Hindawi
International Journal of Chemical Engineering
Volume 2019, Article ID 6454958, 9 pages
https://doi.org/10.1155/2019/6454958

Research Article

Experimental Quantification of Local Pressure Loss at a 90° Bend in Low-Pressure Dilute-Phase Pneumatic Conveying of Coarse Particles

Rui Zhu,[1] Chunsheng Luo,[2] Xin Li,[2] and Fei Yan[2]

[1]*School of Environmental and Chemical Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, China*
[2]*School of Mechanical Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, China*

Correspondence should be addressed to Fei Yan; fyan716@163.com

Received 9 January 2019; Accepted 6 March 2019; Published 1 April 2019

Academic Editor: Doraiswami Ramkrishna

Focusing on the insufficient estimation of the local pressure loss at a 90° horizontal-vertical bend in low-pressure pneumatic conveying of coarse particles, experiments are conducted in a 80 mm inner diameter test bend by using polyethylene particles having an equivalent spherical diameter of 4.00 mm. The influences of the local pressure loss versus the gas flow Reynolds number, the solid-gas ratio, and the bending radius ratio are investigated. Based on the additional pressure theory of Barth, an empirical formula estimating the local pressure loss is obtained using dimensional and nonlinear regression analysis. Summarizing the experiments and literature, the results expound on the local gas flow pressure loss coefficient decreases with increasing Reynolds number, and first decreases and then increases with increasing bending radius ratios from 0.5 to 7. The additional solid flow pressure loss coefficient decreases with the increasing Reynolds number and bending radius ratio in the dilute phase, and linearly increases with increasing solid-gas ratio. Compared with the estimated values with the experimental values, the calculated standard deviation is below 4.11%, indicating that the empirical formula can be used to predict local pressure loss at the bend in the low-pressure dilute-phase pneumatic conveying.

1. Introduction

To improve the flexibility of the pneumatic conveying system, a bend is usually regarded as an important component in the process route. However, a bend makes the flow situation complicated and causes a sharp pressure loss. Especially in engineering, pressure loss is typically used as a key parameter to guide and design pneumatic conveying systems. Hence, to reasonably estimate the local pressure loss through a bend is very significant for pneumatic conveying systems.

Considering the universality of the 90° bend of a circular cross section, it has been applied and studied by numerous researchers. Cornish and Charity [1] listed all the important parameters (e.g., gas density and viscosity, particle density and size, bend curvature radius and diameter, the conveying velocity, and mass flow rate) of the local pressure loss at a 90° bend for a given pneumatic conveying system and found that the local pressure loss is higher for a short bend curvature radius and linearly increases with the increasing solid-gas ratio (i.e., the mass flow rate of solids to gas). Ghosh and Kalyanaraman [2] studied the local pressure loss in dilute-phase (solid-gas ratio <5.3) pneumatic conveyance of coarse particles (e.g., wheat) for a horizontal-horizontal bend. The results show that the additional pressure loss coefficient is constant for all conveying velocities and is a linear function of the solid-gas ratio. Singh and Wolfe [3] considered the angle of bend deflection (i.e., change in flow direction), the changes of local pressure loss versus the conveying velocity, the mass flow rate of solids, and the bend curvature radius were investigated in the pneumatic conveying. An empirical formula for local pressure loss was deduced, but the impact of gravity was neglected. Mason and Smith [4] and Rossetti

[5] reported that the local pressure loss includes gas flow and additional pressure loss of solids. They took the local pressure loss of gas-only flow for a constant, and the additional pressure loss of solids is closely correlated with the particle terminal velocity. Westman et al. [6], based on the additional pressure theory of Barth [7], found that larger curvature radius bends produce lower pressure loss in vacuum pneumatic conveying systems. An empirical formula for local pressure loss was derived from the gas-velocity at the bend exit. Yu and Wang [8] fully considered the bend pressure loss upstream and downstream, where the gas-solid flow was impacted by the bend. They found that the local pressure loss increases with increasing solid-gas ratio in dense-phase conveying of powder and derived an empirical formula for estimating local pressure loss. However, its applicability is limited due to only one bending radius ratio (i.e., the bend curvature radius to diameter). Pan and Chi [9] investigated the effects of local pressure loss for different angles and short curvature radius bends. The results show that the local pressure loss (gas only) decreases with the increasing bend angle and curvature radius, and it proportionally increases with the increasing solid-gas ratio. Moreover, the gas-solid flow was difficult to fully develop in the short straight pipe after the bend. Pan [10] proposed an accurate way of estimating the local pressure loss at a bend (here, the straight pipe and bend are separately dealt with) in high-pressure conveying of fly ash. Based on numerous experiments, a semi-empirical formula was set up to predict additional pressure loss using mathematical and dimensional analyses and starting from the bend exit conditions. After that, Pan and Wypych [11] also considered the compressibility of gas flow due to conveying pressure and mixed particles. On the basis of Barth's [7] and Ito's [12] researches, the semiempirical formula [10] of local additional pressure loss was corrected by the bend exit conditions (e.g., average gas density, velocity, and solid-gas ratio). Furthermore, Das and Meloy [13] found that the local pressure loss through a double-coupled bend conveying solid material is not equivalent to the cumulative effect of two separated bends. The local pressure loss in a double-coupled double bend is less than twice of that in a single bend. Liang et al. [14] considered the influences of the different materials, bend curvature radii, and locations (i.e., horizontal-horizontal, horizontal-vertical, and vertical-horizontal bends) in high-pressure dense-phase of pulverized coal conveying. They found that the pressure loss of a horizontal-vertical bend is the largest than the horizontal-horizontal and vertical-horizontal bends, and the local pressure loss increases with increasing coal size. Accordingly, the corresponding empirical formulas of different bend locations were obtained to estimate the additional pressure loss using Barth's theory [7] and multivariate regression analysis.

Recently, in order to study the applicability of the present empirical formulas, Naveen et al. [15] compared the values calculated by the formulas [3, 5, 6, 10, 11, 13] with experimental values in conveying fly ash, and the results indicate that only the empirical formulas of Pan [10] and Pan and Wypych [11] could be applied to estimate the local pressure loss at bends in a dilute-phase regime. However, the formulas in [10, 11] were only verified in the pneumatic conveying of powders (e.g., fly ash and pulverized coal), and the flow parameters (e.g., gas density, gas velocity, and mass flow rate) of gas-solid flow at the bend exit are difficult to obtain, causing the inconvenience in the design of dilute-phase pneumatic conveying systems in the beginning. In addition, previous literature is almost aimed at the powders [3–5, 7–10, 12–14] or high-pressure pneumatic conveying [9, 10, 13–15]. From the above, the local pressure loss estimates for a bend in low-pressure dilute-phase pneumatic conveying (e.g., air supply from roots blower) of coarse particles are very insufficient.

In this study, based on a low-pressure dilute-phase pneumatic conveying system, the influences of local pressure loss arising from the change of superficial conveying gas velocity, particle mass flow rate, and bending radius ratio are investigated in a horizontal-vertical 90° bend. Meanwhile, to provide theoretical support for designing the low-pressure dilute-phase pneumatic conveying systems as conveying the coarse particles, an empirical formula of the local pressure loss is derived using dimensional and nonlinear regression analysis.

2. Experimental Apparatus

The experimental apparatus of the low-pressure pneumatic conveying system is shown in Figure 1. The system consists of a fan, feed bin, rotary value, separator, bag filter, and several section pipes. The test pipeline frame has a horizontal length $L = 4.0$ m and a vertical height $H = 2.5$ m, connected by two 90° bends and a short straight pipe. The pipes are made of organic glass and have the same inner diameter $D = 80\,\text{mm} \pm 5.85\%$. When conveying, air from the fan blows away the particles fed by the rotary value into the test pipeline, and then, the gas-solid mixture is separated by the separator at the pipeline exit. Meanwhile, the gas flow rate and pressure are measured by the orifice meter and four pressure sensors (P_1, P_2, P_3, and P_4), and the particle mass flow rate is controlled by the rotation speed of the rotary value.

Figure 2 shows three different bend radii of $R = 300$ mm, 400 mm, and 500 mm. They are named as *R*300, *R*400, and *R*500 and corresponded to ratios of curvature radius and inner diameter $R/D = 3.75$, 5, and 6.25, respectively. Figure 3 shows the experimental particle made of polyethylene with an equivalent spherical diameter of $d_s = 4.00\,\text{mm} \pm 5.16\%$. The particles density $\rho_s = 952\,\text{kg/m}^3$, and bulk density $\rho_b = 563\,\text{kg/m}^3$.

3. The Local Pressure Loss

3.1. The Local Pressure Loss of Gas Flow. Figure 4 shows the local gas flow pressure loss (Δp_{eg}) versus the different conveying velocities (U_g) and the bend radii (R). Clearly, the local pressure loss increases with increasing superficial conveying velocity and bend radius. Researchers [16–21] found that the local pressure loss is mainly generated by the flow separation emerging at the concave inner wall and the

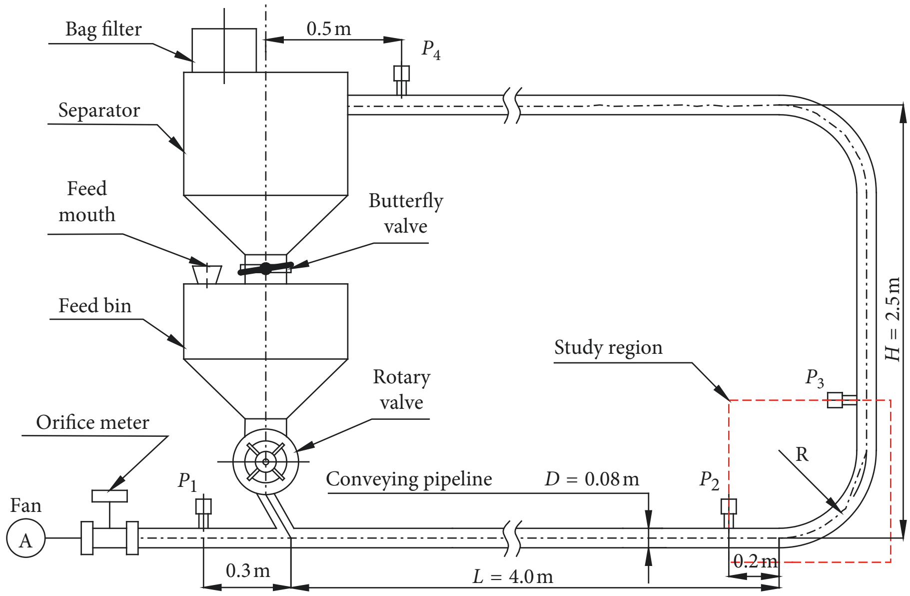


Figure 1: Diagram of experimental apparatus.

Figure 2: Bends.

Figure 3: Experimental particles.

secondary flow arising from the radial pressure gradient at bend. Therefore, with increasing superficial conveying velocity, the flow separation and secondary flow are enhanced by the increased inertial force and radial pressure gradient in the bend [18, 20]. And in the case of the same gas velocity, the flow separation and the secondary flow can be weakened by the large bend radius; however, the wall friction is the dominant factor contributing to pressure loss in the bend [21]. The more pressure loss is generated for the more flow distance.

3.2. The Local Pressure Loss of Gas-Solid Flow. Figure 5 shows the local gas-solid flow pressure loss (Δp_e) for the different bend radii at $G_s = 0.3$ and 0.5 kg/s. It is obvious that the local gas-solid flow pressure loss (Δp_e) decreases first and then increases with increasing conveying velocity. There exists a gas velocity of the minimum local pressure loss, defined as the optimum conveying velocity. As proposed by Zenz [22], the optimum conveying velocity is the critical point between the dense-phase (the gas velocity is lower than the optimum conveying velocity) and dilute-phase (the gas velocity is larger than the optimum conveying velocity) in the same mass flow rate and bend radius. In a dense-phase, higher pressure loss is arisen from the dune flow, slug flow, and other unstable flows in the pipe; serious friction is occurred between the massive particles and the pipe; and the bend can even be blocked by particles lacking kinetic energy in the pattern of dune flow or slug flow. Whereas, in dilute-phase, stratified flow, suspended flow, and other stable flows are distributed in the pipe. The particle kinetic energy is enhanced by increasing conveying velocity, causing violent and frequent collisions among particle and other particles or pipe walls. Hence, very larger conveying velocity can result in larger pressure loss [23, 24].

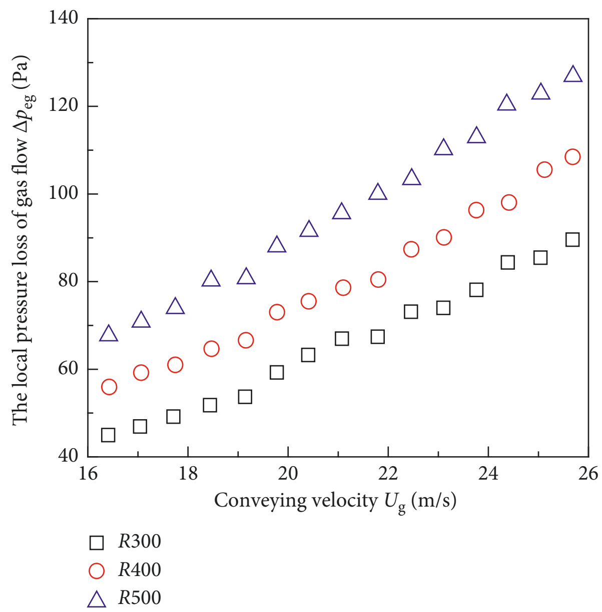


FIGURE 4: The local pressure loss of airflow versus conveying velocities and bend radii.

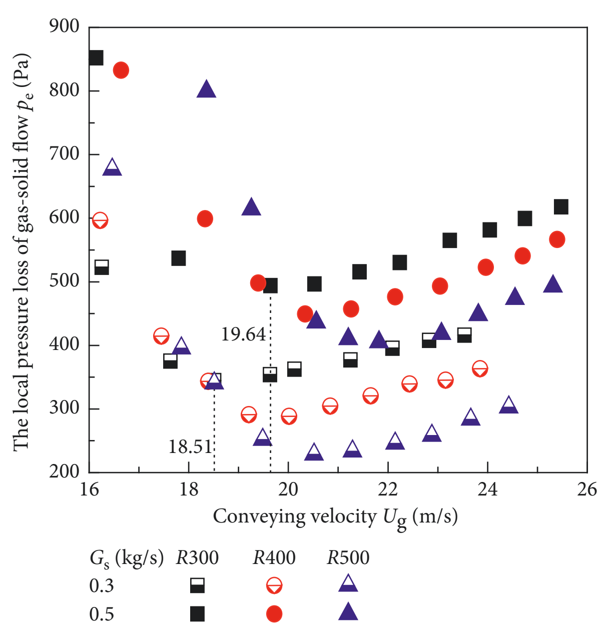


FIGURE 5: The local pressure loss of gas-solid flow for the different bend radii at $G_s = 0.3$ and 0.5 kg/s.

In addition, Figure 5 also obviously shows the local gas-solid flow pressure loss increases with increasing mass flow rate (G_s) in the same bend. The reason is that with the increase of the mass flow rate, the increase of the solid-gas ratio consumes massive gas kinetic energy [24, 25]. In the same mass flow rate, the local gas-solid flow pressure loss increases with increasing bend radius in the lower gas velocity region ($U_g < 18.51$ m/s for $G_s = 0.3$ kg/s; and $U_g < 19.64$ m/s for $G_s = 0.5$ kg/s), but decreases with increasing bend radius in the larger gas velocity region ($U_g > 18.51$ m/s for $G_s = 0.3$ kg/s; and $U_g > 19.64$ m/s for $G_s = 0.5$ kg/s). These phenomena are similar to the conclusions of Pan [10]. Because friction pressure loss plays the leading role in lower gas velocity, the pressure loss is increased by the long sliding distance in the larger bend radius means. And the gravity pressure loss is also increased by the higher height of the larger radius means at the horizontal-vertical bend. However, at higher gas velocity, the inertial centrifugal force of the gas-solid flow is decreased by the larger bend radius for the same mass flow rate and bend radius, and collisions between particles and walls are reduced for the slow vector change of gas-solid flow and lessened flow separation [24–27].

4. Model of Pressure Loss

To set up a formula for estimating the local pressure loss through a horizontal-vertical bend, according to the additional pressure theory of Barth [7], the local gas-solid flow pressure loss through bend Δp_e consists of the pressure loss of gas-phase Δp_{eg} and additional pressure loss of solid-phase Δp_{es}, which can be expressed as follows:

$$\Delta p_e = \Delta p_{eg} + \Delta p_{es},$$
$$\Delta p_{eg} = \zeta_{eg} \frac{\rho_g U_g^2}{2}, \tag{1}$$
$$\Delta p_{es} = \zeta_{es} \frac{\rho_g U_g^2}{2},$$

where ζ_{eg} is the local pressure loss coefficient of gas flow, ζ_{es} is the additional pressure loss coefficient of solid flow, ρ_g is the density of gas, and U_g ($U_g = Q_g/A$) is the superficial conveying velocity, in which Q_g is the volume flow rate of gas flow and A is the conveying pipe sectional area.

Since the local gas flow pressure loss coefficient ζ_{eg} is mainly impacted by the gas velocity and bend radius, the additional solid flow pressure loss coefficient ζ_{es}, besides the above factors, is also impacted by the particle mass flow rate. Hence, they can be expressed as follows:

$$\begin{cases} \zeta_{eg} = f\left(U_g, R\right), \\ \zeta_{es} = f\left(G_s, U_g, R\right). \end{cases} \tag{2}$$

And after nondimensional disposal, it follows the following equation:

$$\begin{cases} \zeta_{eg} = f\left(\mathrm{Re}, \dfrac{R}{D}\right), \\ \zeta_{es} = f\left(m_s, \mathrm{Re}, \dfrac{R}{D}\right), \end{cases} \tag{3}$$

where $m_s = G_s/\rho_g U_g A$ is the solid-gas ratio and $\mathrm{Re} = \rho_g U_g D/\mu_g$ is the Reynolds number in which μ_g denotes the gas viscosity.

4.1. The Local Pressure Loss Coefficient of Gas Flow. Figure 6 shows the relationship between the local gas flow pressure loss coefficient (ζ_{eg}), the Reynolds number (Re), and

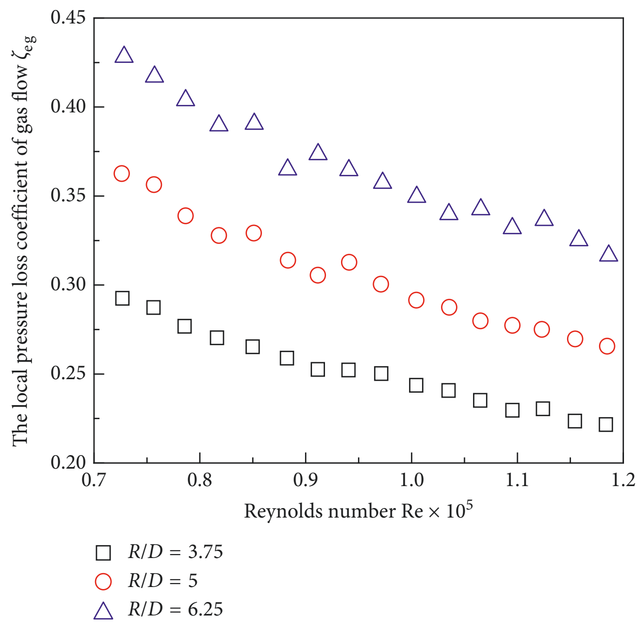


FIGURE 6: Relationships between local pressure loss coefficient (only airflow) and Reynolds number for the different bend radii.

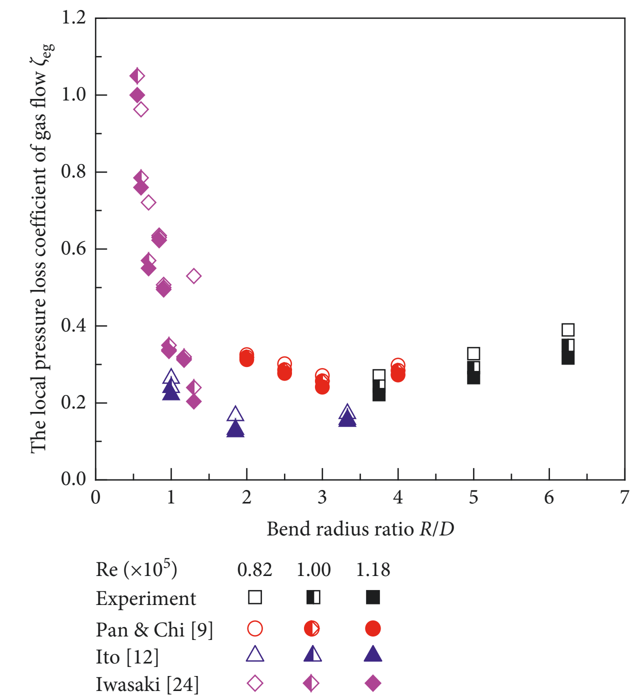


FIGURE 7: Relationships between local pressure loss coefficient (only airflow) and bend radii for the different Re.

the bending radius ratio (R/D). It is evident that ζ_{eg} decreases with increasing Reynolds number from 0.7×10^5 to 1.2×10^5 and increases with the increasing bending radius ratio. According to previous researchers [6, 12, 28, 29], the local pressure loss coefficient (only airflow) ζ_{eg} tends to be stable with increasing Reynolds number. Therefore, the ζ_{eg} can be inversely correlated proportional to the Reynolds number.

To investigate the change in ζ_{eg} with increasing bending radius ratio from 0.5 to 7 in detail, the researches [9, 12, 30] that have the similar test conditions are considered, as shown in Figure 7. It is obvious that ζ_{eg} is quickly decreased and then increased at Reynolds numbers $\mathrm{Re} = 0.82 \times 10^5$, 1.00×10^5, and 1.18×10^5. This result indicates that the relationship between ζ_{eg} and the radius ratio R/D can be correlated to the *Nike function* [31] (Figure 8).

Accordingly, the local pressure loss coefficient (only airflow) ζ_{eg} is deduced by using the nonlinear regression analysis as follows:

$$\zeta_{eg} = \frac{4.452}{\mathrm{Re}^{0.593}} \left(6.55 \left(\frac{R}{D} \right)^{1.25} + \frac{88.66}{(R/D)^{1.25}} \right). \tag{4}$$

In this study, nonlinear regression and analysis of variance (ANOVA) are used to analyse the reliability of the model for the local pressure loss coefficient (only airflow), as shown in Table 1. The $R^2 = 0.921 \approx 1$ and adj-$R^2 = 0.904$ indicate that the fitted model has high accuracy in the 95% confidence interval. Meanwhile, compared fitted with experiment values, as shown in Figure 9, the relative deviation stays between −2.69% and +4.54%, and the calculated standard deviation is 1.52%, proving the reliability of this fitted model.

4.2. The Additional Pressure Loss Coefficient of Solid Flow. Figure 5 illustrates that lower gas velocity is bad for pneumatic conveying in unstable flow. Aiming at industrial

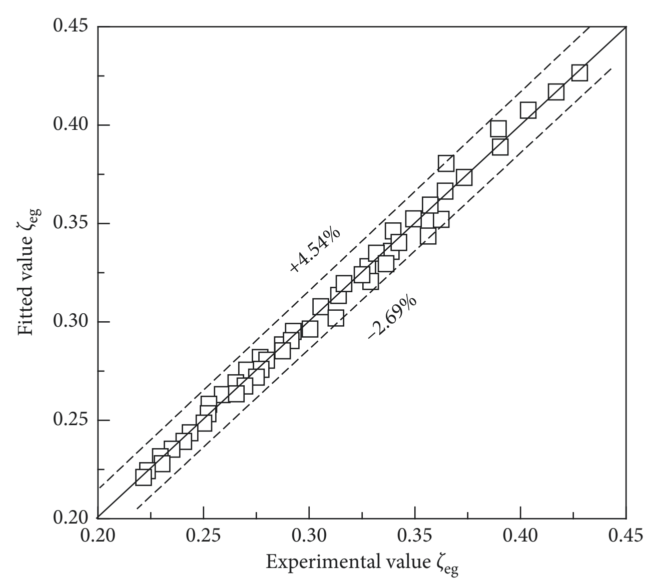
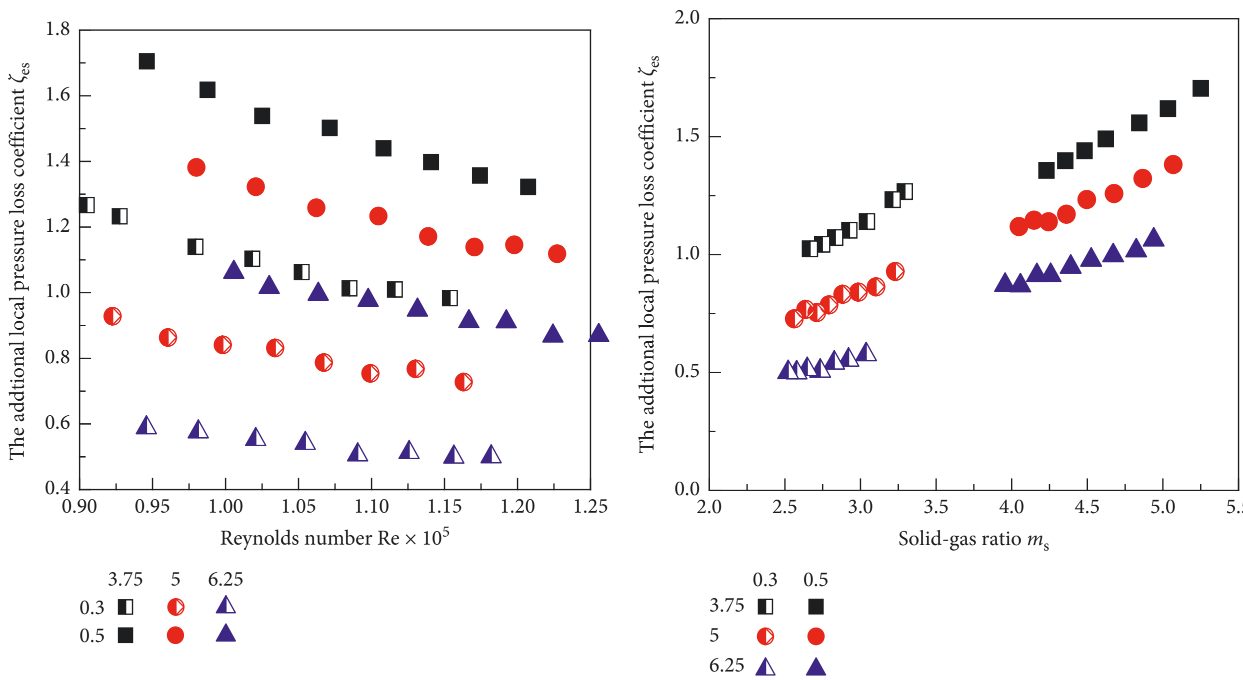


FIGURE 8: Comparison of local pressure loss coefficient (only airflow) between the experimental values and the fitted values.

processes, the gas velocity is usually designed larger than the optimum conveying velocity to prevent pipeline blockage. Accordingly, Figure 10 shows the relationship between the additional solid flow pressure loss coefficient (ζ_{es}) and the Reynolds number (Re), the bending radius ratio (R/D), and the solid-gas ratio (m_s) in dilute-phase pneumatic conveying. As shown in Figure 10(a), it is evident that ζ_{es} decreases with increasing Re and R/D (3.75~6.25). As shown in Figure 10(b), ζ_{es} is increased in proportion to the increasing solid-gas ratio m_s.

Table 1: Analysis of nonlinear regression.

Model : $\zeta_{eg} = \frac{a}{\mathrm{Re}^b}\left(c \cdot \left(\frac{R}{D}\right)^n + \frac{d}{(R/D)^n}\right)$					
Terms	Estimate	Standard error		R^2	
a	4.452	0.161			
b	0.593	0.035			
c	6.55	0.022		0.921	
d	88.66	0.068			
n	1.25	0.083			
ANOVA for significance of regression (adj-$R^2 = 0.904$)					
Source	DF	Sum of squares	Mean square	F value	p value
Model	5	4.674	0.9348	45495.96	0.000
Residual error	43	0.001	2.57×10^{-5}		
Total	48	4.675			



(a)

(b)

Figure 9: Relationships between the additional pressure loss coefficient of solid flow and (a) Reynolds number and (b) solid-gas ratio.

Accordingly, the additional solid flow pressure loss coefficient of ζ_{es} could be deduced by nonlinear regression analysis:

$$\zeta_{es} = \frac{1.353 m_s^{0.85}}{\mathrm{Re}^{0.13} (R/D)^{0.882}}. \quad (5)$$

In this study, nonlinear regression and ANOVA are used to analyse the reliability for the additional solid flow pressure loss coefficient, as shown in Table 2. The $R^2 = 0.907 \approx 1$ and adj-$R^2 = 0.892$ indicate that this fitting model has high accuracy in the 95% confidence interval. Meanwhile, the comparison between the fitted and experiment values are shown in Figure 9, the relative deviation stays between −9.992% and +7.754%, and the calculated standard deviation is 4.52%, which could prove the reliability of this model.

4.3. The Verification of Prediction Model for Pressure Loss. To verify the model reliability, the gas flow pressure loss values from experiment and prediction at a bend are compared in Figure 11(a) and the pressure loss values of gas-solid flow are compared in Figure 11(b) in the case of dilute-phase pneumatic conveying. The results show that the relative deviation of gas flow pressure loss stays between −5% and +5%, and the calculated standard deviation is 3.52%. Meanwhile, the relative deviation of gas-solid flow pressure loss stays between +10% and −10%, and the calculated standard deviation is 4.11%, which indicate that the local pressure loss is more accurately predicted by the empirical formulas in this paper.

5. Conclusions

To accurately estimate the local pressure loss in low-pressure dilute-phase pneumatic conveying of coarse particles, in this

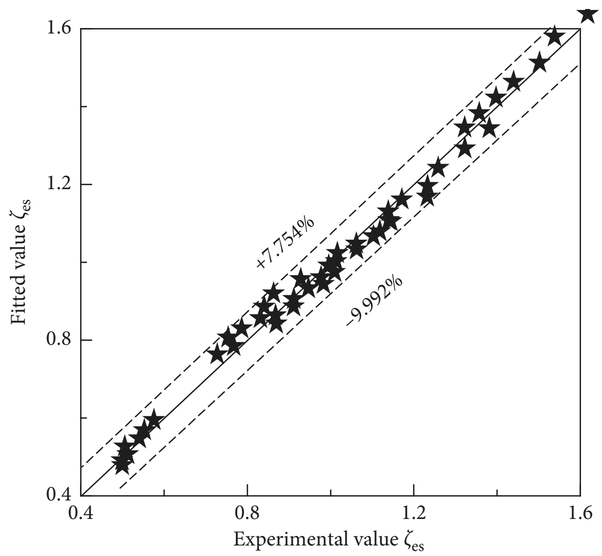


Figure 10: Comparison of the additional pressure loss coefficient of solid flow between experimental values and predicted values.

Table 2: Analysis of nonlinear regression.

Model : $\zeta_{es} = \dfrac{am_s^b}{Re^c (R/D)^d}$			
Term	Estimate	Standard error	R^2
a	1.186	0.080	0.907
b	0.781	0.024	
c	0.196	0.069	
d	0.712	0.039	

ANOVA for significance of regression (adj-$R^2 = 0.892$)

Source	DF	Sum of squares	Mean square	F value	p value
Model	4	53.21	13.30	3678.98	0.000
Residual error	44	0.155	0.004		
Total	48	53.365			

study, the influences arising from different superficial conveying velocities, particles mass flow rates, and bending radius ratios are investigated in a horizontal-vertical 90° bend. Considering the gravity pressure loss, the empirical formula of the local pressure loss is derived using dimensional and nonlinear regression analysis. The significant conclusions are as follows:

(1) In the experiment, the local pressure loss of gas flow increases with increasing conveying velocity and bend curvature radius

(2) For the short straight pipe, a long radius bend causes the large local pressure loss at lower conveying velocity and low local pressure loss at higher conveying velocity for gas-solid flow

(3) Synthesized from the present work and previous researches, the local gas flow pressure loss coefficient decreases with increasing Reynolds number, first decreases and then increases with the increasing bending radius ratio from 0.5 to 7

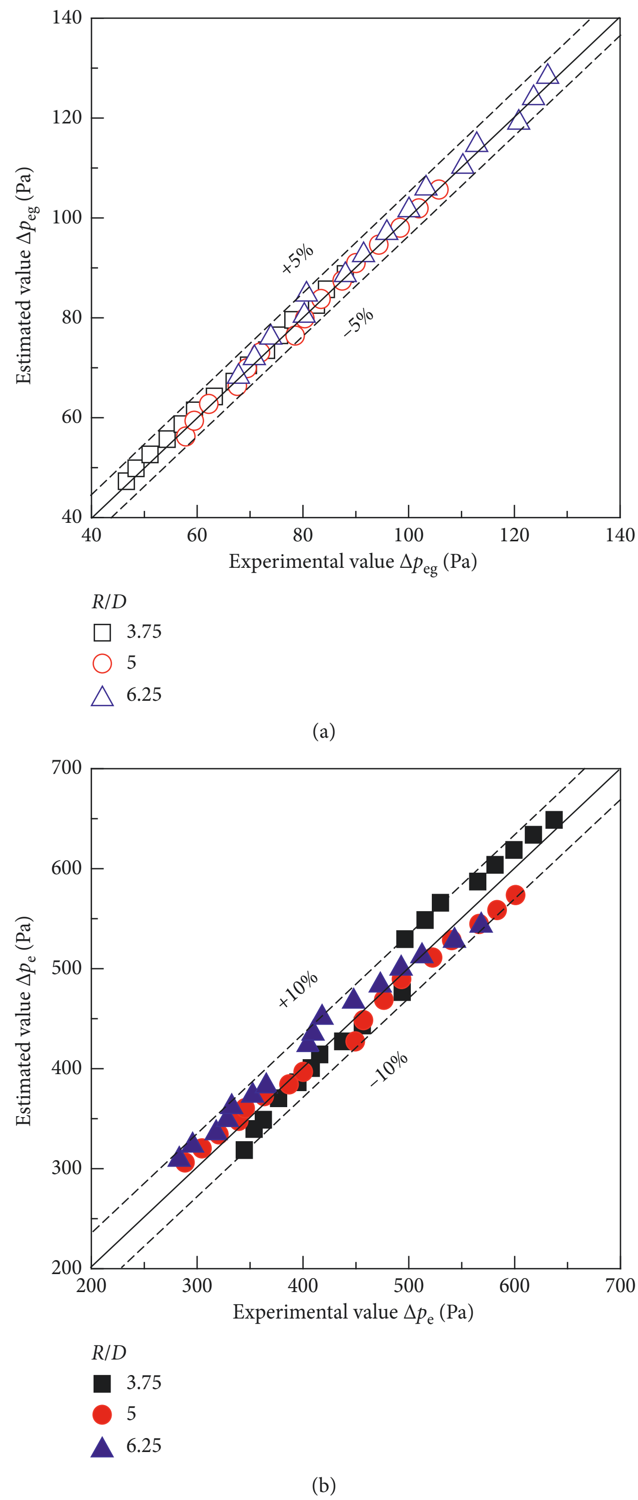


Figure 11: The deviation between the experimental value and the predicted value of the local pressure loss of gas-solid flow.

(4) The additional pressure loss coefficient of solid flow decreases with the increasing Reynolds number and bending radius ratio and increases in proportion with the increasing gas-solid ratio

(5) From the comparison of the estimated local pressure loss values with experimental values in a horizontal-

vertical 90° bend, the relative deviation is ±10% and the calculated standard deviation is below 4.11%

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors acknowledge the support from the Natural Science Foundation of Jiangsu Province of China (nos. BK20180978 and BK20140512) and Scientific Research Foundation for Returned Overseas Chinese Scholars, State Education Ministry.

References

[1] G. K. Cornish and L. F. Charity, "Pressure drop in elbows of a pneumatic conveying system," *Transactions of the ASAE*, vol. 9, pp. 29–31, 1966.

[2] D. P. Ghosh and K. Kalyanaraman, "Pressure drops due to solids around horizontal elbow bends during pneumatic conveyance," *Journal of Agricultural Engineering Research*, vol. 15, no. 2, pp. 117–128, 1970.

[3] B. Singh and R. R. Wolfe, "Pressure losses due to bends in pneumatic forage handling," *Transactions of the ASAE*, vol. 15, pp. 246–248, 1972.

[4] J. S. Mason and B. U. Smith, "Pressure drop and flow behaviour for the pneumatic transport of fine particles around 90 degree bends," in *Proceedings of the Pneumotransport 2nd International Conference on the Pneumatic Transport of Solids in Pipes*, vol. 2, pp. 17–32, Guildford, England, March 1973.

[5] S. J. Rosseti, "Concepts and criteria for gas-solids flow," in *Handbook of Fluids in Motion, Cheremisinoff and Ramesh Gupta*, P. Nicholas, Ed., pp. 635–652, Ann Arbor Science Publishers, Ann Arbor, MI, USA, 1983.

[6] M. A. Westman, E. E. Michaelidies, and F. M. Thompson, "Pressure losses due to bends in pneumatic conveying," *Journal of Pipelines*, vol. 7, pp. 15–20, 1987.

[7] W. Barth, "Strömungsvorgänge beim Transport von Festteilchen und Flüssigkeitsteilchen in Gasen. mit besonderer Berücksichtigung der Vorgänge bei pneumatischer Förderung," *Chemie Ingenieur Technik*, vol. 30, no. 3, pp. 171–180, 1958.

[8] R. X. Yu and W. Q. Wang, "Pressure loss in the pneumatic transport of powder and particle through the pipe bend," *Journal of Southeast University*, vol. 19, pp. 49–54, 1989.

[9] W. G. Pan and Z. H. Chi, "Study on tho pressure drop characteristics and methods for calculating gas and gas-solid flow in circular bends," *Journal of Zhejiang University*, vol. 31, pp. 804–811, 1997.

[10] R. Pan, *Improving scale-up procedures for the design of pneumatic conveying systems*, Ph.D. dissertation, University of Wollongong, Wollongong, Australia, 1992.

[11] R. Pan and P. W. Wypych, "Dilute and dense phase pneumatic conveying of fly ash," in *Proceedings of the 6th International Conference on Bulk Materials Storage and Transportation Wollongong*, pp. 183–189, Wollongong, Australia, September 1998.

[12] H. Ito, "Pressure losses in smooth pipe bends," *Journal of Fluids Engineering*, vol. 82, pp. 1–131, 1960.

[13] P. K. Das and J. R. Meloy, "Effect of close-coupled bends in pneumatic conveying," *Particulate Science and Technology*, vol. 20, no. 4, pp. 253–266, 2002.

[14] C. Liang, L. Shen, P. Xu et al., "Comparison of pressure drops through different bends in dense-phase pneumatic conveying system at high pressure," *Experimental Thermal & Fluid Science*, vol. 57, pp. 11–19, 2014.

[15] T. Naveen, S. Atul, S. S. Mallicka, and P. W. Wypych, "Energy loss at bends in the pneumatic conveying of fly ash," *Particuology*, vol. 21, pp. 65–73, 2015.

[16] K. Sudo, M. Sumida, and H. Hibara, "Experimental investigation on turbulent flow in a circular-sectioned 90-degree bend," *Experiments in Fluids*, vol. 25, no. 1, pp. 42–49, 1998.

[17] H. Zhang, X. Zhang, H. Sun et al., "Pressure of Newtonian fluid flow through curved pipes and elbows," *Journal of Thermal Science*, vol. 22, no. 4, pp. 372–376, 2013.

[18] J. Kim, M. Yadav, and S. Kim, "Characteristics of secondary flow induced by 90-degree elbow in turbulent pipe flow," *Engineering Applications of Computational Fluid Mechanics*, vol. 8, no. 2, pp. 229–239, 2014.

[19] P. Dutta and N. Nandi, "Study on pressure drop characteristics of single phase turbulent flow in pipe bend for high Reynolds number," *ARPN Journal of Engineering and Applied Sciences*, vol. 10, pp. 2221–2226, 2015.

[20] P. Dutta, S. K. Saha, N. Nandi, and N. Pal, "Numerical study on flow separation in 90° pipe bend under high Reynolds number by k-ε modelling," *Engineering Science and Technology, an International Journal*, vol. 19, no. 2, pp. 904–910, 2016.

[21] M. A. Pepple, J. S. Curtis, and C. U. Yurteri, "Pressure loss in pipe bends of large curvature at high *Re*," *International Review of Chemical Engineering*, vol. 11, pp. 439–444, 2017.

[22] F. A. Zenz, *Fluidization and Fluid-Particle Systems*, CRC Press, New York, NY, USA, 1960.

[23] K. Mohanarangam, W. Yang, H. J. Zhang, and J. Y. Tu, "Effect of particles in turbulent gas-particle flow within a 90° bend," in *Proceedings of the 7th International Conference on CFD in the Minerals and Process Industries CSIRO*, Melbourne, Australia, December 2009.

[24] S. Laín and M. Sommerfeld, "Characterisation of pneumatic conveying systems using the euler/lagrange approach," *Powder Technology*, vol. 235, pp. 764–782, 2013.

[25] A. Levy and D. J. Mason, "Numerical investigation of the effect of bend radius on gas-solids flow in pneumatic conveying systems," *Powder Handling & Processing*, vol. 10, pp. 249–253, 1998.

[26] R. J. Reuvekamp, M. B. Ray, and A. C. Hoffmann, "Deposition of a fine powder in horizontal pipelines and bends," *Chemical Engineering Communications*, vol. 189, no. 6, pp. 849–864, 2002.

[27] Y. Q. Tai, A. Chihwa, and M. B. Ray, "Dilute gas–solid flows in horizontal and vertical bends," *Chemical Engineering Journal*, vol. 44, no. 7, pp. 2301–2315, 2005.

[28] Y. Y. He, Y. J. Zhao, S. Q. Sun, and S. M. Mao, "Experimental study on local loss coefficient of bend in pipeline," *Journal of Hydraulic Engineering*, vol. 34, pp. 54–58, 2003.

[29] J. Li, J. H. Yang, T. Huang, and K. Han, "Numerically studying effects of Reynolds number and radius ratio on flow characteristics of 90° arc bend pipe," *Mechanical Science and Technology for Aerospace Engineering*, vol. 36, pp. 1491–1497, 2017.

[30] T. IWASAKI and J. OJIMA, "Pressure loss in elbow pipes of unplasticized polyvinyl chloride," *Industrial Health*, vol. 34, no. 4, pp. 389–401, 1996.

[31] N. M. Crawford, G. Cunningham, and S. W. T. Spence, "An experimental investigation into the pressure drop for turbulent flow in 90° elbow bends," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 221, no. 2, pp. 77–88, 2007.