CORRECTION OF WALL SLIP EFFECTS AND RHEOLOGICAL MEASUREMENT OF HIGH CONCENTRATED COAL WATER SLURRY[①]

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ABSTRACT

Coal-water slurry, a new liquid fuel, began to appear during the world-wide petroleum crisis in the seventies of this century. Its applications to substitute petroleum drew great attention on the investigations of its preparation, combustion and transportation, etc. The rheological behavior is an important quality index for the fuel. However, the conventional viscosimeters designed for true fluids are not suited to the high concentrated slurry due to the complicated rheological behavior. A special viscosimeter of tube type was represented, which was designed and set up by the authors for the measurement of the rheology of high concentrated coal-water slurry and experiments were conducted with two kinds of slurries from P. R. China. In consideration of the wall slip effects the correction of the experimental data were made.

Key words: coal-water slurry diameter effects plastic viscosity

1 INTRODUCTION

The high concentrated coal-water slurry (cws) can be burnt directly like oil. The long-distance transport of the fuel through pipe has been paid great attention due to the lower operating cost than railway. Previous studies[1-3] have pointed out that cws is a time-dependent and viscoelastic non-Newtonian fluid and the measurement of the rheology of cws was a problem remained to be solved. On the design of industrial pipe through which cws is transported the pilot tests of loop pipe are necessary to get the pressure loss and other design parameters, because the results obtained with viscosimeters in laboratory are auxiliary only. One reason is that the wall effects are obvious in small tubes. In this paper a viscosimeter for cws is presented and the wall effects are discussed in laminar tube flow.

2 VISCOSIMETRY FOR CWS

Rotational cylinder viscosimetry is widely used for the measurement of the rheology of Newtonian and non-Newtonian fluids. But problems have been found with such viscosimetry for cws that the range of shear rates is limited for the high viscosity of cws. Besides, there is radial motion of coal particles due to the centrifugal force which makes errors of results[4-6]. With capillary viscosimetry very high shear rates can be got and flow principle in capillary is the same as in pipe, so that the viscosimetry was considered to be a more suitable method in the pipe transport research of cws. However, many

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factors exist with capillary viscosimetry which can cause errors of measured results. They include kinetic-energy losses, elastic energy losses, turbulence, end effects, wall effects and the effects of time-dependent properties, etc. The effects of these factors may be obvious to cws when capillary viscosimetry is used because cws has complicated rheological characters of non-Newtonian, including viscoelastic and time-dependent properties. However, the corrections for these effects are very complicated.

A viscosimeter of tube type for cws was designed and set up by the authors(Fig. 1) in which the pressure losses for friction along tube were measured directly with pressure sensors equipped on tube. The entrance length of tube is long enough that the flow of test fluids has reached the complete stational state and kinetic-energy losses, end effects and elastic energy losses are eliminated. The effects of the time-dependent properties can be neglected because the flowing time is so short(about 1 second only).

However, wall effects, surface phenomena at fluid-wall interface are not able to be known. Four tubes, 6, 8, 10 and 12 mm in diameter, were used to make quantitative estimation of wall effects. Experiments were conducted with two kinds of cws, made from Bayi and Fushun of P. R. China. The test temperature was kept in the range of 25 ± 0.5 ℃ and size distribution and concentration of test cws were measured before and after flowing test to make sure if any changes occured during flowing.

3 RESULTS AND DISCUSSION

The measured shear stress-shear rate relationship curves of two kinds of experimental cws in different diameter tubes are shown in Fig. 2 which are scattered with tube diameters. The diameter effects can be considered as wall slip effects due to the anomalous flow behavior of cws in the vicinity of the tube wall. That is there is a thin slip layer near the tube wall, whose overall effects could be characterized by a positive slip velocity at the wall. The flow rate of the stationary flow

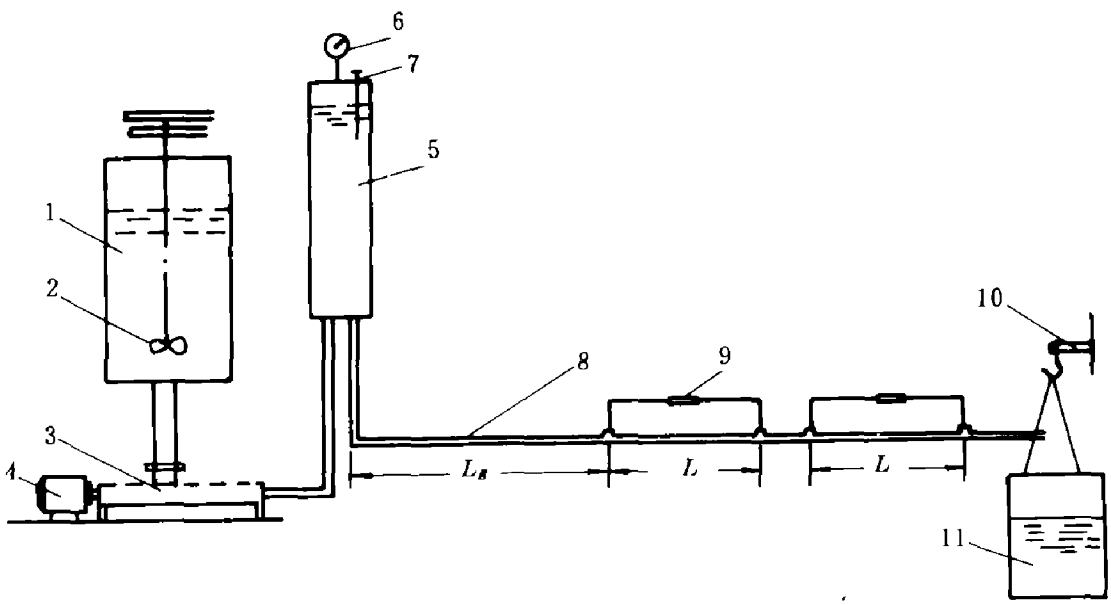

Fig. 1 Tube viscosimeter for coal water slurry

1—bucket with stir; 2—blade; 3—pump; 4—motor; 5—sealed buffer; 6—pressure gauge; 7—temperature sensor; 8—tube; 9—pressure sensor; 10—gravity sensor; 11—container through a circular tube is

$$Q = 2\pi\int_0^R ur\,\mathrm{d}r \qquad (1)$$

or

$$Q = \pi\left[ur^2 - \int r^2\,\mathrm{d}u\right]_0^R \qquad (2)$$

Wall slip velocity is supposed to be u_s, then from the above equation we get

$$Q = \pi R^2 u_s - \pi\int_0^R r^2\,\mathrm{d}u \qquad (3)$$

or

$$Q = \pi R^2 u_s + \frac{\pi R^3}{\tau_w^3}\int_0^{\tau_w}\tau^2 f(\tau)\,\mathrm{d}r \qquad (4)$$

and

$$\frac{8(V-u_s)}{D} = \frac{4}{\tau_w^3}\int_0^{\tau_w}\tau^2 f(\tau)\,\mathrm{d}r \qquad (5)$$

where (formelates (1) ~ (5) Q —volume flowrate; V —averae velocity; D —tube diameter; R —tube radius; τ —shear stress, τ_w—shear stress at wall; $\dot{S}_w$—shear rate at wall; P —pressure;

So that the virtual shear rate at wall is

$$\dot{S}_w = -\left(\frac{\mathrm{d}u}{\mathrm{d}r}\right)_w = f(\tau_w)$$

$$= \frac{1+3n'}{4n'}\left(\frac{8(V-u_s)}{D}\right) \qquad (6)$$

where $n' = \dfrac{\mathrm{d}\ln\tau_w}{\mathrm{d}\ln[8(V-u_s)/D]}$

Generally it is believed that there isn't slipage at wall, that is $u_s = 0$. It is true to Newtonian fluids. However to many non-Newtonian fluids such as polymer solutions and solid suspensions the wall slip velocity u_s can not be negelected particularly in very thin capillary tubes[7-12]. Metzner *et al*[13] believe that the stress gradient in radial direction ($\tau_w = rP/2L$, where P—pressure; L—length of tube) must result in the concentration gradient along radial and a thin slip layer of very low concentration almost near solvent forms at wall.

If $u_s = 0$ is presumed we get from Eq. 6

$$\dot{S}'_w = \frac{1+3n'}{4n'}\left(\frac{8V}{D}\right) \qquad (7)$$

and we can find that $\dot{S}'_w > \dot{S}_w$, i. e. the

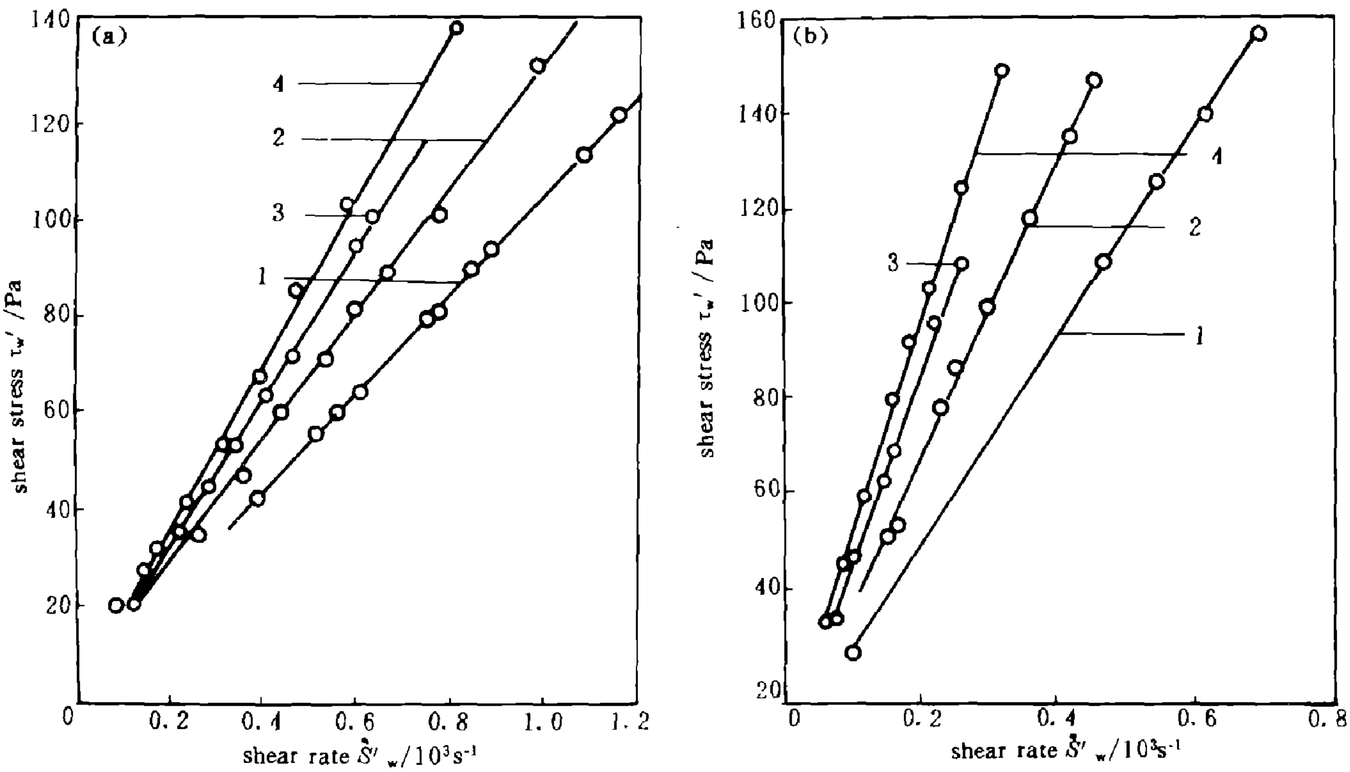

Fig. 2 The shear stress-shear rate relationship curves in tubes of different diameters (absence of wall effects)

(a)—Bayi cws, C =63wt.-%; (b)—Fushun cws, C =62wt.-%

1— D =6 mm; 2— D =8 mm; 3— D =10 mm; 4— D =12 mm calculated shear rate $\dot{S}'_w$ ($u_s = 0$ presumed) is always higher than virtual shear rate $\dot{S}_w$. In other words the calculated apparent viscosity ($u_s = 0$ presumed) is lower than the virtual apparent viscosity of fluid.

Now back to Fig. 2 because wall slip is more obvious in thiner tube the calculated apparent viscosity is lower. To get the virtual viscosity of experimental slurry the correction must be made to shear rate.

From Eq. 4 we get

$$\frac{Q}{\pi R^3 \tau_w} = \frac{u_s}{R\tau_w} + \int_0^{\tau_w} \tau^2 f(\tau) d\tau / \tau_w^1 \quad (8)$$

Oldroyd[11] defined slip coefficient $\beta = u_s/\tau_w$ and presumed that β is only a function of shear stress at wall. However, Jostrzcbski[15] recently found that the slip coefficient β also depends on the diameter of the tube in study of the flow of concentrated suspensions through tube. Further more, Kozicki *et al* [16] introduced a modified slip coefficient

$$\beta_c = R^a \beta(\tau_w, R) \quad (9)$$

substituting Eq. 9 into Eq. 8 we get

$$\frac{Q}{\pi R^3 \tau_w} = \frac{\beta_c}{R^{1-a}} + \frac{1}{\tau_w^1}\int_0^{\tau_w} \tau^2 f(\tau)\, dr \quad (10)$$

Corrected flowrate is

$$Q_c = Q - \pi R^{2-a} \tau_w \beta_c \quad (11)$$

Substituting Eq. 11 into Eq. 7 we obtain

$$\dot{S}_w = -\left(\frac{du}{dr}\right)_w = \left(\frac{3n' + 1}{n'}\right)\left(\frac{Q_c}{\pi R^3}\right) \quad (12)$$

here $n' = \frac{d\ln\tau_w}{d\ln[4(Г - \beta_c R^{-2}\tau_w)/R]}$

Eq. 10 shows that from a plot of $Q/(\pi R^3 \tau_w)$ vs. $(R^{1+a})^{-1}$ at constant τ_w, β_c can be considered as a slope. But α must be given. A method for α was developed. First α is assumed to be a proper value. The plot of $(Q/\pi R^3 \tau_w)$ vs. $(R^{1+a})^{-1}$ can be obtained based on the experimental data in different diameter tubes and then the relative coefficient $\gamma(\alpha)$ is calculated which is the function of α and will be the maximum one when the true α is reached. Therefore, how to determine α is equivalent to solve the minimum of the following function

$$f(a) = 1 - \gamma(a) \quad (13)$$

Table 1 Mearsured and corrected plastic viscosities (Bayi cws)

	concentration /wt.-%	tube diameter /mm	plastic viscosity /Pa. s
Measured	63.00	6	0.104
	63.00	12	0.840
	61.34	6	0.070 9
	61.34	12	0.086 3
	58.91	6	0.051 9
	58.91	12	0.068 4
	55.02	6	0.032 0
	55.02	12	0.040 0
Corrected	63.00	6	0.245
	63.00	12	0.248
	61.34	6	0.099 7
	61.34	12	0.102
	58.91	6	0.084 0
	58.91	12	0.083 7
	55.02	6	0.041 1
	55.02	12	0.042 7

The corrected flowrate is then got and the virtual shear rate at wall can be obtained. It can also be found that the rheological characters of the two slurries are described with Bingham equation of two parameters and the measured shear stress-shear rate curves show that only plastic viscosity is dependent on the tube diameters. The measured and corrected data of plastic viscosity of different concentrations and diameters are shown in Tables 1 and 2 and it can be found that the diameter effects have been eliminated.

4 CONCLUSIONS

(1) The capillary viscosimetry was used

and a tube viscosimeter was designed and set up for the measuement of rheology of cws. The experiments indicates that the viscosimeter is satisfactory for cws than the commonly used viscosimeters designed for the true fluids;

Table2 Measured and corrected plastic viscosities (Fushun cws)

	concentration /wt. -%	tube diameter /mm	plastic viscosity /Pa. s
Measured	62.00	6	0.223
	62.00	12	0.466
	60.14	6	0.127
	60.14	12	0.168
	57.54	6	0.057 3
	57.54	12	0.076 7
Corrected	62.00	6	0.867
	62.00	12	0.882
	60.14	6	0.187
	60.14	12	0.192
	57.54	6	0.081 2
	57.54	12	0.084 3

(2) The diameter effects in different thin tubes of the measured shear rate-shear stress relationships were corrected by considering the anomalous behavior of cws in the vicinity of tube wall characterized by a positive slip velocity at the wall. The corrected shear rate-shear stress relationship curves are identical very well.

REFERENCES

1 Keller, D S. J Rheol, 1990, 34(8):845.
2 Schwartz, A M. Ind Eng Chem, 1969, 61(1):41.
3 Lian, Juntai. M. S. Thesis, China University of Mining and Technology, 1990.
4 Tai, S C; Knell, E W. Fuel, 1986, 65: 566.
5 Wu, Wenggun. MS. Thesis, China University of Mining and Technology, 1990.
6 Gao, Wenping. MS. Thesis, China University of Mining and Technology, 1991.
7 Markus, Reiner. J Rheol, 1993, Oct, 129.
8 Schofield, B K; Scottblair, G W. J Phys Chem, 1930, 34: 218.
9 Cheng, J E. IEC Fundls., 1965, 4(3): 332.
10 Carreau, P J. Rheol Acta, 1979, 18: 600.
11 Jian, Tiqian. Dynamics Development, 1987, 17(2): 176.
12 Morrison, S R. IEC Fundls., 1965, 4(2): 176.
13 Metzner, A B *et al*. J Non-Newtonian Fluid Mech, 1977, 5: 449.
14 Oldroyd, J G. J Colliod Science, 1949, 5: 449.
15 Jastrzebski, Z K. IEC Fundam., 1967, 6(3): 445.
16 Kozicki, W; Tiu, C. Chem Eng Science, 1968, 23: 231.