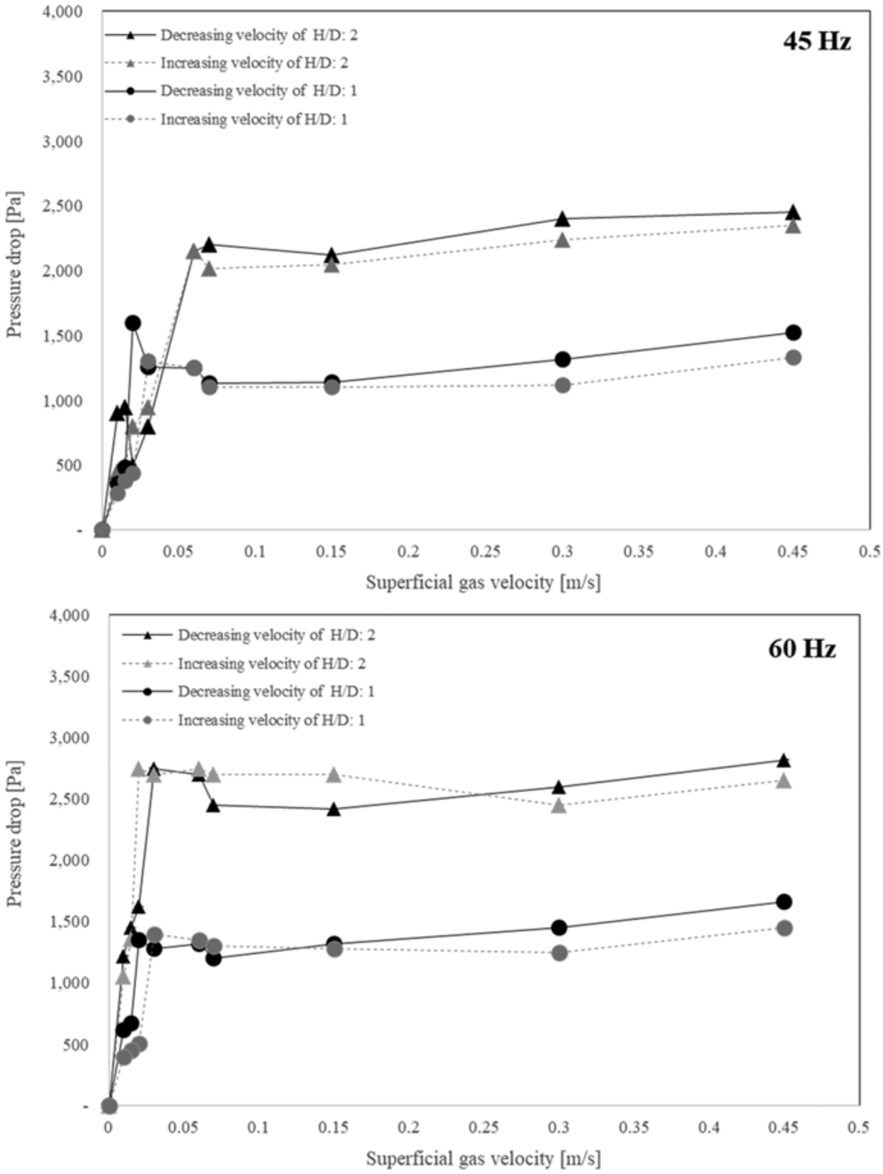

Fig. 4. Continued.

for H/D of 1 with an increasing method at 0.45 m/s superficial gas velocity under 60 Hz and 15 Hz was measured as 1,450 and 850 Pa, and those for H/D of 2 under 60 Hz and 15 Hz as 2,650 and 1,710 Pa.

We checked that the fine powder, under no vibration, agglomerates on the wall or bottom of the fluidized bed reactor to reduce the porosity of the layer, coheres on one side to allow the air to escape through vacant space without agglomeration of the fine powder, and value of pressure drop falls fast. However, we also checked that the value of pressure drop becomes stable as vibration frequency increases, and agglomeration of the fine powder on fluidization is removed with the help of vibration rather than fluidization method without vibration.

Time to begin fluidization for H/D of 1 and 2 was found to be similar, depending on the effects of the vibration frequency. It was verified that H/D of 2 has a large powder charge and proportionally higher pressure drop than H/D of 1.

2. Minimum Fluidization Velocity

Minimum fluidization velocity is defined under a condition that drag force applied on powders by powder weight and ascending gases become equivalent. It is at a point of time when a solid powder injected in the fluidized bed reactor meets fluid and moves slowly to conduct behavior like fluid, and a point at which the fluidization phenomenon begins. It is the most important part of the fluidization system [33,34].

As shown in Eq. (3), P_e is expressed as the minimum fluidization velocity when gravity and pressure drop are parallel against the bed area.

$$P_e \simeq \frac{m \cdot g_{aef}}{S} \quad (3)$$

In Eq. (3), m is the mass of the powders, g_{aef} is the average effec-

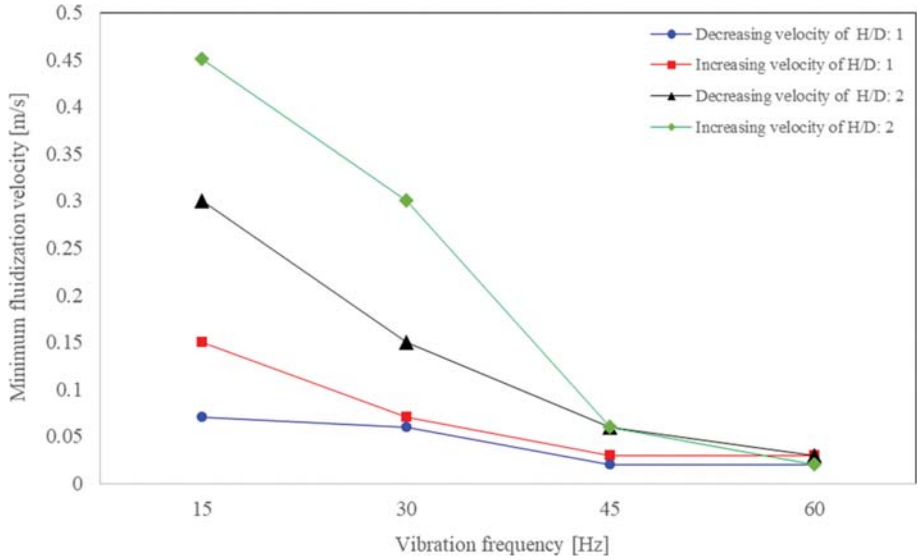

Fig. 5. Minimum fluidization velocity for H/D of 1 and 2 with vibration frequency.

tive acceleration, S is the cross section area of the fluidized bed reactor.

Fig. 5 shows the results of minimum fluidization velocity for H/D of 1 and 2 in 0 to 0.45 m/s of superficial gas velocity range with vibration frequency. We could not find a trend of minimum fluidization velocity without vibration. As vibration frequency increased, minimum fluidization velocity showed a lower trend in H/D of 1 than in H/D of 2.

It was checked that vibration frequency relieves the force between particles of the fine powder, and the fine powder has homogeneous fluidization status. It was checked that vibration increases the fluidization quality, and fluidization start point that is minimum fluidization velocity, arrives fast as the vibration frequency increases. Since H/D of 1 and 2 show almost the same value at vibration frequencies 45 and 60 Hz, it was determined that the effects of vibration on the fine powder over 45 Hz were equivalent.

3. Bed Expansion

The bed expansion ratio can be found according to heights of the powders into the fluidized bed reactor before and during the fluidization, as shown in Eq. (4) [35,36].

$$\text{Bed expansion ratio} = \frac{H_i - H}{H_i} \tag{4}$$

In Eq. (4), H_i is the height of the initial static bed, and H is the height of the bed.

In the case of fine particles, as the force between particles is strong, mechanical vibration is effective as the external force for fluidization. g_{ef} is expressed as effective acceleration as shown in Eq. (5) [37].

$$g_{ef} \simeq g\left(1 + \frac{A_V \omega^2}{g}\right) \tag{5}$$

In Eq. (5), g is the acceleration due to gravity, A_v is the vibration amplitude, ω is the vibration frequency.

The powder filled in the fluidized bed reactor varies in its force according to supplied gas and the height increases when supplied gas is increased. However, those fine powders with a strong force between particles do not result in bed expansion, and require fluidization from an external force as indicated by studies on various kinds of fine powders.

Fig. 6 shows the results of the bed expansion ratio for H/D of 1 and 2 at 0 to 0.45 m/s of superficial gas velocity and 0 to 60 Hz vibration frequency. When superficial gas velocity increases without vibration, it shows a pressure drop without any trend. There is a trend of an increased bed expansion ratio over 0.07 m/s at 15 Hz and a pressure drop without any trend that is determined to have a fixed bed or channeling phenomenon under 0.07 m/s. When superficial gas velocity increases at 30, 45, and 60 Hz, bed expansion shows a proportional increase.

To utilize fine powders for high value-added industries, it is important to visually check the behavior of the fine powders. There have been studies to examine the visual fluidization phenomenon, the eventual purpose of which was to find the optimal fluidization conditions of the fine powders to be applied for industrial fields [38-40].

This study analyzed the fluidization phenomenon with mechanical vibration in a fluidized bed reactor of acryl material to allow for visual observation of the fluidization phenomenon of fine powders. As the production rate and fluidization phenomenon are also influenced by the charging amount of fine powders in actual fields, the ratio of H/D is an important element. The experiment was carried out under a condition without vibration and at 0.07 m/s of superficial gas velocity and at 30 Hz when fluidization had stably started. The narrow type of channeling phenomenon and small agglomeration occurred at H/D of 1 without vibration. However, bubbling actively occurred at 30 Hz. A wide type of channeling phenomenon and large agglomeration in H/D of 2 without vibration occurred at the bottom of the fluidized bed reactor. However, it was been observed that at 30 Hz, large bubbles were generated and circulation was generated at the bottom of the fluidized bed

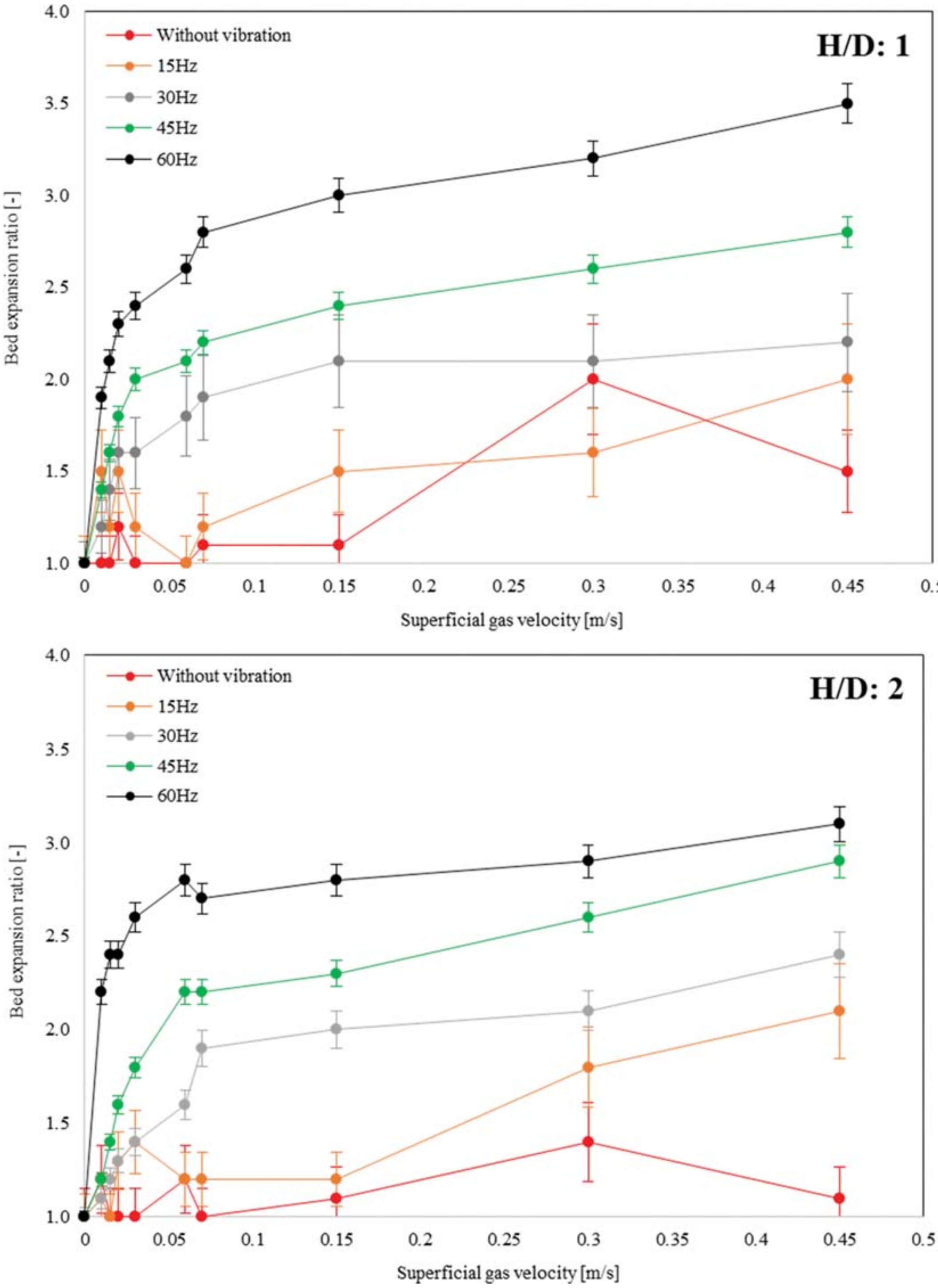

Fig. 6. Bed expansion results for H/D of 1 and 2 upon increased superficial gas velocity at a 0 to 60 Hz vibration frequency.

reactor. As a result, vertical vibration relieved channeling and agglomeration of the fine powders and resulted in active bubbling and circulating. Fig. 7 shows a photograph of fluidization phenomenon with the vertical vibration of fine powder.

As effects of vibration frequency of fine powder within the fluidized bed reactor are almost the same at 60 Hz and 30 Hz, effects on the fine powder are equivalent when the external force is over a certain value.

CONCLUSION

A fluidization experiment for fine powders in group C was conducted in a fluidized bed reactor using vertical vibration. Under conditions without vibration, the fine powder showed a heterogeneous fluidization phenomenon with channeling and agglomeration, and it was difficult to expect the trend of the pressure drop and changing minimum fluidization velocity. For H/D of 1 and 2,

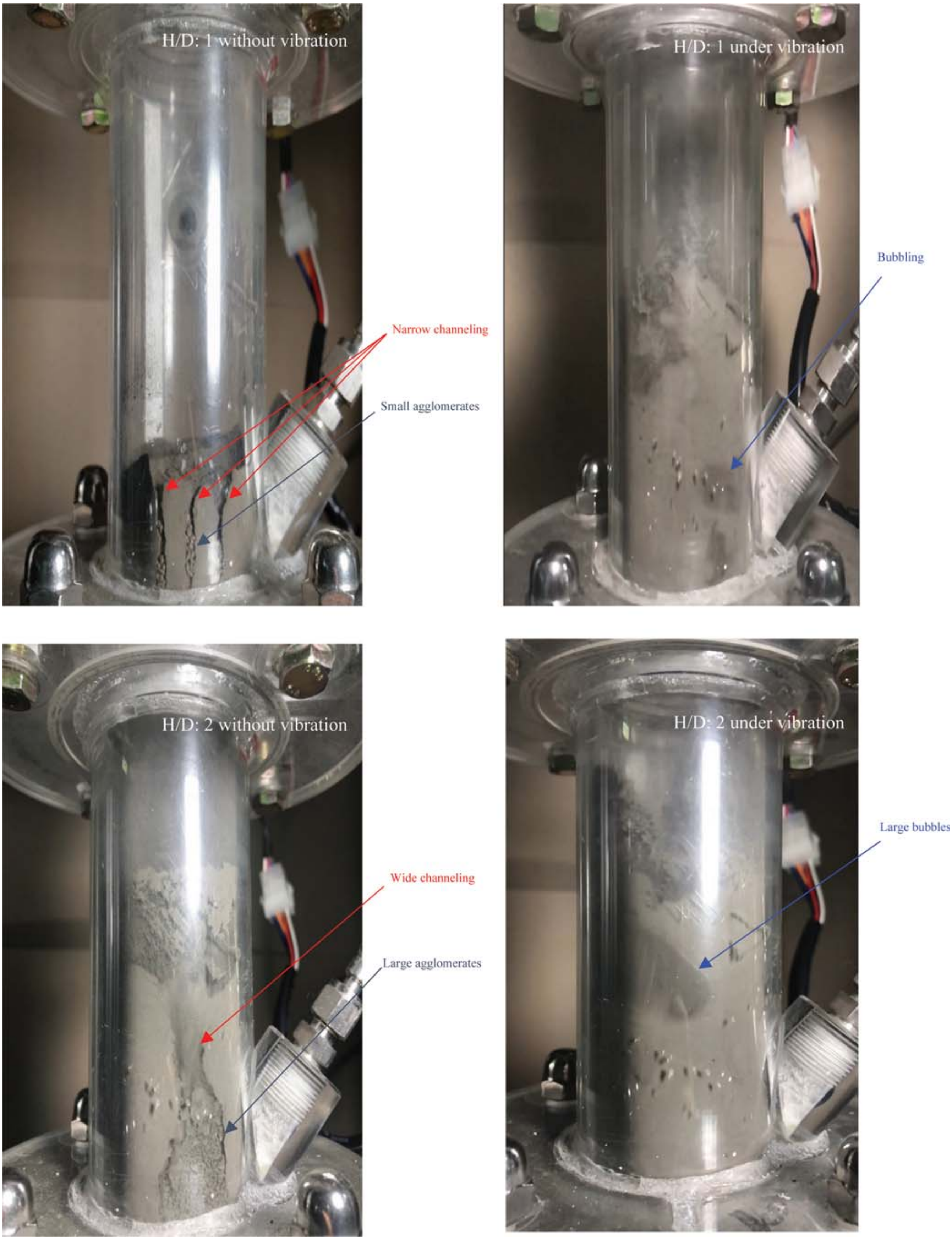

Fig. 7. Comparison of fluidization phenomena for H/D of 1 and 2 under conditions of without vibration and 30 Hz of vibration frequency.

the pressure drop stabilized under conditions of stabilized fluidization at 0.07 m/s of superficial gas velocity, and 30 Hz or higher vibration frequency. As vibration frequency increased, minimum fluidization velocity decreased, the bed expansion ratio increased, and the pressure drop was stabilized.

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