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Local resistance characteristics of highly concentrated coal-water slurry flow through fittings

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Abstract−The local resistance characteristics of high concentration coal-water slurry (CWS) flowing through three types of local fittings, namely the gradual contractions, sudden contractions and 90º horizontal elbows, were investigated at a transportation test facility. Results show that the local resistance loss of gradual contractions decreases as the contraction angle increases. When pipe diameter ratio varies little, local resistance loss of sudden contractions changes insignificantly. There is an optimal value of bend diameter ratio, at which the local resistance loss of horizontal elbows is the least. As Reynolds number increases, the resistance coefficients of all the three fittings first reduce and then stabilize, while the three pipes have different ratio of equivalent length to pipe diameter L_e/D behaviors, that is, L_e/D of the gradual contractions decreases gradually and then keeps stable; that of the sudden contractions diminishes at first and then increases, and that of the horizontal elbows increases linearly.

Key words: Coal-water Blurry, Resistance Characteristics, Gradual Contraction, Sudden Contraction, Elbow

INTRODUCTION

The Coal-water slurry (CWS) is a typical liquid-solid non-Newtonian fluid, which also has great development potential as a new fuel. At present the technology of CWS research is focused on pulp, atomized combustion, rheological properties, thixotropy, stability and other aspects [1-4], but there are many problems of pipeline transportation to be solved, such as characteristics of pipeline pumps, forecast of pipeline resistance, pipeline resistance loss of the local fittings, etc.

Pipe fittings like valves, bends, elbows, tees, contractions etc. are the indispensable part of any piping system. Flow through piping components is more complex than through the straight pipes. The losses caused by the local fittings are usually due to disturbances of the flow, which is forced to change direction to overcome path obstructions and to adapt itself to sudden or gradual changes in the cross section or shape of the duct. The prediction of pressure losses in pipe fittings is much more uncertain than for the straight pipe, and the mechanism of internal flow is not clearly defined.

Many scholars have investigated the local resistance characteristics of different non-Newtonian fluids flowing through the sudden enlargements, sudden contractions, bends, valves and other parts of the local fittings, and have arrived at several empirical formulas [5-9]. Turian et al. reported the resistance coefficient for laminar flow of non-Newtonian fluids was dependent on the size of different fittings [10]. Tarun et al. also reported experimental investigation of the resistance characteristics of non-Newtonian liquid flow through the small diameter piping components. They developed an empirical correlation for pressure drop [11]. Javier found the loss coefficients of different local fittings were correlated as a function of Reynolds number by two-k method [12]. Veruscha studied energy losses of Newtonian and non-Newtonian fluids in the different diameter ratio sudden contractions [13].

Considering the lack of published data and the practical importance of the high concentration CWS flowing through the different local fittings, the purpose of this work was to obtain local resistance characteristics in the laminar flows of CWS through gradual contractions, sudden contractions and elbows.

THEORY AND METHOD

The pressure drop while coal-water slurry flows in local fittings may be defined from values of pressure at any two arbitrary points. According to Fig. 1 the overall pressure drop consists of three contributions:

(1) The pressure drop caused by the upstream disturbance, ΔP_{up}

(2) The pressure drop within the disturbance itself, ΔP_{local}, which

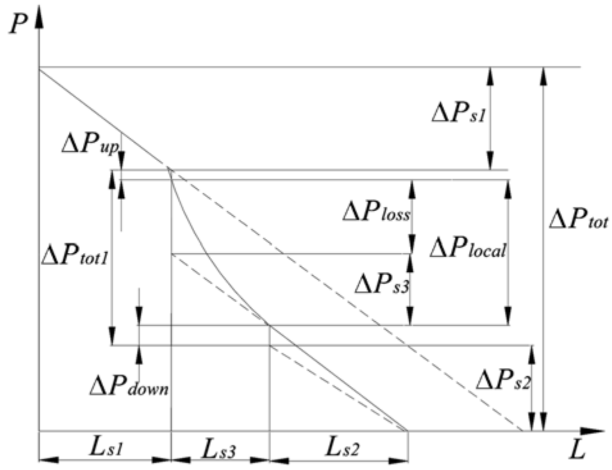

Fig. 1. Pressure distribution along centerline of local fitting.

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includes the contribution of the friction loss of the fitting ΔP_{s3} and geometry loss of the fitting itself ΔP_{loss}.

(3) The pressure drop caused by the downstream disturbance, ΔP_{down}.

So the total pressure loss due to the disturbance is given by Eq. (1):

$$\Delta P_{tot1}=\Delta P_{up}+\Delta P_{s3}+\Delta P_{loss}+DP_{down} \tag{1}$$

However, it is difficult to measure each pressure drop separately; we are interested in the total effect. Some researchers [5,10,14] put forward a simplified method to get the ΔP_{tot1}:

$$\Delta P_{tot1}=\Delta P_{tot}-\Delta P_{s1}-\Delta P_{s2}=\Delta P_{tot}-\lambda_1\cdot\frac{L_{s1}}{D_1}\cdot\frac{\rho v_1^2}{2}-\lambda_2\cdot\frac{L_{s2}}{D_2}\cdot\frac{\rho v_2^2}{2} \tag{2}$$

Evaluation of the friction loss in fittings usually is expressed by the resistance coefficient, K, which is calculated from experimental measurement of the pressure drop in the fittings.

$$K=\frac{2\cdot\Delta P_{tot1}}{\rho v^2} \tag{3}$$

It is noteworthy that the resistance coefficient K_{excl} of elbows should exclude the contribution of the actual physical length of the elbows, ΔP_{s3}

$$\Delta P_{s3}=\lambda\cdot\Theta\cdot\frac{R_c}{D}\cdot\frac{\rho\cdot v^2}{2} \tag{4}$$

So the K_{excl} can be deduced by Eq. (3) and (4):

$$K_{excl}=K-\lambda\cdot\Theta\cdot\frac{R_c}{D} \tag{5}$$

The Reynolds number that best describes the viscous properties of the fluid should be used. The Metzner & Reed Reynolds number Re_{P-L} will be used to define the power-law fluids [15].The Reynolds numbers is defined in Eq. (6):

$$Re_{P-L}=\frac{8\rho V^2}{k'(8V/D)^{n'}} \tag{6}$$

The relationships between k′ and k and n′ and n for a power-law fluids are given as:

$$n'=n \text{ and } k'=k\left(\frac{1+3n}{4n}\right)^n$$

Due to the centrifugal and viscous forces in the curved portion, the CWS flowing through the elbow may generate some characteristic motion, known as secondary flow. Dean [16,17] showed a dimensionless parameter, De, which takes into account the interaction of centrifugal and viscous, forces, and is expressed as the ratio of the square root of the product of inertia and centrifugal forces to the viscous forces, so for the curved pipe we have:

$$\frac{\Delta P}{\rho\cdot V^2}=F(De) \tag{7}$$

Moreover, several authors reported empirical correlations for the Dean Number with the ratio of a friction factor f_c and correlated to a friction factor for a fully developed pipe flow f_p [14,18,19].

Alternatively, the friction loss can be expressed by the equivalent length L_e [20-23]; this is a useful way to combine the friction losses for local fittings with those for the straight pipes for computational purposes. The equivalent length of a local fitting is the length of straight pipe, usually given in numbers of pipe diameters (L_e/D), which results in the same pressure loss as the fitting. Based on the definition of equivalent length, we could get the L_e by Eq. (8):

$$\Delta P_{tot1}=\lambda\cdot\frac{L_e}{D}\cdot\frac{\rho\cdot v^2}{2} \tag{8}$$

The relationship between the equivalent length and K is given by:

$$L_e/D=K/(4*f) \tag{9}$$

It is very evident that equivalent length for a given fitting is not constant; it mainly depends on the Reynolds number, geometric size, roughness, rheology [10].

$$L_e=F(Re_g, \text{Geometric Size, Roughness, Rheology}) \tag{10}$$

EXPERIMENTAL

The pilot scale slurry transport system, consisting of stirring device, slurry tank, screw pump (20 m^3/h) and data acquisition system, is shown schematically in Fig. 2. The flow rate Q and the pressure drop ΔP were measured by an electro-magnetic flow meter and electric differential-pressure manometer, respectively. The slurry temperature was regulated by a heat exchanger at the beginning of the

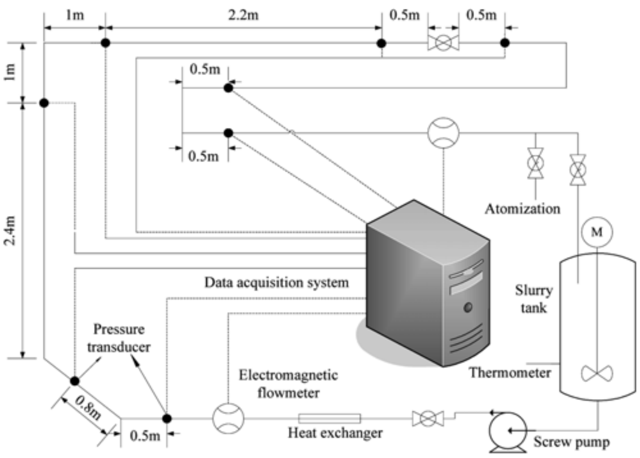

Fig. 2. Schematic diagram of experimental setup.

Table 1. Different local fittings used in experiments

90° Horizontal Elbows 5.0 cm pipe	Rc/D=1.5 Rc/D=2.0 Rc/D=4.0 Rc/D=6.0
Gradual contraction 50 mm×25 mm	θ=3° θ=5° θ=10° θ=20°
Sudden contraction 50mm×25 mm 68 mm×25 mm	

test loop. At each test, the slurry temperature was kept constant. The resistance properties of different local fittings, which are used commonly in the industry, can be seen in Table 1.

The test slurries were made by mixing SHEN-HUA coal powder (low rank coal) with tap water and additives (provided by Nanjing University Surface and Interface Chemical Engineering and Technological Research Center Co. Ltd) in a slurry tank. The mass concentrations of coal-water slurry are 57% and 59%. Rheological properties of slurries were measured experimentally by straight pipe before experiments for local resistance. The constitutive equations of the two concentration CWS, which belong to a power-law model, are:

Cws=57%	$\tau=0.0678\gamma^{1.07}$	(25 °C)
Cws=59%	$\tau=0.304\gamma^{0.935}$	(25 °C)
	$\tau=0.557\gamma^{0.835}$	(32 °C)

RESULTS AND DISCUSSION

1. Flow of High Concentration CWS through Gradual Contractions

According to Fig. 3, the local pressure loss of different angle gradual contractions increases as the Reynolds number increases. When Reynolds number is constant, the local pressure loss is reduced as the angle of gradual contraction increases. The main reason is that the friction pressure loss of CWS flowing through the gradual contraction decreases much when the angle of gradual contractions increases, but the small change in gradual contraction angle cannot induce eddies; thus the geometric pressure loss decreases hardly [24]. It can be seen from Fig. 4, as the Reynolds number increases, the resistance coefficient of gradual contraction first decreases rapidly and then gradually becomes a certain value. The effect of angle on the resistance coefficient of gradual contractions is insignificant. The empirical correlation for resistance coefficient K with Reynolds Number for non-Newtonian suspension flowing through local fittings is given by Eq. (11), which is suitable for different fittings [9-12]. The results for gradual contraction are listed in Table 2:

$$K=a\cdot Re_g^b \tag{11}$$

The research by Hooper [25] showed that the relationship between Re_g and L_e/D of gradual contraction is close. From Fig. 5 we can see that L_e/D (D is the smaller pipe diameter, the same as sudden contraction) of different angle gradual contractions first decreases quickly and then gradually stabilizes as Reynolds number increases; the change of angle on the L_e/D of gradual contraction is insignificant. The relationship between L_e/D and Reynolds number of gradual contraction is obtained based on the regression, and the correlation coefficient is 0.97846.

$$L_e/D=2.44\times10^4\cdot Re_g^{-0.492} \tag{12}$$

2. Flow of High Concentration CWS through Sudden Con-

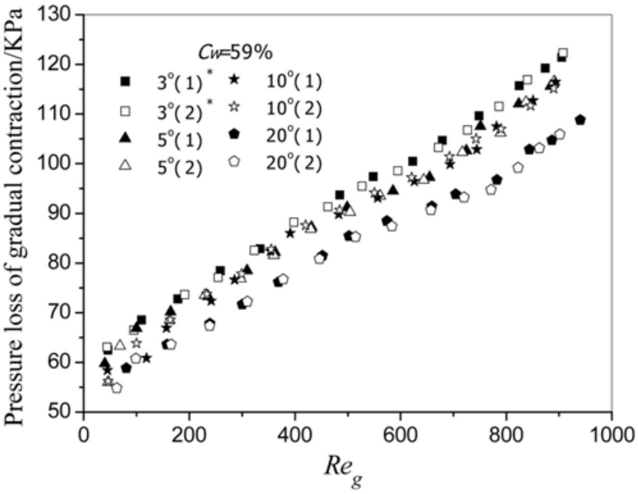

Fig. 3. Effects of angle of gradual contraction on local pressure loss. *(1) and (2) represents the upward and downward in the experiment.

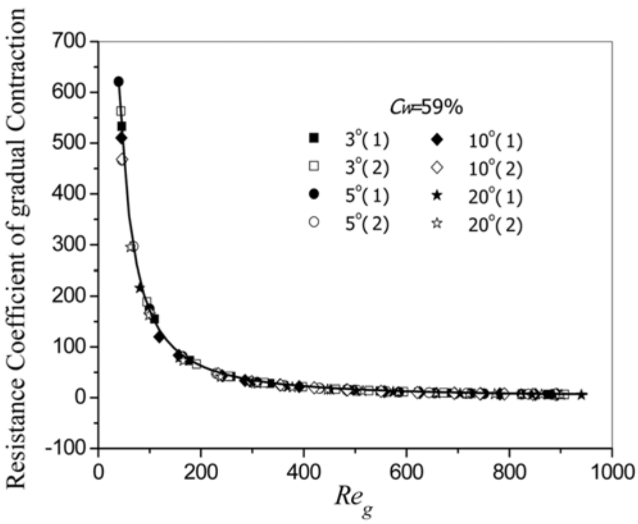

Fig. 4. Effects of angle of gradual contraction on K.

Table 2. Parameters of fitting using empirical formula

Local fittings		Fitting parameters						
		a	b	A_1	B_1	K_1	K_2	K_3
Gradual contraction		1.38×10^5	−1.45	——	——	——	——	——
Sudden contraction		1.5×10^3	−1.2	——	——	——	——	——
Bend diameter	1.5	323	−0.983	0.021	−5.36	0.895	0.00018	10.4
ratio	2.0	81.8	−0.734	0.015	−5.57	1.02	3.63E-8	18.6
	4.0	799	−1.05	0.012	−4.85	0.543	0.001	7.99
	6.0	766	−1.05	0.018	−8.93	0.56	0.00062	8.56

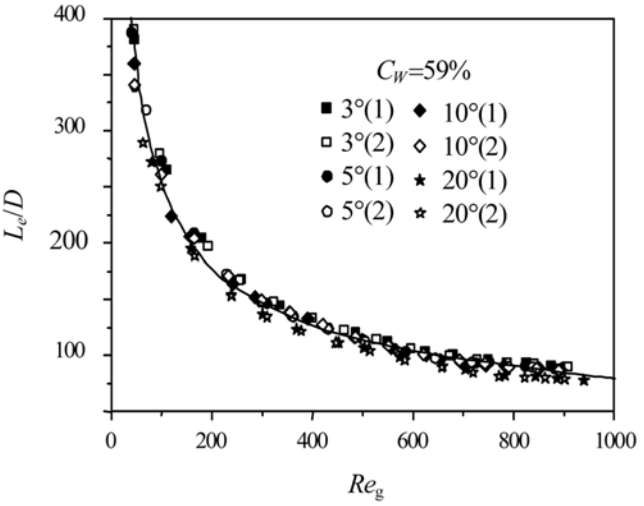

Fig. 5. Effects of angle of gradual contraction on L_e/D.

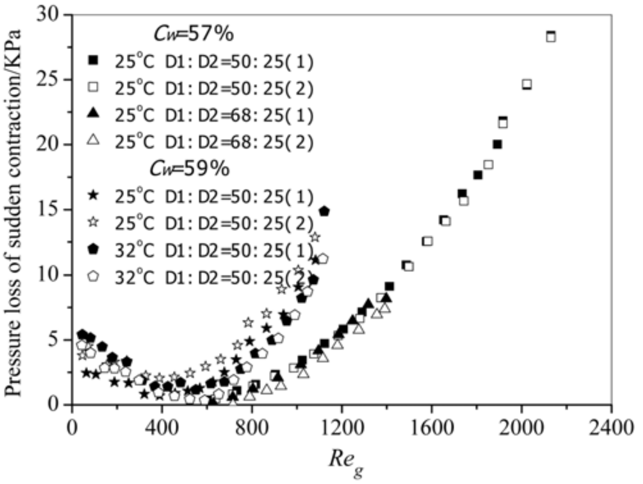

Fig. 6. Effects of diameter ratio on local pressure loss.

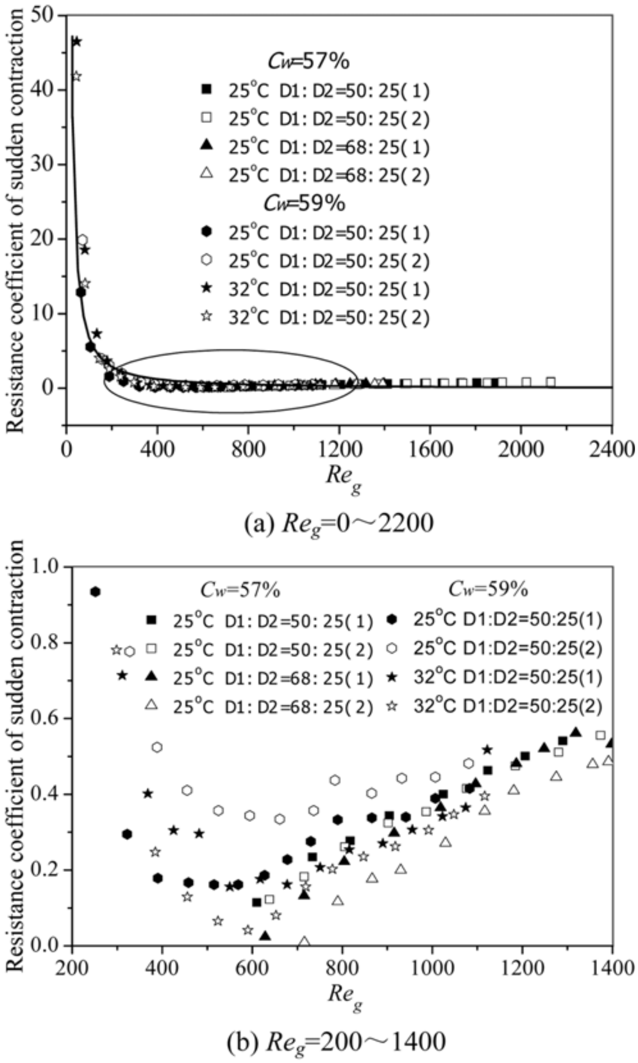

Fig. 7. Effects of diameter ratio on K.

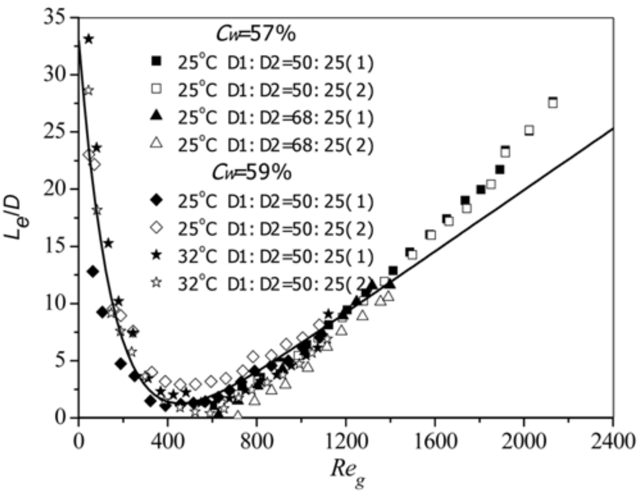

Fig. 8. Effects of diameter ratio on L_e/D.

tractions

As can be seen from Fig. 6, the local pressure loss of CWS flowing through the sudden contractions decreases and then increases quickly. The local pressure loss of two kinds CWS of different concentrations flowing in different diameter ratio has no great difference when Reynolds number is small, because the high viscosity reduces the effect of varied diameter ratio on the local resistance loss [5].With Reynolds number further increasing, the pressure loss of the 59% CWS is significantly larger than 57% CWS. In addition, a smaller temperature rise can reduce the local resistance loss of CWS flowing in the sudden contraction to a certain extent. As the temperature of slurry increases, the viscosity of the liquid in the CWS, especially the viscosity of freedom water will be significantly reduced, resulting in reducing the viscosity of integrated CWS, thereby reducing the flow resistance losses [26]. From Fig. 7, the local resistance coefficient is first reduced and then stabilized as Reynolds number increases; however, the effect of diameter ratio and concentration on local resistance coefficient is neglected. Furthermore, looking into Fig. 7 locally, it can be found that the local resistance coefficient reduces quickly to the minimum and then increases slowly as Reynolds number further increases. Fitting Fig. 7 by Eq. (11), the results can be obtained in Table 2.

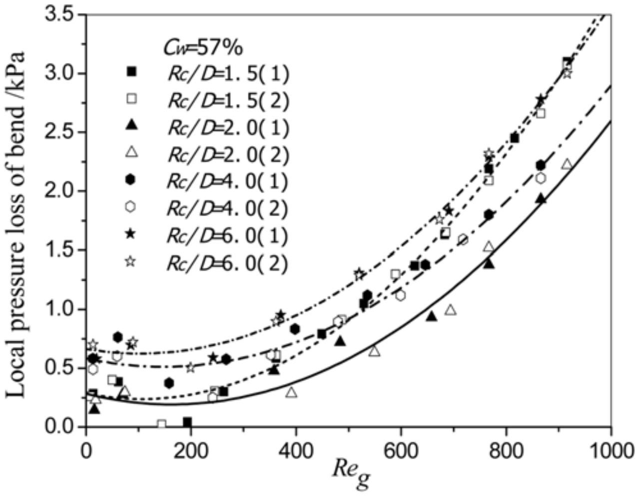

Fig. 9. Effects of Rc/D on local pressure loss.

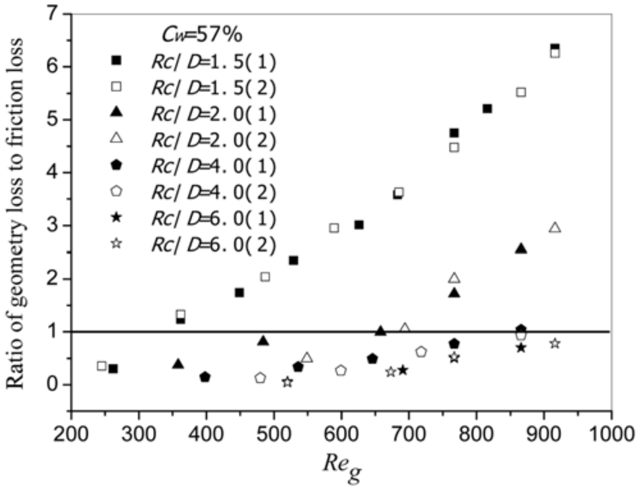

Fig. 10. Relationship between Rc/D and ratio of geometry loss to friction loss.

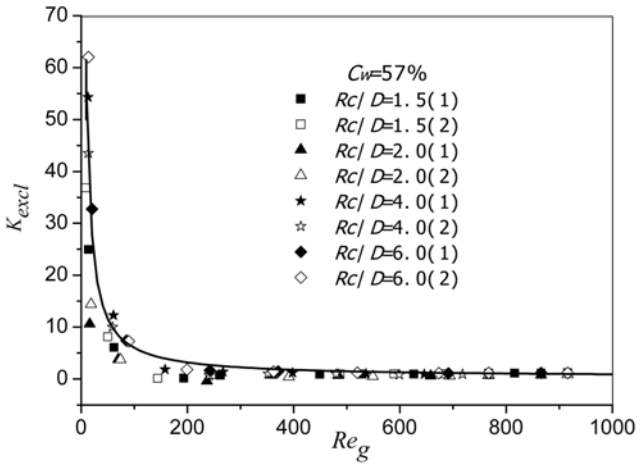

Fig. 11. Effects of Rc/D on K_{excl}.

As can be seen from Fig. 8, the L_e/D of sudden contraction decreases quickly and then increases gradually as Reynolds number increases, which is contradictory to the finding by Boger [21] that the L_e/D of sudden contraction increases linearly all the way as Reynolds number increases. The experimental data deviates from the correlations available in the literature, which is attributed to the size of pipe fittings, rheological properties of the liquid, the circuit employed in transporting the liquid, and so-called "mutual influence effect" of the pipe fittings [8].The diameter ratio in the present study is 0.5 and 0.368. Moreover, the rheological properties of CWS are different from other non-Newtonian fluids. The relationship between L_e/D and Reynolds number of a sudden contraction is obtained based on the regression, and the correlation coefficient is 0.94635.

$$L_e/D=40\cdot e^{(-Re_g/140.7)}-7+0.0147\cdot Re_g \quad (13)$$

3. Flow of High Concentration CWS through Elbows

Fig. 9 shows that the local pressure loss of CWS flowing in the elbows has some fluctuation at small Reynolds number, but the pressure loss increases quickly as the Reynolds number increases. This is because CWS is a thixotropic non-Newtonian fluid. The internal structure is destroyed by shear and the viscosity of slurry is reduced, but the internal structure is recovered gradually and the viscosity of slurry increases if the shear stops, so the pressure loss increases quickly with transportation again. The resistance loss is stabilized when there is a balance between destruction and recovery of the CWS internal structure.

As the bend diameter ratio Rc/D increases, the local resistance loss of CWS flowing in the elbows does not increase. There is an optimal value of bend diameter ratio, where the local pressure loss of a horizontal elbow is the least. Fig. 9 shows that the Rc/D of 2.0 has the least pressure loss and 6.0 having the maximum pressure loss. The local resistance loss of CWS flowing in elbows mainly includes the geometric loss and friction loss. As Rc/D increases, there is a net decrease in total pressure loss resulting from the fact that the change in direction of the flow is becoming gentler. This happens because the contribution to the total pressure loss due to geometry loss, ΔP_{loss}, at first decreases more rapidly than the increase in the contribution due to the friction loss, ΔP_{s3}. However, as Rc/D increases further, the rate of increase in the contribution due to increasing friction loss of the fitting exceeds the rate of decrease in the contribution due to geometry loss [10]. From Fig. 10, it is very obvious that the main resistance loss of bend diameter ratio of 4.0 and 6.0 is friction loss, and bend diameter ratio of 1.5 is the geometric loss.

As can be seen from Fig. 11, the resistance coefficient K_{excl} of different bend diameter ratio elbows decreases quickly and then tends to be stable, as the Reynolds number increases. Moreover, the bend diameter ratio has no great effect on the $K_{excl.}$ Fitting Fig. 10 by Eq. (11), the result is shown in Table 2.

The f_c/f_p is only dependent on De and it does not depend on the value of n and Rc/D when the Rc/D>10 [27,28], but when Rc/D< 10, it is found that the f_c/f_p is a function of Rc/D from Fig. 12. As can be seen From Fig. 12, the f_c/f_p increases quickly with the De increases. At the same De, the f_c/f_p of the Rc/D of 2.0 is the least and 1.5 is the largest. Furthermore, there is no great difference between 4.0 and 6.0. Marn [14] presented the relationship between De and f_c/f_p of non-Newtonian flowing in the small bend diameter ratio elbows.

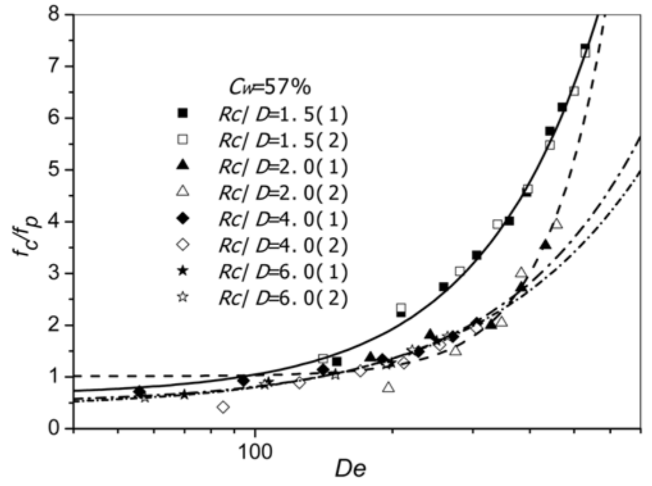

Fig. 12. Relationship between De and f_c/f_p.

$$\frac{f_c}{f_p}=1+K_1(\log De)^{K_2} \quad (14)$$

But we find that the experimental data deviates from the correlations available, so in order to describe the relationship between De and f_c/f_p, the Marquardt-Levenberg algorithm for nonlinear regression analysis is used to correlate the present experiment with the expression being very similar to that of Eq. (14):

$$\frac{f_c}{f_p}=K_1+K_2(\log De)^{K_3} \quad (15)$$

Eq. (15) is used to fit Fig. 12 and the results are obtained in Table 2.

The L_e/D of vertical elbows increases linearly with Reynolds number increases and meets the following relationship [23]:

$$L_e/D=A_1\cdot Re_g+B_1 \quad (16)$$

The same as the vertical elbows, the L_e/D of horizontal elbows increases linearly with increases in Reynolds number, and bend diameter ratio of 1.5 is larger than the others at the same Reynolds number from Fig. 13. Fitting Fig. 13 by Eq. (16), the result is shown in Table 2.

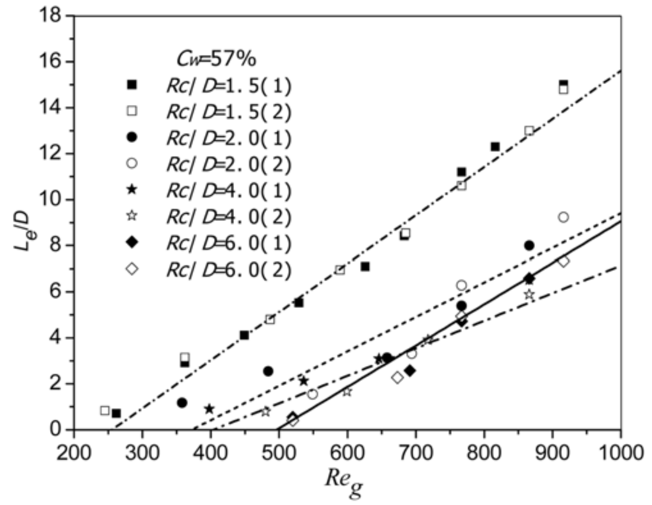

Fig. 13. Effects of Rc/D on L_e/D.

CONCLUSIONS

In this study, the local resistance characteristics of high concentration CWS is investigated on a pilot scale transport system. The effects of several factors, including gradual contraction angle, diameter ratio and bend diameter ratio on the resistance properties are analyzed. The main conclusions are as follows:

(1) The local pressure loss of CWS flowing through z gradual contraction reduces with increase in the contraction angle, when the Reynolds number is given. The local resistance coefficients and L_e/D of a gradual contraction reduce quickly and then gradually become a certain value as Reynolds number increases.

(2) The local pressure loss of CWS flowing through the sudden contraction declines fast at first, and then increases quickly. The change of contraction ratio has no significant effect on the flows; the L_e/D first decreases and then increases.

(3) The local pressure loss of CWS flowing through the 90° horizontal elbows does not always reduce as the Rc/D increases; there is an optimal value of bend diameter ratio. The resistance coefficient reduces first and then tends to be stable and the L_e/D increases linearly with increase in Reynolds number.

ACKNOWLEDGMENTS

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NOMENCLATURE

a, b : constants in Eq. (11)
A_1, B_1 : constants in Eq. (16)
D : pipe diameter [m]
De : dean number
f_c : friction factor of elbow $f_c=(\Delta P_{tot1}\cdot D)/(2Rc\cdot\Theta\cdot\rho\cdot v^2)$
f_p : friction factor of straight pipe ($f_p=16/Re_g$)
K_1, K_2,K_3 : constants in Eq. (14), (15)
K : resistance coefficient
K_{excl} : resistance coefficient of elbow
k' : generalized consistency ($k'=\tau_w/(8v/D)^{n'}$) [$Pa\cdot s^{-n'}$]
k : constant in the power-law [Pa s^n]
L_e : equivalent length [m]
L_{s1}, L_{s2} : length of upstream and downstream [m]
n' : generalized index flow behavior
n : power law exponent in the power-law model
ΔP : pressure drop across the pipe of length L [Pa]
Q : (total) volumetric flow rate [m^3/s]
Rc : curvature radius [m]
V : average velocity [m/s]

Greek Letters

ρ : density [kg/m^{-3}]
Θ : angle of bend
θ : contraction angle
τ_w : wall shear stress [Pa]
t : shear stress [Pa]

γ : shear rate [s^{-1}]
λ : Darey-Weisbach resistance coefficient (λ=64/Re_g)
v_1, v_2 : velocity of upstream and downstream [m/s]

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