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Effects of non-Newtonian liquid properties on pressure drop during horizontal gas-liquid flow

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Abstract: An experimental study was performed on two-phase pressure drop of gas/non-Newtonian liquid systems in co-current horizontal flow. The effects of superficial velocities and polymer concentrations on two-phase pressure drop were investigated. A total of 180 experimental tests were conducted for the following conditions: superficial liquid velocity from 0.18 m/s to 1.42 m/s, and superficial gas velocity from 0.13 m/s to 2.59 m/s. The results show that the drag reduction will occur when the value of flow behavior index, n, is smaller than 0.6, and the lower the value of n is, the greater the effect of drag reduction will be.

Key words: gas-liquid flow; pressure drop; drag reduction; non-Newtonian liquid

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1 Introduction

The calculation of the two-phase pressure drop is a key research field in petroleum engineering and in the design of steam-power, refrigeration and air-conditioning systems. In recent years, considerable effort has been paid to study the pressure drop for the flows of two-phase mixtures in pipe when the liquid phase exhibits Newtonian fluid behaviour[1−4]. However, a limited amount of information is available concerning the determining of pressure drop in two-phase flow of non-Newtonian liquids[5−7]. In general, the impact of non-Newtonian fluid behavior is often treated by assuming Newtonian behavior and analyzing a range of apparent viscosities. The shortcomings of such an approach is that the apparent viscosity of a non-Newtonian fluid is shear rate dependent, and it is not necessarily clear what are the appropriate values to apply, particularly for two-phase flow[8]. In practice, A gas/non-Newtonian flow occurs in a wide range of practical application in the chemical, oil and process industries. For example, a two-phase flow of gas/non-Newtonian liquid in a pipe enables a significant reduction in the average pressure gradient to be reached, which is of great practical importance in transporting non-Newtonian liquids. Therefore, the aim is to study experimentally the characteristics of pressure drop when a gas is introduced into a shear-thinning fluid in this study.

2 Experimental

2.1 Flow loop and procedure

The experiments were performed on the multiphase flow facilities at Institute of Mechanics, Chinese Academy of Sciences. The experimental investigations were conducted in the setup as shown in Fig.1. Air came from a compressor pump via gas mass flowmeter, and different carboxymethyl cellulose(CMC) solutions used as the liquid phases were conveyed from liquid phase tank into the pipeline. Liquid phase and gas phase were fed into the pipeline via a T-junction. The volumetric flow rates of all phases could be regulated independently and were measured by thermal mass flowmeter for air phase and electromagnetic flowmeter for polymer solutions.

The multiphase flow pipeline was manufactured of perspex tubing with an internal diameter of 50 mm through which the flow could be observed. The total length of this pipeline between the entrance and the separation unit was approximately 30 m. The pipeline consists of two horizontal legs with a leg length of 10 m and 14 m, respectively, connected by a horizontal U-bend. After the flow pipeline, the mixture flowed to the separator tank, and the separated liquid phase were then returned to its respective storage tanks and used as test fluids again.

The sampling frequency of the pressure was 2 kHz and a total of 240 000 samples which corresponds to

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2 min sampling time were collected at sampling point. Flow patterns were recorded using a high-speed video camera, and the flow patterns for each test condition were recorded and could be observed later in slow motion.

A total of 180 experimental tests were conducted for the following conditions: superficial liquid velocity from 0.18 m/s to 1.42 m/s and of superficial gas velocity from 0.13 m/s to 2.59 m/s.

2.2 Fluid characteristics

The CMC solutions were prepared by adding small quantities of dry polymer powders accompanied by gentle stirring to prevent the formation of lumps. The density of each solution was measured using a constant volume density bottle. The CMC solutions rheology experiments were measured with a ThermoHaake RS300 rheometer. A double gap cylinder sensor system with an outside gap of 0.30 mm and an inside gap of 0.25 mm was used.

As expected, CMC solutions in this study are shear-thinning fluids whose rheology can be described by a two-parameter power-law fluid model. For a power-law fluid, the shear stress is related to the shear rate[7] by

$$\tau = m(\dot{\gamma})^n \tag{1}$$

where $\dot{\gamma}$ is the shear rate, m and n are the fluid consistency coefficient and the flow behaviour index, respectively. The values of m, n and other properties of the CMC solutions are listed in Table 1.

3 Results and discussion

3.1 Effects of superficial velocities on two-phase pressure drop

For gas-Newtonian liquid two-phase flow, it is well-known that the two-phase pressure drop increases with the increase of the gas flow rate. The main reason is that gas phase will always disturb the flow, and there will be additional pressure losses in the mixture of gas-Newtonian liquid flow. But for the mixture flows of gas/non-Newtonian liquid, the pressure drop might, in some circumstance, actually be reduced below the value for the liquid flowing alone at the same volumetric rate. Fig.2 shows the effects of superficial velocities on the pressure drop at constant superficial liquid velocity, and for a range of values of superficial velocity, and the corresponding values of its Reynolds number (*Re*) are given. It can be seen from Fig.2 that for air-CMC-1 solution flow and air-CMC-2 solution flow the pressure drop increases with the increase of the superficial air velocity, v_{SA}, at constant superficial liquid velocity. This characteristic is similar to the one of gas/Newtonian liquid flow. But for air-CMC-3 solution flow and air-CMC-4 solution flow, the pressure drop decreases when the superficial air velocity is increased. This inconsistency shows that drag reduction can not

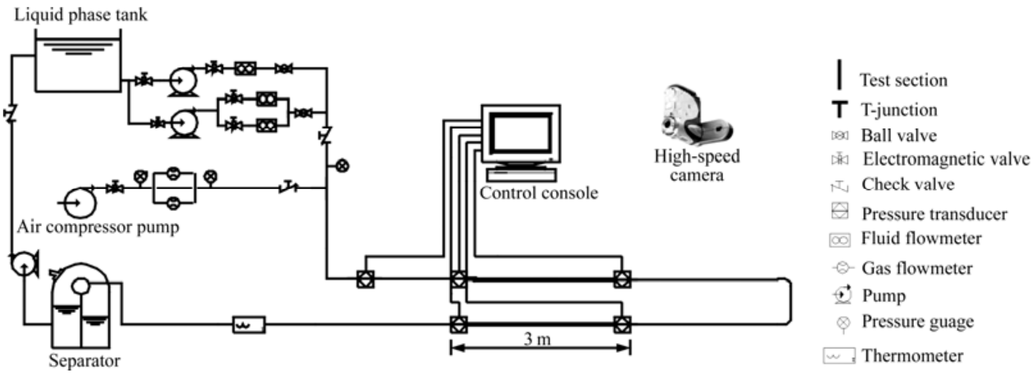

Fig.1 Schematic diagram of flow loop

Table 1 Physical properties of CMC solutions measured at 20 ℃ and 0.101 MPa

CMC solution	Mass concentration /(kg·m^{-3})	Density /(kg·L^{-1})	Surface tension/ (N·m^{-1})	Fluid consistency coefficient	Flow behavior index
CMC-1	1.0	0.999 9	0.071 4	0.034	0.952
CMC-2	2.0	1.000 0	0.071 8	0.407	0.765
CMC-3	2.5	1.000 2	0.072 3	1.365	0.595
CMC-4	3.5	1.000 4	0.072 7	2.434	0.535

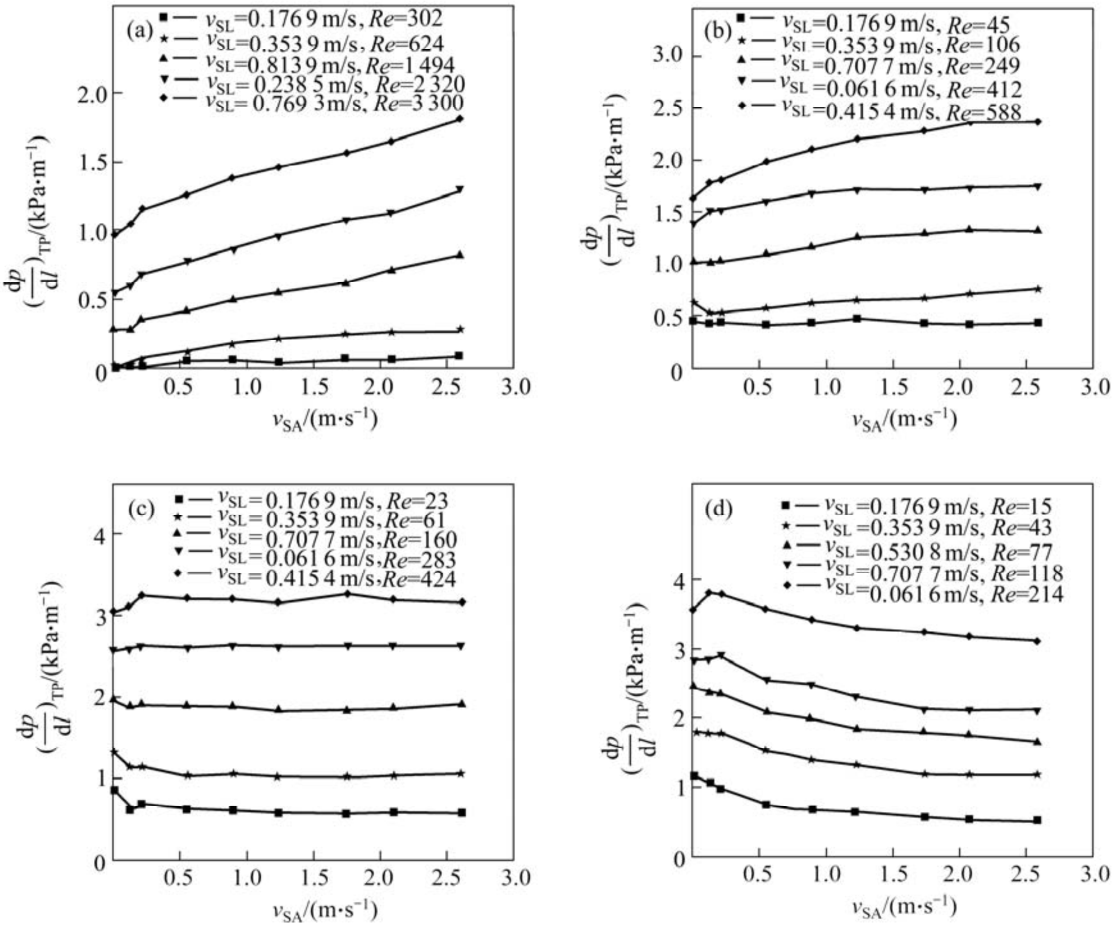

Fig.2 Effects of superficial velocities on pressure drop for different CMC solutions

(a) Air-CMC-1 solution flow; (b) Air-CMC-2 solution flow; (C) Air-CMC-3 solution flow; (d) Air-CMC-4 solution flow

always occur for all the air/shear-thinning liquid flow and only for fluids with the high degree of shear-thinning behaviour (i.e. the small value of flow behavior index, *n*). Moreover, it can also be seen that the lower the value of *n* is, the greater the effect will be.

3.2 Effects of polymer concentrations on pressure drop

A typical plot of the variation of pressure drop with v_{SA} at constant superficial liquid velocity for different CMC solutions is shown in Fig.3. It can be seen that, for fluid with the high degree of shear-thinning behaviour, the mixture of gas/non-Newtonian liquid in a pipe enables a significant reduction in the average pressure gradient to be reached. In this study drag reduction will occur when the value of flow behavior index, *n*, is smaller than 0.6, and therefore the value of flow behavior index plays a key role on drag reduction. Furthermore, the smaller the superficial liquid velocity is, the greater the extent of the drag reduction is. Drag reduction offers the possibility of lowering both the pressure drop and the power requirements in process industries. In practice, air injection could be used to reduce the pressure drop, and enhance the upstream pressure in a pipe for a given flow rate of shear-thinning liquid.

4 Conclusions

The flows of shear-thinning power-law fluids on their own and with air across pipe are studied. In particular, the effects of superficial velocities and polymer concentration on pressure drop of gas/non-Newtonian flow are elucidated. The drag reduction can not always occur for all the air/shear-thinning liquid flow and only for fluids with the high degree of shear-thinning behaviour (i.e. the small value of flow behavior index, *n*). Furthermore, the lower the value of *n* is, the greater the effect of drag reduction will be.

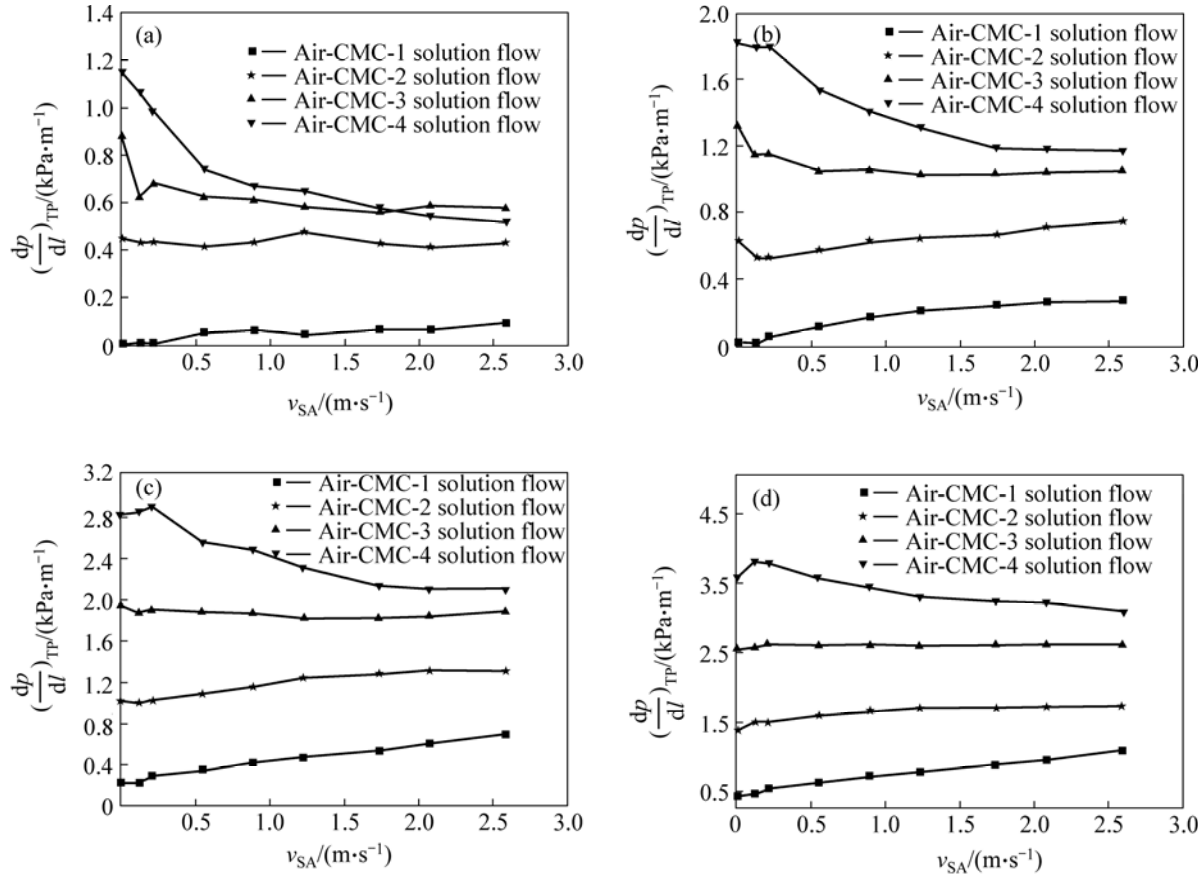

Fig.3 Effects of polymer concentrations on frictional pressure drop at constant v_{SL}

(a) v_{SL}=0.176 9 m/s; (b) v_{SL}=0.353 9 m/s; (c) v_{SL}=0.707 7 m/s; (d) v_{SL}=1.061 6 m/s;

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