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Flow enhancement in pulsating flow of non-colloidal suspensions in tubes

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ABSTRACT

The flow enhancement of non-colloidal suspensions in pulsating flow is experimentally investigated. At low flow-rate range, a flow enhancement of up to 10% was observed due to the shear thinning of viscosity, while a slightly negative flow enhancement can be observed at high flow-rate range, maybe due to the Newtonian plus a slight amount of shear thickening nature of the suspension at high shear rates. At low flow rates, the flow enhancement is found to be insensitive to the mean pressure gradient.

1. Introduction

Pulsating pressure gradient flows of non-Newtonian fluids in circular tubes have attracted a great deal of interest, with potential applications in biological flows, polymer extrusion using oscillatory dies, etc. A pulsating flow is a steady flow with pressure gradient of $P_s = dp/dz$ superimposed by a zero-mean pressure gradient noise, $P_s \varepsilon w(t)$:

$$P = P_s(1 + \varepsilon w(t)), \tag{1}$$

where ε is the amplitude of the noise. In pulsating flow, whether the flow rate increases compared to the steady flow at the same time-average pressure gradient is of great interest. The flow enhancement is usually defined by:

$$I = \langle Q \rangle / Q_0 - 1, \tag{2}$$

where $\langle Q \rangle$ and Q_0 are the mean flow rates of the pulsating and steady-state flows, respectively. Theoretical approaches have been developed based on a quasi-static perturbation solution in terms of the small parameter ε with a relevant constitutive equation for the non-Newtonian fluids, for examples, the generalized Maxwell, power-law [1], non-affine network [2], Ellis [3], Bingham [4], Oldroyd [5], Goddard-Miller [6], and McDonald-Bird-Carreau [7] models. Experimental studies were also carried out by Barnes et al. [5,8], Phan-Thien and Dudek [4,9], Sundstorm and Kaufman [3], and Khabakhpasheva et al. [10] on polymeric liquids. It has been found experimentally and theoretically that shear thinning behavior of the fluid causes the flow enhancement proportional to the square of the amplitude of the oscillating pressure gradient, ε^2. It was also shown that the pulsating flow of polymeric fluids is characterized by a pulsation Reynolds number, $Re_f = \rho R^2 f/\eta$, a Deborah number, $De = \lambda f$ and a Weissenberg number $We = \lambda v/R$, where R is the inner radius of the tube; ρ is the density; f is the frequency of pulsation; η is the viscosity; λ is the relaxation of the polymeric liquid and v is a characteristic shear velocity [10]. The flow enhancement effect is only obvious at small Re_f, because if $Re_f \gg 1$, the pulsating component of the shear wave is not able to propagate over the whole tube section during a pulsation period. We and De numbers collectively define how important is the non-Newtonian and relaxation character of the fluid in the pulsatile flow. $De \ll 1$ means that the relaxation properties of the fluid are not expected to be important, and the pulsation effect will be defined only by the nonlinear viscous properties of the fluid, which therefore depends solely on We. The flow enhancement can either decrease or increase with f depending on We. Recently, studies on pulsatile flow of liquid crystalline materials [11,12], as well as a worm-like micellar solution [13] have been carried out, in which the flow enhancement is observed in all of these materials.

However, as far as we know, no investigation has been made on the flow enhancement of typical suspensions in pulsating flow. A suspension is non-Newtonian in that it shear-thins at low shear rates and shear-thickens at high shear rates, depending on its particle microstructure [14,15]. Therefore, flow enhancement might also be observed for suspensions. In this paper, we study the flow enhancement in pulsating flow for non-colloidal suspensions in a tube. The results are compared qualitatively to the power-law constitutive equation in an effort to quantify the flow enhancement.

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It is found that particle migration may be important and therefore should be taken into account in the study of flow enhancement of suspensions.

2. Experiments

Pulsating flow experiments are carried out in a perspex circular pipe of inner diameter $2R = 10.9$ mm; the length of the test section is $L = 1.8$ m – the experimental setup is shown in Fig. 1. Due to the particulate nature of the suspension flow system, an air-powered double-diagram pump (Pump 1 in the figure) is chosen to drive the suspension flow. The pressure gradient is then stabilized by a dampener in order to obtain a relatively steady flow rate. Pump 2, whose inlet and outlet are connected together using a T-joint, is used to produce the pulsatile pressure gradient with zero mean. The perturbation frequency is kept at 2 Hz and the amplitude is adjustable. The pressure drop signal is measured by a differential pressure transducer and recorded with a PC data acquisition system (DAQ); the flow rate is measured by a graduated cylinder with a stop watch. Experiments are carried out at room temperature of around 25 °C. The flow rate with pulsation is measured between two corresponding flow-rate measurements without pulsation (by isolate pump 2 with valve 3 in Fig. 1 closed), and the flow enhancement is than calculated by Eq. (2). Here, Q_0 is obtained by averaging over the foregoing mentioned two flow-rate measurements without pulsation. In this procedure, the influence of the flow rate drift, caused by possible particle sediment in suspension can be minimized. The time between measurements is less than 5 min, during which the suspension is kept circulating to avoid any obvious sedimentation (this can be effected if the valve 2 is closed, and valve 1 is open). The total fluid volume displaced in each measurement by pump 1 is about 800 ml at low pressure (below 20*PSI*) and about 1200 ml at high pressure (pressure larger than 25*PSI*). The flow enhancement data is averaged over five measurements for each level of mean pressure-gradient and perturbation amplitude.

The suspension consists of hollow glass spheres (Dantec Dynamics) of average diameter $2a = 3.35$ μm, and a silicon oil KF-96-100 (Shin-Etsu) of viscosity $\eta_0 = 0.096$ Pa s and density 0.965 g/cm^3. The suspended hollow glass spheres (effective density 1.1 g/cm^3) are polydisperse in size [16]. Viscometric properties of the suspension are measured by a HAAKE MARS III rotational rheometer (Thermo Scientific).

3. Results and discussion

The viscosity curve for the suspensions are shown in Fig. 2. For 20% suspension, the viscosity data is truncated at low shear rate range due to the limitation of the sensor, and no shear thinning behavior is observed for suspensions at this volume fraction. At volume fraction of 30%, there is an obvious shear thinning at shear rate lower than 20 s^{-1}. At high shear rate range, it can be found that the viscosity is Newtonian plus a very slight shear thickening behavior. In the following, we only study the pulsating flow of the 30% suspension.

The measured pressure signals for the pulsating flow of 30% suspension with the driven air pressure of 20*PSI* are shown in Fig. 3 as an example. The amplitudes (amp0, amp50, amp65, amp100) are read directly from Pump 2. "amp0" refers to the case where there is no introduced pressure perturbation. It can be seen from Fig. 3(a) that, though a dampener is used in the pipe flow system, the base pressure signal, in which no perturbation noise is added, is in fact not steady itself. It fluctuates periodically with a frequency around 0.2 Hz, which can be identified in the frequency domain shown in Fig. 3(b). Note that the slightly vertical shift of the voltage signal in Fig. 3(a) is caused by the data acquisition device itself, as the shift is also found in the static base signal with no flow. As shown in Fig. 3(b), the perturbation pressure signals, which is introduced by pump 2, have harmonic frequency of multiple of 2 Hz. Although the base pressure signal is not steady, it is of a considerable lower frequency to the perturbed pressure signals in frequency domain, and we still call the flow driven by the base pressure signal the steady flow in the following. The measured steady flow rates, the corresponding steady pressure gradients and the driven pressures of pump 1 are listed in Table 1.

From the base and perturbed pressure signals (Fig. 3), the perturbed pressure $\varepsilon w(t)$ can be identified. Here, we define the relative amplitude by

$$\varepsilon_r^2 = \langle [\varepsilon w(t)]^2 \rangle, \tag{3}$$

since $\langle w^2(t) \rangle$ is proposed to be identical in all our experiments. The dependence of the flow enhancement, *I*, defined by Eq. (2) on ε_r is shown in Fig. 4(b). In our experiment, a maximum flow enhancement of around 10% can be observed. At low pressure gradient (pressure $\leqslant 25$*PSI* or steady flow-rate, $Q_0 < 9.46$ ml/s as shown in Table 1), no significant dependence of flow enhancement on the steady pressure-gradient is observed, which seems different from the polymer solution case [1,9]. At high pressure gradient (> 25*PSI*), it seems that the growth of I with ε becomes less significant.

To analyze the flow enhancement behavior of suspension theoretically, a constitutive model accounting for the rheological behavior of suspension is essential. The rheological behavior of particle suspension in a Newtonian solvent depends on the microstructure of particles, which may be characterized by a

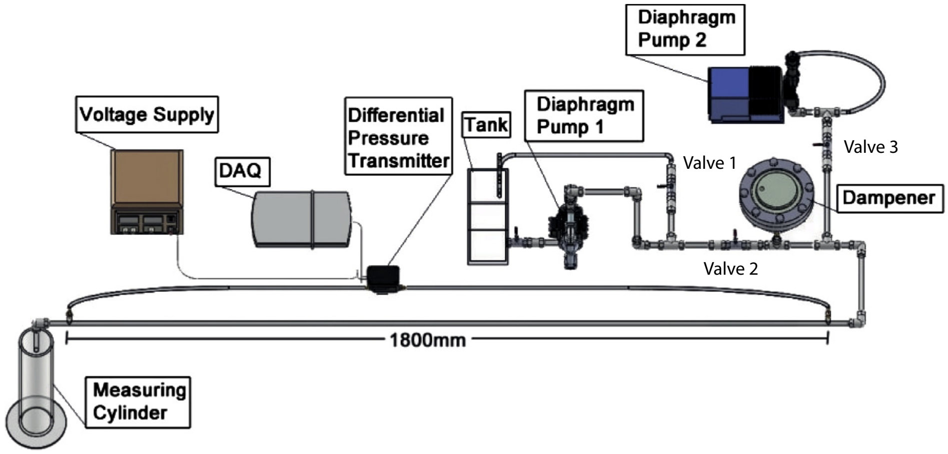

Fig. 1. Diagram of the pulsating pipe flow system.