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Temperature effects on riser pressure drop in a circulating fluidized bed

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Abstract−Effects of temperature on pressure drop across a riser due to solids holdup in the riser of a circulating fluidized bed (CFB) were investigated at the atmospheric pressure condition. The bed material was a group of sorbent particles and the experimental variables included temperature, gas velocity, and solids flux in the riser. With gas velocity and solids flux held constant, the riser pressure drop decreased as temperature increased. However, temperature effects decreased with increase in gas velocity. The effects of temperature on riser pressure drop were confirmed qualitatively by the same effects on the average ratio of gravity to drag force on a single spherical particle while the particle was accelerated. The pressure drop across the riser increased almost linearly with the ratio of solids flux to gas flux at the given gas velocity. Because gas momentum per unit mass of gas transferred to solids increased, the slope of the linear relationship decreased as temperature increased. This result confirmed the validity of the concept of momentum transfer from gas to particles at high temperature, proposed at ambient temperature in the prior study. The amount of gas momentum per unit mass of gas available to carry over the solid particles was finite; thus as the solids flux increased at the given gas velocity, the gas momentum shared to the unit mass of solids decreased and the mean residence time of solids in the riser, i.e., the pressure drop across the riser increased linearly. The slope of the linear relationship was proportional to the ratio of momentum flux by gravity and buoyancy forces on solids to gas momentum per unit mass of gas by drag force transferred to solids. Correlations were proposed to predict effects of temperature on the pressure drop across the riser and the solids flux in the riser within the range of experimental conditions.

Keywords: Circulating Fluidized Bed, Riser, Solids Circulation Rate, Riser Pressure Drop, Temperature Effect

INTRODUCTION

Circulating fluidized bed (CFB) systems, comprising a riser and a bubbling bed, are used for chemical looping combustion (CLC) of fuel gas [1], carbon dioxide (CO_2) capture from flue gas [2], and desulfurization from coal gas [3]. Different from the CFB combustor, they are a kind of CFB system valved with solids reservoirs in solids circulation loop, controlled in solids circulation rate, variable in solids mass of the riser, and simulating the fluid catalytic cracking (FCC) unit system [4,5]. The bubbling bed in their systems takes the role of the reservoir initially filled with bed material. However, the CFB combustor system is uncontrolled (or automatically controlled) in solids circulation rate and fixed in solids mass of the riser. The riser employs a gas velocity greater than the terminal velocity, and particles lifted by gas flowing upwardly react with target components in the gas phase. Particles separated from gas by the cyclone separator outside the riser move into the bubbling bed for regeneration and return to the bottom of the riser. Then the mass flux and mass of solids in each reactor are essential factors affecting overall process performance. In the riser, the solids flux at a given gas flow rate has effects on solids mass, conversion of chemical reaction, and mass and energy balances. The solids mass in the riser is mainly responsible for the pressure drop across the riser and related to sizing the fan that supplies fluidizing gas to the riser. The mass of riser solids should also be provided to meet the mean residence time of solids required for proper conversion of chemical reaction [6,7]. The solids circulation rate is often controlled by a mechanical or a nonmechanical valve in the solids return line of the solids circulation loop with the aid of two-stage solids reservoirs located above the valve. The two-stage solids reservoirs equipped with an on-off valve in the solids line connecting two reservoirs are necessary to quantify the solids circulation rate [6-8]. However, a simple control system using a single-stage solids reservoir is preferred in high-pressure, high-temperature, large-scale units for cost-effectiveness. As for the simple system, it requires a relationship adequate to estimate both solids flux and solids mass in the riser with each other. On the design stage of this system, we need to know the solids mass in the riser from the given mass fluxes of solids and gas, and during operation with a fixed gas flux, our interest is to know the solids flux from the solids mass given by the pressure drop across the riser of the system. The relationship can be applied for determining the solids mass and flux in the riser of the CFB combustor that is different from the system of this study in type though.

There are a few studies on the direct relationship between the solids mass and the solids flow rate in the riser within the limited process conditions [6,7,9]. Although considering effects of solids mass and flux, correlations about the axial solids holdup profile in the riser have been too complicated and insufficient to come up with the proper estimation of both effects in the riser, as discussed

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in our previous study [6]. Lee et al. [9] proposed a direct relationship between the solids holdup and the mass flux of solids in the riser at ambient temperature and pressure. Changing gas velocity, mass ratio of primary to secondary gas, and system's total solids inventory, they obtained experimental data in a cold model CFB riser with three different groups of particles as bed materials. However, the validity of their correlation to the riser conditions had to be proved because some of their gas velocities were smaller than the terminal velocity. Yin et al. [10] studied the pressure drop across the riser of a pressurized, high-flux CFB at ambient temperature with glass bead as the bed material but without proposing correlations. Cho et al. [6] related the pressure drop across the riser to the solids flux at ambient pressure and temperature. Khurram et al. [7] examined the pressure drop across the riser with variations in pressure, gas velocity, solids flux, and particle size and density at ambient temperature. The pressure drop across the riser decreased as the absolute gas pressure in the riser increased. They proposed a correlation between the pressure drop across the riser and the mass flux of solids in the riser.

To understand the underlying basic mechanism, Khurram et al. [7] interpreted the effect of each variable on the riser pressure drop. They explained consistently their experimental result by transfer of gas momentum to particles in the riser: the amount of gas momentum per unit mass of gas consumed to lift over the particles was shown to be finite; the time required to lift over the solids increased linearly with the solids flux because the amount of gas momentum shared to unit mass of solids decreased. Therefore, the pressure drop across the riser increased linearly with the solids flux at a gas velocity. The slope of the linear relationship was proportional to the ratio of momentum flux by gravity and buoyancy forces on solids to gas momentum per unit mass of gas by drag force transferred from gas to solids; and the gas momentum by drag force per unit mass of gas increased as gas velocity increased or as either particle diameter or pressure decreased. However, to extend their concept to the riser condition of the actual CFB reactor system, the validity of their concept must be proved at high temperatures.

The purpose of this study was to examine the effects of temperature and validity of the concept of Khurram et al. [7] to the pressure drop due to solids holdup across the riser of a hot CFB. A laboratory-scale CFB was used to investigate pressure drop across the riser with variations in temperature, gas velocity, and solids flux in the riser.

EXPERIMENTAL METHODS

Fig. 1 illustrates the flow diagram of the laboratory-scale, atmospheric pressure, CFB system made of stainless steel for this study. The system consisted of (1) a riser (0.015 m in diameter and 6.46 m in height), (2) cyclones, (3) a dipleg-loopseal (0.025 m in diameter), (4) a bubbling fluidized-bed as a solids reservoir (0.053 m in diameter and 1.2 m in height), and (5) a variable opening slide valve. The dipleg-loopseal was made bigger than the riser in diameter to provide the role of another solids reservoir when the solids circulation rate was measured. The system was furnished with several sets of an electric heater and a temperature controller: a preheater (7 kw) for fluidizing gas, four heaters (66 kw) for the riser, and two heaters for the bubbling bed (14 kw).

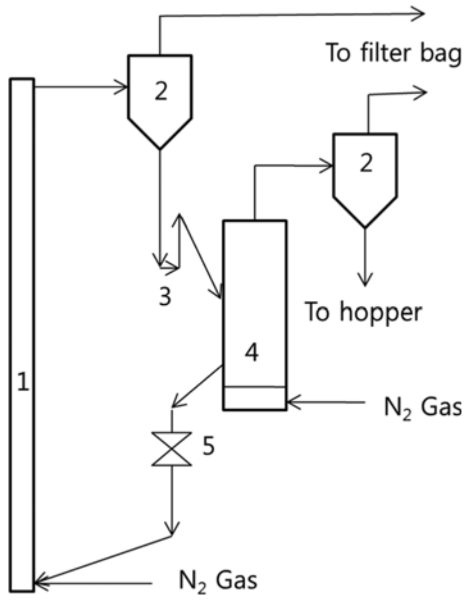

Fig. 1. Circulating fluidized bed system with (1) a riser, (2) cyclones, (3) a loopseal, (4) a bubbling bed, and (5) a slide valve.

Nitrogen gas was used as fluidizing gas, adjusted by mass flow meter controllers for the riser and the bubbling bed, respectively. The gas velocity was applied as the superficial velocity, the actual volumetric flow rate at the operating temperature divided by the cross-sectional area of the column. Two pressure taps in the bottom and the top of the riser (0.01 m and 6.46 m levels from the bottom), respectively, were connected to a pressure transducer to measure the pressure drop across the riser, and the same was for the bubbling bed (0.05 m and 1.2 m levels from the distributor). K-type thermocouples were placed at the inlet and outlet of the preheater, various levels in the riser (0.01, 0.6, 2.35, 4.1, 5.85, 6.46 m from the bottom) and in the bubbling bed (–0.1, 0.15, 0.57 and 0.99 m from the distributor). The arithmetic mean temperature of thermocouples in the riser was used as the riser temperature.

The bubbling bed, the reservoir initially containing about 1.7 kg of solids, was equipped with a perforated plate distributor (orifice diameter: 0.5 mm; number of orifices: 16) and fluidized at a gas velocity about two times greater than the minimum fluidizing velocity. Solid particles were fed to the bottom of the riser from the bubbling bed through the slide valve that controlled the solids flow rate in accordance to the opening area of the valve calibrated by the same method as that of previous studies [6-8] (see Fig. 2). Particles ascended the riser with the aid of transport gas, entered the cyclone to be separated from the transport gas, and returned to the bubbling bed through the loop seal. Particles elutriated from the cyclone and the bubbling bed were captured by the bag filter but measured negligible in total amount. The solids flow rate was measured under the same conditions after the steady state operation. The measurement started with turning off the aeration of the loopseal, thereby cutting off the transport of the particles from the loopseal to the bubbling bed and allowing buildup of solids in the dipleg under

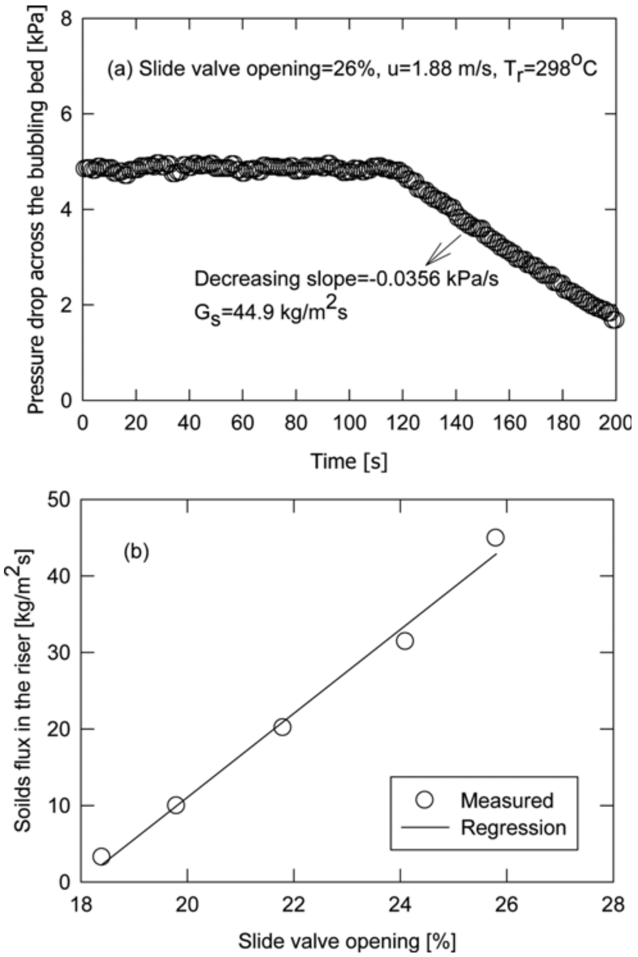

Fig. 2. Calibration of slide valve: (a) transient change of the pressure drop across the bubbling bed and (b) solids flux in the riser.

the cyclone. The ensuing decrease in solids inventory of the bubbling bed indicated the transient decrease in pressure drop across the bubbling bed. The solids flux in the riser was calculated based on the initially decreasing slope of the pressure drop and the ratio of the bubbling bed area to the riser area [6-8]. The bubbling bed held most of solids inventory of the CFB system, maintaining it nearly constant throughout all experiments.

Table 1. Particle size distribution of bed material

Diameter range [mm]	Weight fraction
0-0.042	0.029
0.042-0.052	0.024
0.052-0.062	0.049
0.062-0.075	0.084
0.075-0.105	0.249
0.105-0.150	0.346
0.150-0.215	0.200
0.215-0.255	0.020

Specific surface mean diameter $= \dfrac{1}{\Sigma_i^N \dfrac{x_i}{d_{p,i}}}$

The bed material was a group of particles formed by a spray drying method (1,370 kg/m^3 in apparent density and 94.3 μm in specific surface mean diameter (see Table 1)). The pressure drop across the riser was measured under steady conditions of the riser between 18 °C and 527 °C, between 1.91 m/s and 3.84 m/s in gas velocity, and between 3.23 kg/m^{2}s and 44.9 kg/m^{2}s in solids fluxes. Effects of temperature were considered in terms of gas density and viscosity calculated by the state equation of Peng-Robinson [11] and by Lucas method [12], respectively.

The pressure drop across the riser Δp_r, attributable to the solids mass in the riser, was determined by Eq. (1) as the value after subtracting pressure losses by wall friction and particle acceleration from measured pressure drop Δp_{ro} [8,13,14]. It determines the average solids holdup (ε_s) in the riser by Eq. (2).

$$\Delta p_r = \Delta p_{ro} - (\Delta p_{fg} + \Delta p_{fs} + \Delta p_{ac}) \quad (1)$$

$$\varepsilon_s = \Delta p_r / (\rho_s g H) \quad (2)$$

where ρ_s is apparent solid density, g gravitational acceleration and H riser height. The Fanning equation determines the pressure loss by gas-wall friction [15,16].

$$\Delta p_{fg} = 2 f_g \varepsilon \rho_g u^2 H/D \quad (3)$$

where ε is gas holdup, ρ_g gas density, u gas velocity and D riser diameter. The friction factor f_g is given by Eqs. (4a), (b) and (5) [16].

$$f_g = 16/Re \qquad Re \le 2300 \quad (4a)$$
$$f_g = 0.0014 + 0.125/Re^{0.32} \qquad Re > 2300 \quad (4b)$$

$$Re = D u \rho_g / \mu \quad (5)$$

The pressure loss due to solids-wall friction was calculated by the following equation of Konno and Saito [17].

$$\Delta p_{fs} = 2(f_s H/D)(G_s^2/\varepsilon_s \rho_s) \quad (6)$$

where

$$f_s = 0.0285(gD)^{0.5}/(G_s/\varepsilon_s \rho_s) \quad (7)$$

where G_s is solids flux. According to Bai et al. [8], Eq. (8) approximates the pressure drop due to particle acceleration, neglected reasonably when the solids flux is smaller than 200 kg/m^{2}s [13,14].

$$\Delta p_{ac} = G_s^2/\varepsilon_s \rho_s \quad (8)$$

The Fanning equation [16] is used to determine the pressure drop by gas-wall friction because the equation has been acceptable in wide ranges of temperature and pressure to calculate the frictional pressure drop in a homogeneous fluid flow. The correlation on f_s Eq. (7) was derived from the experimental data obtained at ambient temperature and pressure. According to the study of Konno and Saito [17], the velocity profile of the air in the vertical pipe was symmetrical, not appreciably affected by addition of particles, and it could be deemed that collision of particles on surface of pipe wall brought about the pressure drop of particles-wall friction that mainly depended on particle properties. Therefore, it was a good approximation to use Eqs. (3) to (7) in calculating the pressure drop by wall friction. However, the validity of those equations to high temperature and pressure conditions could not be assured

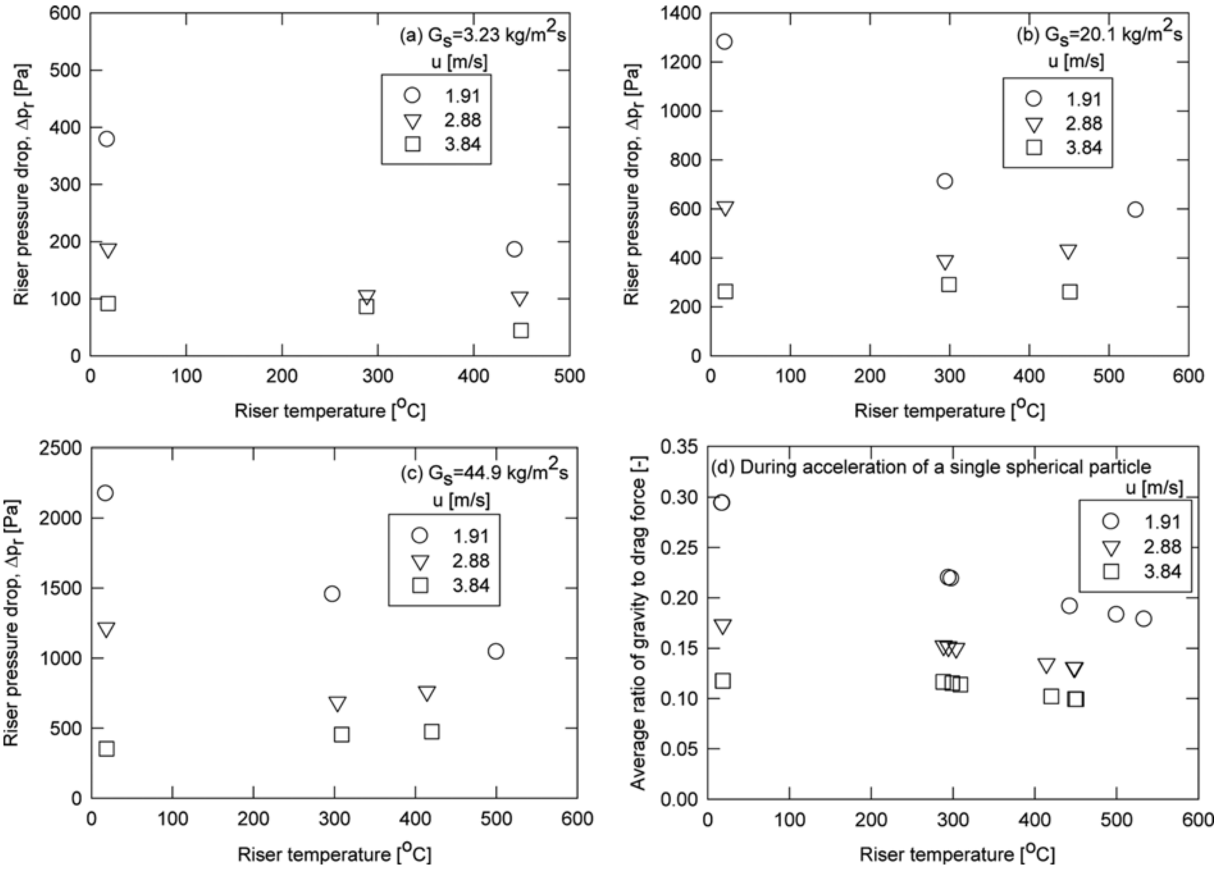

Fig. 3. Effects of temperature on (a)-(c) riser pressure drop and (d) calculated average ratio of gravity to drag force during acceleration of a single spherical particle.

by this study.

RESULTS AND DISCUSSION

Fig. 3 shows effects of temperature on the pressure drop due to the solids holdup across the riser with variation in gas velocity and solids flux in the riser. As expected, the riser pressure drop increased as the gas velocity decreased or solids flux increased [6,7]. The drag force acting on the particle surface decreases with gas velocity. The associated decrease in particle velocity subsequently leads to increases in particle retention time, solids holdup of the riser, and pressure drop across the riser. Because particles share gas momentum [7], it takes more time for particles to be carried out of the riser and, therefore, the pressure drop across the riser increases as the solids flux increased [6,7,10].

The riser pressure drop decreased as temperature increased. The effects of temperature decreased with increase in gas velocity at all solids flow rates and were insignificant at the gas velocity of 3.84 m/s. Solid particles are accelerated in rise velocity by gas in the bottom of the riser, the acceleration zone where most of solids in the riser are located. The riser pressure drop due to the solids holdup is proportional to the ratio of gravity to drag force as the buoyance force is negligible. Therefore, the effects of temperature on riser pressure drop can be confirmed qualitatively by the same effects on the average ratio of gravity to drag force while particles are accelerated. Fig. 3(d) shows the predicted average ratio of gravity to drag force, while a single spherical particle is being accelerated in experimental conditions of gas velocity and temperature. The trend of the force ratio agreed well with the measured one of the riser pressure drop and proved that the measured result was appropriate. Because the gravity force is constant with fixed particle diameter and density, Fig. 3(d) indicates the complicated effects of temperature through the drag force that is a function of gas density and viscosity, and relative velocity between gas velocity and particle velocity. The force ratio was calculated with the arithmetic mean relative velocity $(u+u_t)/2$ between gas velocity (u) and particle velocity as the particle was accelerated from zero to gas velocity minus terminal velocity $u-u_t$. The terminal velocity ranged from 0.178 m/s to 0.380 m/s [7,16] and the relative velocity from 1.04 m/s to 2.11 m/s.

Fig. 4 shows various relationships between the mass ratio of solids to gas and the pressure drop across the riser. The pressure drop increased linearly with the mass ratio of solids to gas, the same trend as that of prior studies [6,7,10]. The slope of the linear relationship decreased as temperature increased. In a prior study carried out at ambient temperature, Khurram et al. [7] found that the gas momentum per unit mass of gas available to accelerate solid particles was finite under fixed gas flow conditions. The time required for gas to accelerate solids increased linearly with increase in solids flux because the gas momentum shared to the unit mass of solids decreased. Thus, the solids holdup in the riser (and associated pressure drop across the riser) increased linearly with increase in solids flux for the given gas velocity [6,7,10], which agreed with the trend of this study shown in Fig. 4.

In addition, the slope of the linear relationship was inversely related to the gas momentum per unit mass of gas transferred to solids [7]. The momentum transfer from gas to solids referred to the drag force acting on a single spherical particle. As shown in Eq. (9), the drag force (F_d) per unit mass of gas increases with decrease in gas density or increase in gas viscosity because of drag coefficient (C_d) [7].

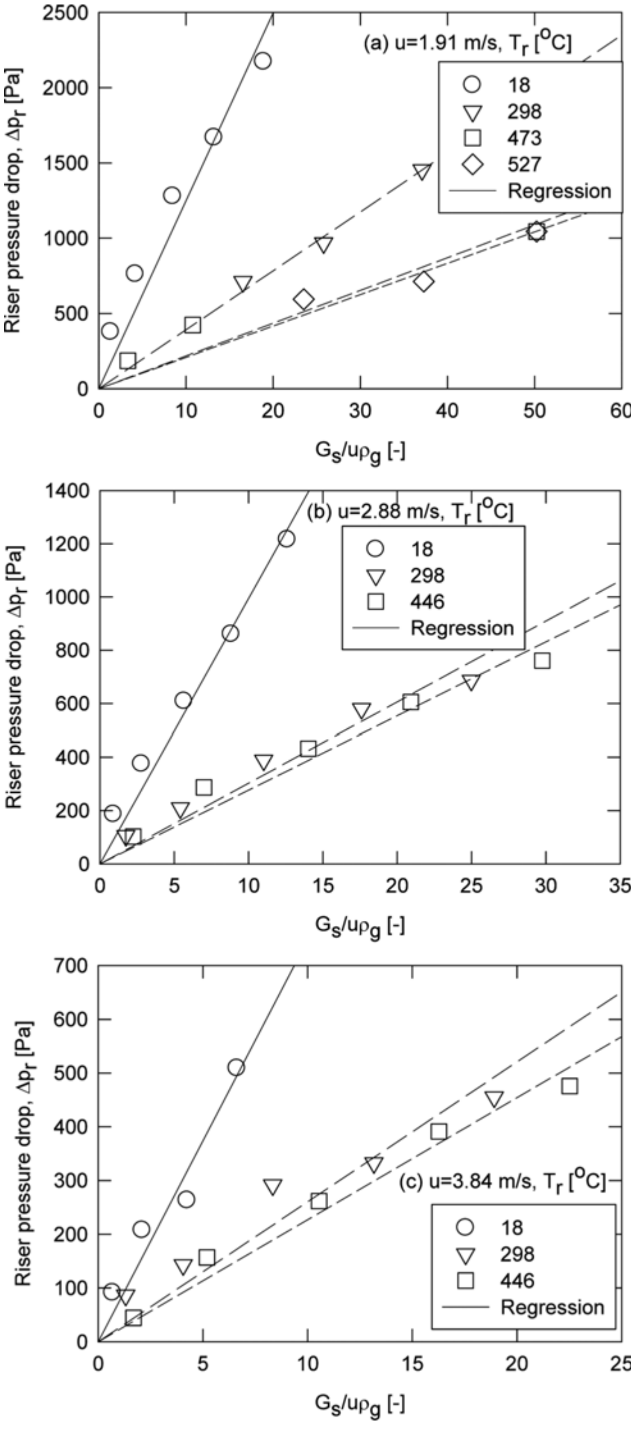

Fig. 4. Temperature effects on relationship between riser pressure drop and mass flow ratio of solids to gas.

(gas momentum flux)/(gas mass flux)

$$= \frac{F_d/A_p}{\rho_g u} = \frac{C_d \rho_g u^2/2}{\rho_g u} = C_d u/2 \tag{9}$$

The drag coefficient (C_d) is calculated as follows:

$$C_d = 24/Re_p \quad \text{for } Re_p \le 5.8 \tag{10a}$$

$$C_d = 10/Re_p^{0.5} \quad \text{for } 5.8 < Re_p \le 540 \tag{10b}$$

$$C_d = 0.43 \quad \text{for } 540 < Re_p \tag{10c}$$

$$Re_p = d_p u \rho_g / \mu \tag{11}$$

Eqs. (9) to (11) consider the case of a single spherical particle being accelerated from zero particle velocity for simple and qualitative comparison. The value of C_d increases with decrease in particle Reynolds number (Re_p). As temperature increases, gas density decreases but gas viscosity increases. This leads to a decrease in Re_p, subsequent increases in C_d and gas momentum per unit mass of gas transferred to a particle, and finally by the concept of Khurram et al. [7], a decrease in the slope of the linear relationship that agrees with the trend shown in Fig. 4. This result supports at high temperatures the validity of the concept that Khurram et al. [7] proposed about the momentum transfer from gas to solids. Thus, their concept describing effects of pressure, particle diameter and density, and gas velocity in the previous study could be extended successfully to explain effects of temperature on riser pressure drop.

According to Khurram et al. [7], the pressure drop across the riser is written:

$$\frac{\Delta p_r}{\left(\frac{G_s}{\rho_g u}\right)} = \frac{4}{3}\alpha g\left(\frac{d_p(\rho_s - \rho_g)g}{C_d u}\right) \tag{12}$$

where α (in seconds) is a correction factor that considers various particle conditions and is expressed by

$$\alpha = 1.77\times10^{-5} d_p^{-1.12} \rho_s^{0.865} G_s^{-0.308} \tag{13}$$

The parenthetical term on the right-hand side of Eq. (12) is the

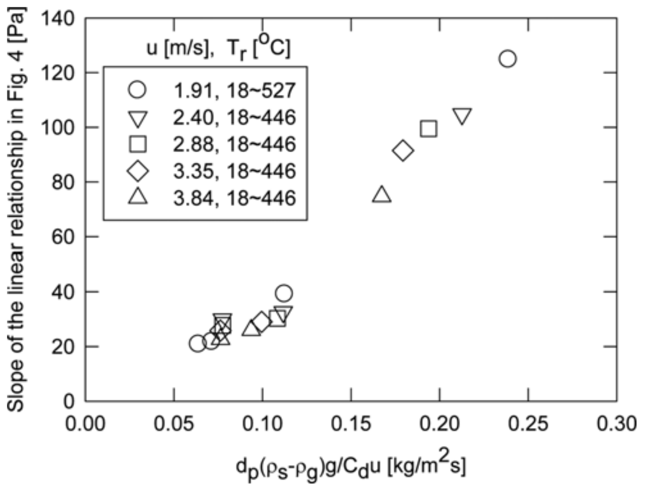

Fig. 5. Variable effects on the slope of the linear relationship in Fig. 4.

ratio of the momentum flux by gravity and buoyancy forces acting on a single particle to the gas momentum per unit mass of gas transferred to the particle. As the ratio increased throughout all the parameters considered (gas velocity, pressure, and particle size and density), the slope of the linear relationship between the pressure drop across the riser and the mass flux ratio of solids to gas ($G_s/u\rho_g$) increased regardless of the correction factor (α) [7]. The same trend could be confirmed on the parameter of temperature, as shown in Fig. 5 depicting the slope of the linear relationship in Fig. 4 with the parenthetical term on the right-hand side of Eq. (12).

CORRELATION

Based on experimental data of this and prior studies [6,7,10], following correlations on riser pressure drop across the riser (Δp_r) and solids flux (G_s) in the riser are proposed:

$$\Delta p_r=2.00\times10^{-7}C_d^{-0.864}d_p^{0.232}u^{-2.44}\rho_g^{-0.712}G_s^{0.667}(\rho_s-\rho_g)^{2.73}\mu^{-0.517} \quad r^2=0.922 \quad (14)$$

$$G_s=6.16\times10^{7}\Delta p_r^{1.25}C_d^{1.60}d_p^{-0.136}u^{3.64}\rho_g^{1.22}(\rho_s-\rho_g)^{-3.55}\mu^{0.367} \quad r^2=0.877 \quad (15)$$

Dependence of each parameter was similar to that of the Eq. (12). Therefore, it is claimed that the physical meaning mentioned in the derivation of Eq. (12) as a combined effect of the gravity, buoyance and drag forces and the mass fluxes of gas and solids [7] is somewhat valid. Correlations are applicable in following ranges of operating parameters:

$5.45\times10^{-5}<d_p$ [m] $<6.46\times10^{-4}$	$918<\rho_s$ [kg/m^3] <2490
$2<G_s$ [kg/m^{2}s] <969	$0.440<\rho_g$ [kg/m^3] <6.38
$1.91<u$ [m/s] <22	$1.74\times10^{-5}<\mu$ [Pa s] $<3.58\times10^{-5}$
$0.015<$ riser diameter [m] <0.068	$2.75<$ riser height [m] <6.46

Table 2 summarizes experimental conditions of the data. Fig. 6 compares the measured riser pressure drop and solids flux in the riser with values predicted by correlations. On the data of Yin et al. [10], Eq. (8) often seems to overestimate considerably the pressure drop due to particle acceleration, bringing about negative riser pressure drop. Therefore, the pressure drop due to particle acceleration was neglected in case of the data of Yin et al. [10]. Table 2 also gives the average relative deviation (ARD) of correlation from data in each group.

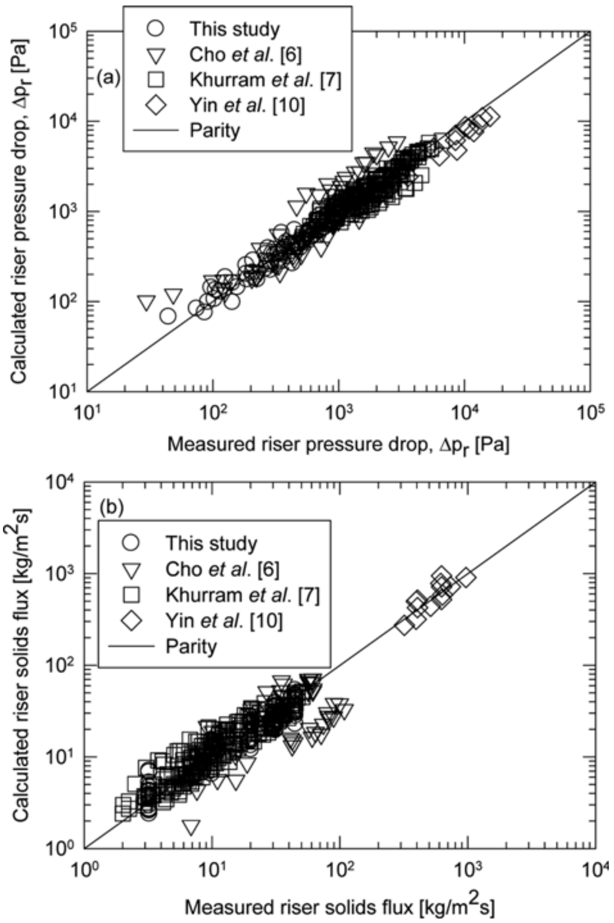

Fig. 6. Comparison between measured and calculated pressure drop and solids flux.

$$\mathrm{ARD}=\frac{\Sigma_i^N\left(\frac{|Y_{mea}-Y_{cal}|}{Y_{mea}}\right)i}{N} \quad (16)$$

The accuracy of correlation was reasonable in riser pressure drop, but the correlation on solids flux needed further improvement with

Table 2. Experimental conditions for data used in correlations

Authors	Solids	Mean size [mm]	Apparent density [kg/m^3]	Riser diameter [mm]	Riser height [m]	Gas velocity [m/s]	Gs [kg/m^{2}s]	Pressure [kPa-abs]	Average relative deviation (ARD) [%]	
									Δp_r	Gs
Yin et al. [10]	Glass bead	0.137	2490	68	5.2	4.20-22	395-969	101-507	26.7	17.9
Cho et al. [6]	FCC	0.0799	1588	25	3	3-7	7.75-122	101	16.2	35.5
	Glass bead	0.0926	2480						113	66.9
	Plastic powder	0.348	918						48.7	36.3
Khurram et al. [7]	Glass bead	0.0545	2440	25	2.75	2.1-6.2	2-50	101-405	14.8	32.7
		0.130	2440						9.42	16.3
		0.283	2440						19.1	22.8
		0.646	2440						28.9	78.5
This study	Sorbent	0.0943	1370	15	6.46	1.91-3.84	3.23-44.9	101	15.6	22.4

Table 3. Comparison of pressure drop and solids flux measured by Johnsson and Leckner [18] with ones calculated with correlations of this study

No.	d_p [mm]	x_c [-]	u [m/s]	u_t [m/s]	$\Delta p_{r, mea}$ [kPa]	$\Delta p_{r, cal}$ [kPa]	$G_{s, mea}$ [kg/m^{2}s]	$G_{s, cal}$ [kg/m^{2}s]
1	0.20	0.15	2.7	1.25	8.32	2.94	18	54.3
2	0.32	0.08	4.7	2.98	7.91	2.92	45	113
3	0.32	0.15	3.5	2.98	6.91	1.54	7.1	41.5
4	0.32	0.25	3.2	2.98	5.85	1.53	5.4	25.9

Temperature 850 °C, pressure 1 atm-abs, flue gas, apparent particle density 2,600 kg/m^3, riser cross-sectional area 1.5×1.4 m^2, riser height 13.5 m

efforts for understanding details of the basic mechanism on momentum transfer from gas to solids in the future.

There are scant studies on the high temperature CFB riser that give all information on solids circulation rate, pressure drop across the riser and gas velocity. Table 3 compares pressure drop and solids flux measured in the riser of a pilot-scale CFB combustor by Johnsson and Leckner [18] with values predicted by correlations of this study. They determined the net solids flux from the solids concentration at the gas exit as $G_s=\rho_{exit}(u-u_t)$. In their bed material, there was a considerable number of coarse particles greater in diameter than the size of which terminal velocity was equal to the gas velocity. The correlation of this study underestimates the riser pressure drop but overestimates the solids flux. Fig. 7 compares experimental data of this study with correlation of Lee et al. [9]. Their correlation underestimated the riser pressure drop but overestimated the solids flux in the riser, as expected, because the correlation was based on some data obtained at gas velocities smaller than the terminal velocity. Table 4 compares riser pressure drop and solids flux measured by Lee et al. [9] with values predicted with correlations of this study. It was regarded that all solids were present in the riser and loopseals, and the amount of secondary gas was neglected because information was not available. In addition, a considerable number of coarse particles greater in diameter than the size of which terminal velocity was equal to the gas velocity was present in their bed material. The correlations of this study overestimated in riser pressure drop but underestimated in solids flux. Now, discrepancies in riser pressure drop of Tables 3 and 4 were assumed to contain the scale-up effect in riser specifications and the effect of the coarse particles. These effects must be identified in future study to improve correlations. The discrepancies in solids circulation rate would come from those in riser pressure drop. However, as can be seen in Tables 3 and 4, correlations of this study were able to predict in large scale systems similar values with measured ones in order of magnitude.

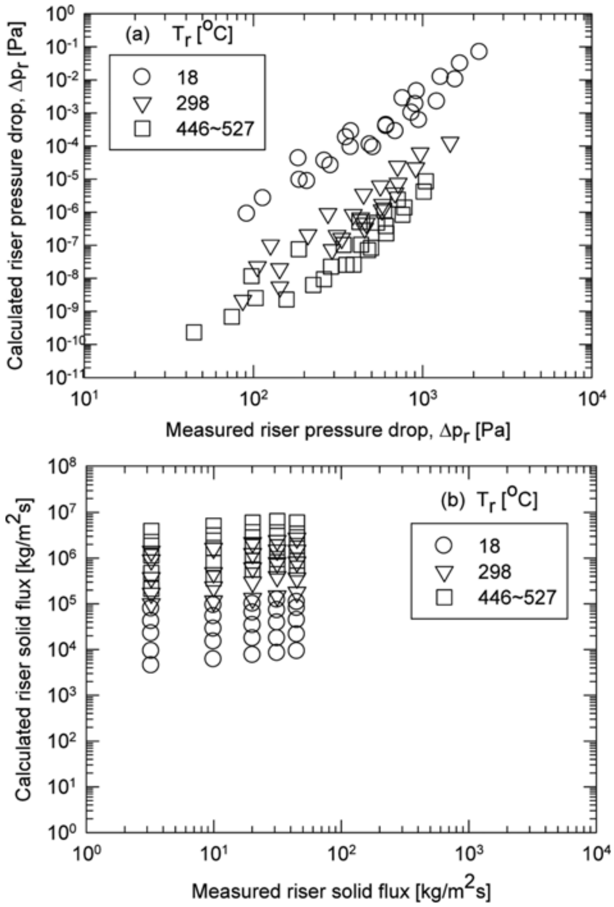

Fig. 7. Comparison of correlation of Lee et al. [9] with experimental data of this study.

CONCLUSIONS

We investigated effects of temperature on pressure drop across the riser of a CFB, due to the solids holdup in the riser, and came to the following conclusions:

Under the conditions of fixed gas velocity and solids flux in the riser, the pressure drop across the riser decreased as temperature

Table 4. Comparison of pressure drop and solids flux measured by Lee et al. [9] with ones calculated with correlations of this study

No.	M [kg]	x_c [-]	u [m/s]	u_t [m/s]	$\Delta p_{r, mea}$ [kPa]	$\Delta p_{r, cal}$ [kPa]	$G_{s, mea}$ [kg/m^{2}s]	$G_{s, cal}$ [kg/m^{2}s]
1	100	NR	1.8	1.69	5.84	12.7	13.0	3.69
2	150	NR	1.9	1.69	8.97	15.5	20.5	7.35
3	200	NR	1.9	1.69	12.1	16.4	22.3	10.7

Ambient temperature and pressure, air, mean particle diameter 0.199 mm, apparent particle density 2,800 kg/m^3, riser cross-sectional area 0.25×0.62 m^2, riser height 10 m, NR: not readable increased. Temperature effects decreased with increasing the gas velocity. The effects of temperature on riser pressure drop were confirmed qualitatively by the same effects on the average ratio of gravity to drag force on a single spherical particle while the particle was accelerated. The pressure drop across the riser increased linearly with the mass ratio of solids to gas at a given gas velocity. The slope of the linear relationship decreased as temperature increased. This result affirmed under the high temperature conditions the validity of the concept of Khurram et al. [7] on momentum transfer from gas to particles: the gas momentum per mass of gas available to lift solid particles was finite, the gas momentum shared to the unit mass of solids decreased with increase in solids flux at the given gas velocity. Thus the slope of the linear relationship between the riser pressure drop and the ratio of solids to gas in mass flux was proportional to the ratio of momentum flux by gravity and buoyancy forces on solids to gas momentum per unit mass of gas by drag force transferred to solids. Correlations to predict effects of temperature on pressure drop across the riser and associated solids circulation rate in the riser were proposed within the range of experimental conditions.

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NOMENCLATURE

A_p : projection area of a single particle [m^2]
C_d : drag coefficient [-]
D : riser diameter [m]
d_p : particle diameter or specific surface mean diameter [m]
F_d : drag force acting on the particle surface [N]
f_g : fanning friction coefficient [-]
f_s : friction coefficient for solids-wall friction [-]
g : gravitational acceleration, 9.8 [m/s^2]
G_s : solids flux in the riser [kg/m^2s]
H : riser height [m]
M : total solids inventory in the CFB system [kg]
Δp_{ac} : pressure drop due to particle acceleration [Pa]
Δp_{fg} : pressure drop by gas-wall friction [Pa]
Δp_{fs} : pressure drop by solids-wall friction [Pa]
Δp_r : riser pressure drop caused by solids inventory [Pa]
Δp_{ro} : overall riser pressure drop [Pa]
Re : Reynolds number, $Du\rho_g/\mu$ [-]
Re_p : particle Reynolds number, $d_p u\rho_g/\mu$ [-]
r^2 : correlation coefficient [-]
T_r : riser temperature [°C]
u : superficial gas velocity in the riser [m/s]
u_t : terminal velocity [m/s]
u_{tr} : transport velocity [m/s]
x : mass fraction [-]
x_c : fraction of coarse particles greater than the diameter of which terminal velocity is equal to u [-]
Y : dependent variable [Pa or kg/m^2s]

Greeks

α : proportional constant [s]
ε : average gas holdup in the riser [-]
ε_s : average solids holdup in the riser [-]
μ : gas viscosity [Pa s]
ρ_{exit} : solids concentration at the gas exit [kg/m^3]
ρ_g : gas density [kg/m^3]
ρ_s : apparent particle density [kg/m^3]

Subscripts

cal : calculated
i : data number [-]
mea : measured
N : number of data [-]

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