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Prediction of Axial Solid Holdups in a CFB Riser

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Abstract – A circulating fluidized bed (CFB) has been used in various chemical industries because of good heat and mass transfer. In addition, the methanol to olefins (MTO) process requiring the CFB reactor has attracted a great deal of interest due to steep increase of oil price. To design a CFB reactor for MTO pilot process, therefore, we has examined the hydrodynamic properties of spherical catalysts with different particle size and developed a correlation equation to predict catalyst holdup in a riser of CFB reactor. The hydrodynamics of micro-spherical catalysts with average particle size of 53, 90 and 140 mm was evaluated in a 0.025 m-ID x 4 m-high CFB riser. We also developed a model described by a decay coefficient to predict solid hold-up distribution in the riser. The decay coefficient developed in this study could be expressed as a function of Froude number and dimensionless velocity ratio. This model could predict well the experimental data obtained from this work.

Key words: Decay factor, Axial solid holdup, Circulating fluidized bed (CFB)

1. Introduction

Circulating fluidized beds (CFBs) operating in a fast fluidized bed with high gas-solid mass transfers and low-pressure drops have been utilized in numerous petrochemical industries for fluid catalytic cracking (FCC), coal combustion, and various catalytic reactions, including the methanol to olefins (MTO) process [1]. CFB catalytic reactors utilize Geldart A group particles and operate at a high gas velocity and high solid circulation rate. On the other hand, CFB combustors, using Geldart B group particles, operate at lower gas velocities and solid circulation rates [2]. Understanding the axial and radial solid distributions and flow pattern in CFB risers is the key to the successful design and scale-up of a CFB system [3]. Matsen [4] reported that "scale-up is still not an exact science, but is rather a mix of physics, mathematics, witchcraft, history and common sense that we call engineering." The axial solid holdup distribution in a riser was found to be dependent on the gas flow rate and solid mass flux as well as on the inert particle properties, riser inlet diameter and height of the apparatus [5]. Many studies on various aspects of CFB hydrodynamics have been reported [6-8]. Many researchers believe that the axial solid holdup profile in a riser typically represents a S-shape profile combining the dense phase at the bottom of the riser and a dilute phase at the top. However, other experiments did not show an S-shape profile. Therefore, the design and scale-up of CFB reactors is by no means an easy task, particularly when the circulation of solids is involved. Li and Kwauk [9] first demonstrated the S-shape solid holdup profile with an inflection point in a fast fluidized bed. Hartge *et al.* [10] measured the axial solid holdup profile using a γ-ray absorption method to confirm the axial solid holdup profile that was well described by Li and Kwauk [9]. Kato *et al.* [11] determined the height of the inflection point from the height where the second differential coefficient of the axial pressure profile curve equals zero, and equation for the empirical correlation for the inflection point. There are several experimental results and empirical correlations for understanding the axial solid holdup profile of cold-mode CFB with many variables. Despite the necessity of being able to design lab-scale CFB reactors to work in CFB applications, there are insufficient experimental data for a CFB design in the literature. In the present study, therefore, the prediction of axial solid holdups was developed in a 0.0254 m-ID x 4 m-high cold-bed CFB for MTO process.

2. Theory

2-1. Axial solid hold-up in a riser

The axial solid holdup in the riser was determined by measuring the pressure differences on the riser height by the assumption where gas friction on the pressure drop can be neglected. The solid holdup can be expressed as follows:

$$\frac{\Delta P_r}{\Delta Z} = \rho_S \varepsilon_S g \qquad (1)$$

2-2. Decay factor in a riser

Kunii and Levenspiel [12] proposed a free-entrainment model to

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‡ This article is dedicated to Prof. Yong Kang on the occasion of his retirement from Chungnam National University.

estimate the decay factor in a riser, and used it to represent the axial solid holdup profile in the fast fluidized bed as follows:

$$\frac{\varepsilon_s-\bar{\varepsilon}_s}{\varepsilon_{sd}-\varepsilon_s^*}=\exp(-aZ_f) \tag{2}$$

The axial solid hold-up with the axial riser height can be expressed as follows:

$$\varepsilon_s=\varepsilon_s^*+(\varepsilon_{sd}-\varepsilon_s^*)\exp(-aZ_f) \tag{3}$$

The axial solid hold-up at the exit of riser can be expressed as

$$\varepsilon_{se}=\varepsilon_s^*+(\varepsilon_{sd}-\varepsilon_s^*)\exp(-aZ_e) \tag{4}$$

$$\varepsilon_{se}=G_s/[\rho_s\times(U_r-U_t)] \tag{5}$$

The mean axial solid hold-up at the entrainment region of Z_f is

$$\bar{\varepsilon}_s=\frac{1}{z_e}\int_0^{z_e}\varepsilon_s dZ_f \tag{6}$$

Inserting Eq. (3) into (6) and integrating gives

$$\bar{\varepsilon}_s=\varepsilon_s^*+\frac{\varepsilon_{sd}-\varepsilon_s^*}{aZ_e}=[1-\exp(-aZ_1)]+\varepsilon_s^*+\frac{\varepsilon_{sd}-\varepsilon_{se}}{aZ_e} \tag{7}$$

The decay factor is dependent on the operating conditions and physical properties of the bed materials. Adánez *et al.* [13] and Lei and Horio [14] proposed the following correlations of Eq. (8) and Eq. (9), respectively:

$$a(U_r-U_t)^2D_r^{0.6}=0.88-420d_p \tag{8}$$

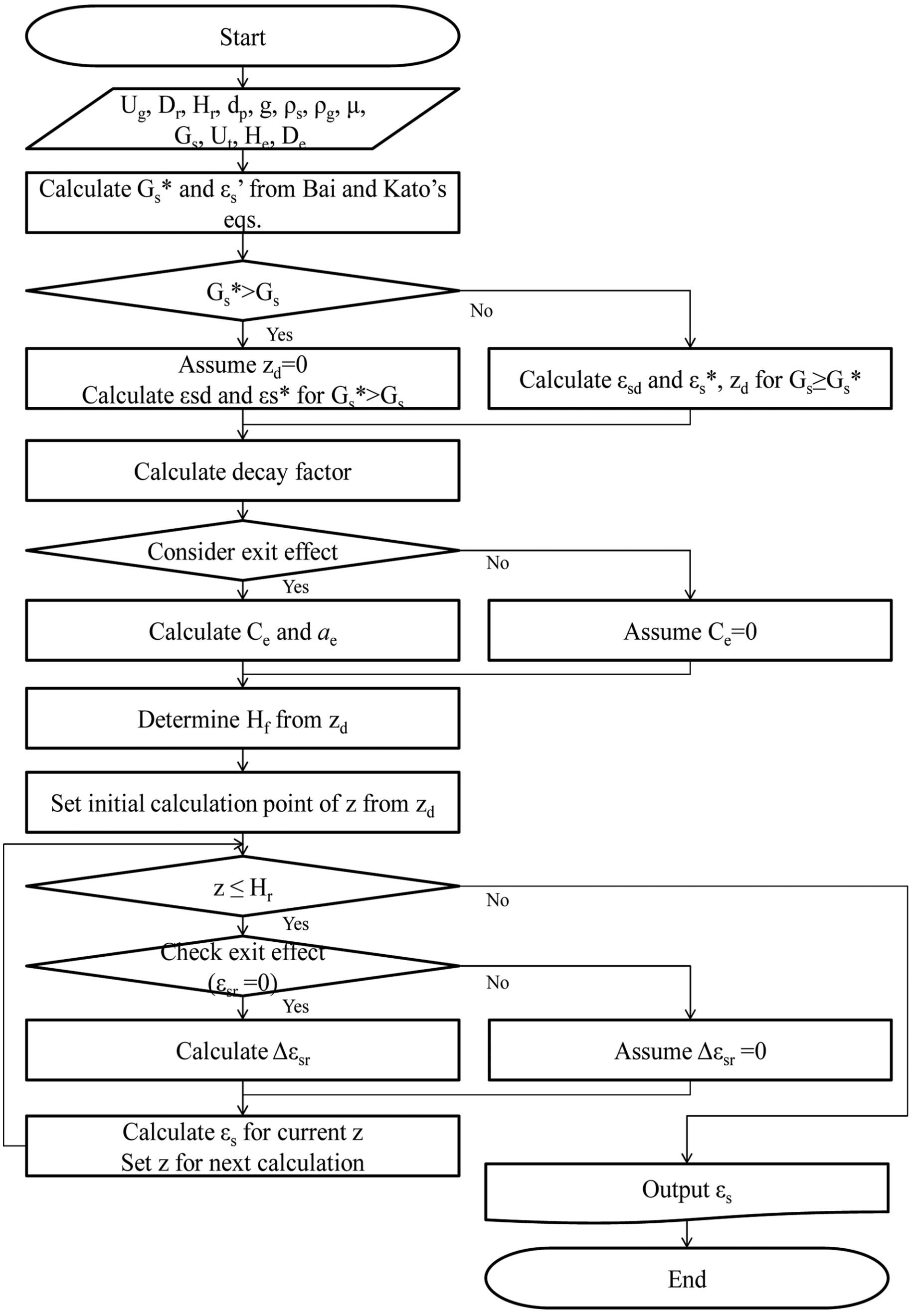

Fig. 1. Flow chart for the axial solid holdup in a CFB riser.

$$aD_r = 0.019\left(\frac{G_s}{U_r\rho_g}\right)^{-0.22}\left(\frac{U_r}{\sqrt{gD_r}}\right)^{-0.32}\left(\frac{\rho_p-\rho_g}{\rho_g}\right)^{0.41} \tag{9}$$

Bai and Kato [15] proposed the following correlations of Eqs. (10) and (11) for ε_{sd} and ε_s^* in case of $G_s < G_s^*$:

$$\frac{\varepsilon_{sd}}{\varepsilon_s'} = 1+6.14\times10^{-3}\left(\frac{U_r}{G_s/\rho_s}\right)^{-0.23}\left(\frac{\rho_p-\rho_g}{\rho_g}\right)^{1.21}\left(\frac{U_r}{\sqrt{gD_r}}\right) \tag{10}$$

$$\varepsilon_s^* = 4.04\varepsilon_{se}^{1.214} \tag{11}$$

Kunii and Levenspiel [16] proposed the equation to describe the deviation affected by riser exit:

$$\Delta\varepsilon_{sr} = C_e\varepsilon_{se}\exp[-a_e(H_f - z_f) \tag{12}$$

Kim et al. [17] proposed for decay factor and reflux constant in Eqs. (13) and (14) based on Eq. (9):

$$a_eD_r = 1.27\left[\frac{(U_g-U_t)^2}{gD_r}\right]^{1/2}\left[\frac{G_s}{\rho_p(U_g-U_t)}\right]^{-1/2}\left[\frac{D_e}{D_r}\right]^{-1/2}\left[\frac{\rho_p-\rho_g}{\rho_g}\right]^{-1} \tag{13}$$

with a correlation coefficient of 0.90 and a standard error of estimate of 1.73:

$$C_e = 0.046\left[\frac{(U_g-U_t)^2}{gD_r}\right]^{1/2}\left[\frac{G_s}{\rho_p(U_g-U_t)}\right]^{-1/3}\left[\frac{H_e}{d_p}\right]^{1/3}\left[\frac{D_e}{D_r}\right]^{-3/4} \tag{14}$$

With a correlation coefficient of 0.92 and a standard error of estimate of 0.012.

A block diagram of the calculation procedure for the axial solid holdup is presented in Fig. 1.

3. Experimental

The experiments were carried out in a 0.0254 m-ID x 4 m-high cold-type CFBs. The CFBs consisted of a riser, a bubbling bed, a cyclone and bag filter to separate the fine particles and a non-mechanical valve. The components were made from a transparent acrylic column equipped with a seal-pot, as a non-mechanical valve for the return of entrained particles. Fig. 2 shows the schematic diagram of the experimental apparatus. For smooth solid circulation, air was injected individually into four parts (riser, seal-pot, bubbling bed and seal-pot dipleg). All parts of the equipment were connected to copper lines and grounded. The pressure taps were mounted flush on the column and covered with a 250-mesh screen to prevent the particles from entering. The pressure transducer (Cole-Parmer Co., C-68071-12) was calibrated using a U-tube manometer and the pressure drops were converted to a current signal. An A/D converter (COMI-ZOA, SD202) was connected to a PC used to read the continuous pressure drop in the riser and convert the current to a voltage at 1 Hz for 200 s. The bubbling bed was filled with FCC particles and used as inert particles. Table 1 lists the physical properties of the solid particles. A ball valve was installed between the bottom of the cyclone and bubbling bed to measure the solid mass flux of the solids circulating with a height of accumulated particles, time period and bulk density. To evaluate the hydrodynamics, including the axial solid holdup in a riser and solid mass flux, a steady-state was maintained in all experiments and carried out according to experimental variables.

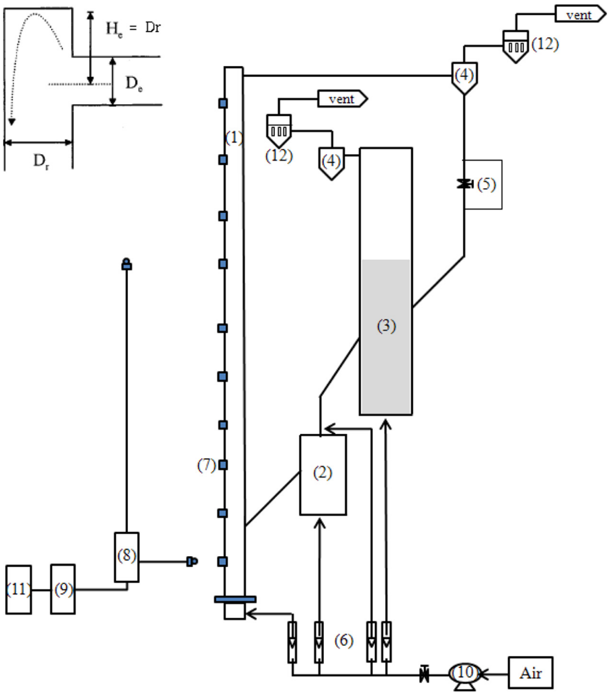

Fig. 2. Schematic diagram of the experimental apparatus.
1. Riser
2. Seal-pot
3. Bubbling bed
4. Cyclone
5. Ball valve
6. Air flow meter
7. Pressure tap
8. Pressure transmitter
9. A/D converter
10. Compressor
11. Personal computer
12. Bag filter

4. Results and Discussion

Fig. 3 shows the change in the axial solid hold-up profile with the dimensionless height including the data from previous studies. The axial solid holdup in the riser was determined by measuring pressure differences according to the riser height. The axial solid holdup can be calculated using Eq. (1) with the measured pressure drop along the axial riser height. The axial solid holdup in a riser is affected by the operating conditions, such as gas velocity, solid mass flux, particle

Table 1. Physical properties of bed materials

Bed materials	$\overline{d_p}$, [μm]	ρ_s, [kg/m^3]	U_{mf}, [m/s]	U_t, [m/s]	Geldart classification
FCC	53	1,886	2.6×10^{-3}	0.18	A
	90		6.6×10^{-3}	0.47	
	141		11.1×10^{-3}	0.86	

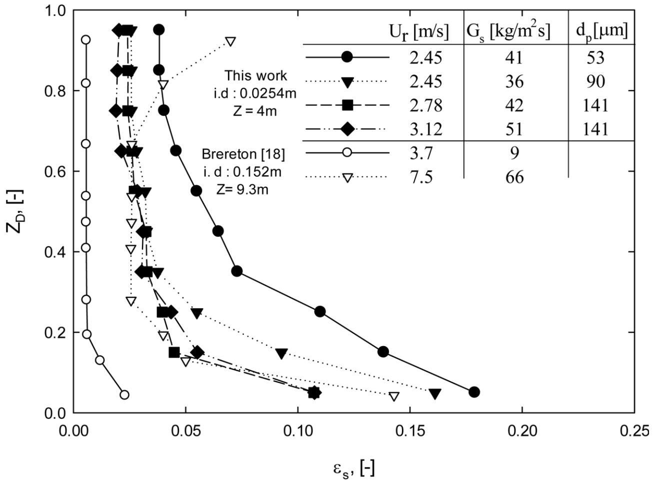

Fig. 3. Variation of the axial solid hold-up profile with the experimental variables.

properties, bed geometry, diameter of riser and exit geometry in a riser. Many researchers [11,12] believe that the solid holdup profile in a riser has an S-shape with a dense zone at the bottom of the riser, a dilute phase at top of the riser and an inflection point dividing the two regions. However, the S-shape solid holdup profile was not observed in this study or other experiments [18,19]. In this study, the riser was divided into two sections, an acceleration zone and a fully developed zone equipped with a smooth exit. At a constant riser inlet velocity, solid holdup in a riser increased with increasing solid mass flux. From the smooth exit geometry in the riser in this study, a fully developed region emerged over a 1/2-riser height from the bottom in a 0.0254 m-ID x 4 m-high CFB risers. These results showed a similar trend to that of simple exponential decay type reported by Brereton and Stromberg [18], who used an abrupt exit, except for the top-section of the riser due to an end effect phenomenon. Kunii and Levenspiel model [12] was used to analyze the axial solid holdup profile in this study. In this model, as the riser height increases in the free-board zone, the axial solid holdup profile in a riser appears to have the form of a simple exponential decay type with a lower dense region and an upper dilute region. The calculated decay factor was determined based on the Kunii and Levenspiel [12] model using Eqs. (2) to (7).

Fig. 4 shows a comparison between measured solid holdup and predicted values with experimental variables in a 0.0254 m-ID x 4 m-high CFB. Fig. 4(a) and (b) represent the axial solid holdup profile with the experimental variables in comparison with the correlations by Adánez *et al.* [13] and Lei and Horio [14], respectively. In addition, Bai and Kato [15] proposed Eqs. (10) and (11) to determine the solid concentration of the inlet and outlet of a riser. As can be seen, results of correlations reported by Adánez *et al.* [13] and Lei and Horio [14] underestimated the solid concentration in the dilute phase compared to the measured data of a 0.0254 m-ID x 4.0 m-high CFB.

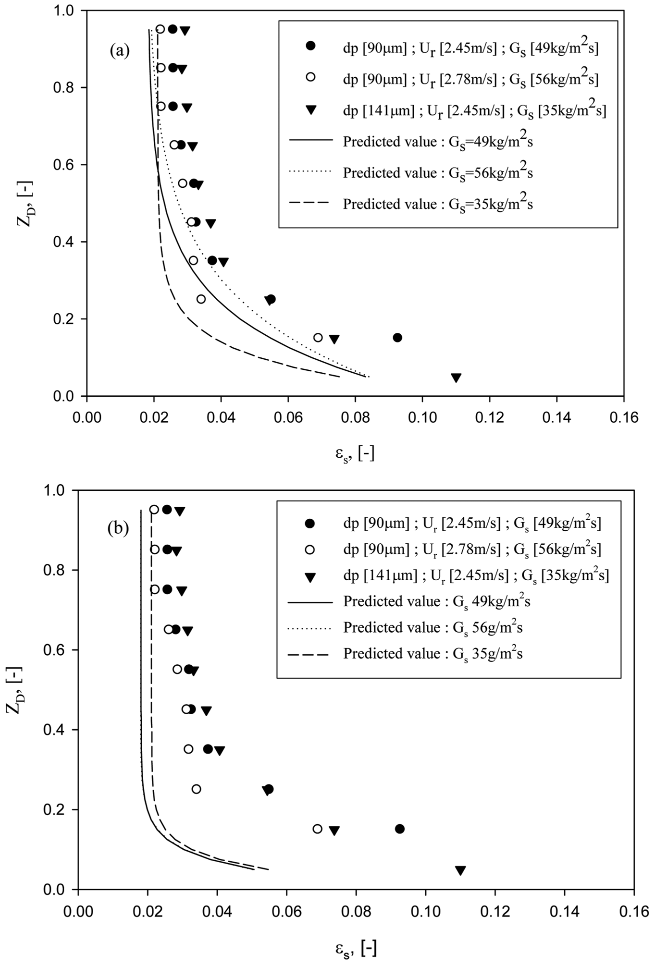

Fig. 4. Comparison between measured solid holdup and predicted values with experimental variables in a 0.0254 m-ID x 4 m-high CFB riser. (a) Adanez et al. [13]'s correlation and (b) Lei and Horio [14]'s correlation.

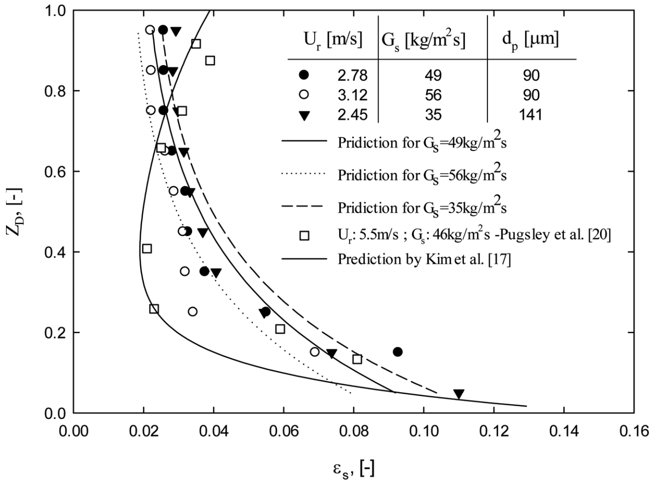

Fig. 5. Comparison between measured solid holdup and predicted values with experimental variables in a 0.0254 m-ID x 4 m high CFB and previous data.

Fig. 5 shows the prediction of axial solid holdup in 0.0254m-ID riser. As can be seen, prediction of solid holdup in Eqs. (13) and (14) has a significant deviation. However, data from Pugsley *et al.* [20] are well matched with the prediction of Kim *et al.* [17].

In this study, the empirical correlation was obtained for decay factor to estimate the axial solid holdup in a riser based on Eq (10) by Lei and Horio [14]:

$$aD_r = 2.2\times10^{-3}\left[\frac{U_r}{\sqrt{gD_r}}\right]^{(-6.3\times10^{-2})}\left[\frac{U_r}{G_s/\rho_p}\right]^{0.23}\left[\frac{\varepsilon_{sd}}{\varepsilon_{se}}\right]^{0.57} \tag{15}$$

with a correlation coefficient of 0.91 and standard deviation of 0.46x10^{-3}. The range of variables for Eq. (16) covers $7.3 \le U_r / \sqrt{gD_r} \le 11.8$,$120.3 \le U_g / (G_s/\rho_p) \le 260.2$, $4.1 \le \varepsilon_{sd}/ \varepsilon_{se} \le 6.5$. As can be seen in Fig. 5, the axial solid holdup by proposed correlation predicted well in comparison with the prediction of Adanez *et al.* [13] and Lei & Horio [14].

5. Conclusion

We examined the change in the axial solid hold-up profile in a 0.0254 m-ID x 4 m-high CFB. The axial solid holdup profile in a riser had a simple exponential decay type with two sections, an acceleration zone and a fully developed zone in a riser equipped with sharp right angle exit. Based on the experimental results from a 0.0254 m-ID x 4 m-high CFB, the decay factor in a riser was affected by the riser diameter. The decay coefficient developed in this study could be expressed as a function of Froude number and dimensionless velocity ratio. This model could predict well the experimental data obtained from this work.

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Nomenclature

A : Riser surface area [m^2]
A : Decay constant in a riser [m^{-1}]
d_p : Mean diameter of particle [μm]
D_r : Diameter of riser [m]
G_s : Solid mass flux [kg/m^{2}s]
G_s^* : Saturation carrying capacity [kg/m^{2}s]
G : Gravitational acceleration [m/s^2]
ΔP_r : Differential pressure drop in a riser [Pa]
U_b : Bubbling bed inlet velocity [cm/s]
U_{mf} : Minimum fluidization velocity [cm/s]
U_r : Riser inlet velocity [m/s]
U_{seal} : Seal-pot inlet velocity [cm/s]
U_t : Terminal velocity of single particle [m/s]
Z_d : Axial height of dense region at the bottom of the riser [m]
Z_e : Axial height of riser at the riser exit [m]
Z_f : Axial height of riser at entrainment region [m]
Z_t : Total height above the distributor in the riser [m]
ρ_g : Gas density [kg/m^3]
ρ_s : Particle density [kg/m^3]
ε_s : Solid hold-up [-]
ε_{sd} : Solid hold-up at the dense region of the riser [-]
ε_{se} : Solid hold-up at the dilute region of the riser [-]
$\overline{\varepsilon_s}$: Average solid hold-up in a riser [-]
ε_s^* : Saturated carrying capacity of maximum volume fraction of solids that can be pneumatically conveyed by gas [-]

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