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Pseudo-laminarization effect of dilute and ultra-dilute polymer solutions on flows in narrow pipes

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ABSTRACT

The properties of dilute and ultra-dilute polymer solutions flowing in a narrow pipe (inner diameter: 680, 400, and 125 μm) were evaluated experimentally by measuring the pressure drop at constant flow rate. Deionized water, silicone oil, and several aqueous solutions of polyacrylamide (PAA), polyethylene oxide (PEO), and xanthan gum (X-Gum) were used. In viscosity measurements, 100- and 10-ppm solutions exhibited non-Newtonian viscosities whereas 1-ppm solutions exhibited Newtonian viscosities. We applied a power-law model to the non-Newtonian viscosities and estimated a generalized Reynolds number. Moreover, we focused on the transition and turbulent regions because the flows being observed were through narrow pipes. For water and silicone oil, good agreement was obtained between the resultant pressure drop and the predicted value. Furthermore, the critical Reynolds number for water and silicone oil was approximately 1.8×10^3. In contrast, laminar flow was maintained in the transition region for the dilute and ultra-dilute polymer solutions. In the 125-μm capillary flows, the maximum critical Reynolds numbers for the ultra-dilute polymer solutions were 2.4×10^3 (PAA), 3.9×10^3 (PEO), and 3.0×10^3 (X-Gum). Even though ultra-dilute solutions were used, pseudo-laminarization was obtained. To understand the experimental results, we estimated the first normal stress difference. All such values were correlated with the wall shear rate. We conclude that the pseudo-laminarization can be associated with the elasticity of the polymer solutions and is typified by the appearance of strong elastic properties in small-scale flows.

1. Introduction

Pipe flows are widely used in various industrial fields to transport fluids (e.g., oil transportation and heat exchange in heating and cooling systems). Meanwhile, there has been much work on the important problem of reducing frictional losses in fluid flows. In a seminal study, Toms reported drag reduction (the pressure drop was decreased in the turbulent region) by adding dilute polymer solution to pipe flows [1]. Virk et al. summarized the “Toms effect” [2] and investigated it using dilute aqueous solutions of polymer and surfactant; it was concluded subsequently that polymers and surfactants have similar effects [3]. Thereafter, many studies were reported on polymer-solution flows. Chauveteau investigated flows of xanthan gum solution under conditions in which the flow properties were not influenced by polymer adsorption or retention as the solution passed through calibrated cylindrical pores [4]. He found that the viscosity decreased with pore size if the pore diameter was larger than the length of the polymer chains. Cohen et al. measured flow rates in laminar flows of organic polymer solutions in pipes with an inner diameter of 0.19–1.1 mm (ratio of length to diameter: 20–2700) [5], obtaining flow rates that were higher than those predicted from cone-and-plate viscometric data. They explained this by postulating an effective slip velocity that increased with wall shear stress. They concluded that this apparent slip phenomenon would occur in flows of highly elastic liquids. Binding observed vortex motion in contraction flows of a polymer solution [6]. He reported the influence of elongational viscosity, particularly with regard to the occurrence and enhancement of significant vortex motion in the entry corners.

The aforementioned studies show the importance of quantitatively measuring the physical properties of dilute polymer solutions and the effects of their characteristic lengths on flow fields. In small-scale flows of such solutions, the Reynolds number (the dimensionless ratio of the inertial force to the viscous force) is relatively small because the characteristic length is small, but the Weissenberg number (the

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Nomenclature

D	Inner diameter of pipe (μm)
k	Gradient of plotting log (T_{pre}−T_m) against log SR_w (–)
L	Length of pipe (mm)
m	Dilatant viscosity (Pa·s^n)
n	Power-law index (–)
N_1	First normal stress difference (Pa)
Q	Flow rate (m^3/s)
Re	Reynolds number (–)
Re^*	Generalized Reynolds number (–)
Re_c	Critical Reynolds number (–)
SR_w	Shear rate on wall (s^{-1})
T	Temperature (°C)
T_m	Jet thrust (N)
T_{pre}	Predicted value with Hagen-Poiseuille flow (N)
V	Mean speed of flow through pipe (m/s)
Δp	Pressure drop (Pa)
η	Shear viscosity (Pa·s)
λ	Frictional coefficient of pipe (–)
μ	Newtonian viscosity (Pa·s)
ρ	Density (kg/m^3)
τ_w	Wall shear stress (Pa)

dimensionless ratio of the viscous force to the elastic force) is relatively large. Thus, strong elastic properties are exhibited even though the flow is laminar. Therefore, flows of ultra-dilute (<100 ppm) polymer solutions in micro-scale flow fields are of great interest. In many previous studies, a "small" characteristic length was one on the order of millimeters; there have been very few studies of polymer-solution flows with micron-scale characteristic lengths. However, because of the development of microelectromechanical systems (MEMS) technology in recent years, micron-scale flow fields can now be produced precisely. Moreover, a characteristic of micron-scale flow fields is that their Reynolds numbers are typically in the laminar and transitional regions, leading to flow states that differ from those encountered in millimeter-scale flows.

Meanwhile, Serizawa et al. reported reduced frictional loss in the flow of a microbubble mixture in a straight pipe [7]; the frictional loss in the turbulent region was lower than that for water alone. However, no non-Newtonian viscosity was found for the microbubble mixture; the viscosity was that of water alone in the laminar region and coincided with that predicted theoretically for laminar flow. Serizawa et al. concluded the presence of a "pseudo-laminarization" effect and focused on maintaining laminar flow in the transitional and turbulent regions, a task that differs from drag reduction. In turn, we have previously studied the flow of a solution of surfactant containing rod-like micelles in narrow pipes with inner diameters of 133 μm to 2.87 mm [8], finding the surfactant solution to have a pseudo-laminarization effect. In that study, we estimated a generalized Reynolds number and discussed the relationship between pseudo-laminarization and non-Newtonian viscosity. Based on that work, in the present study we investigate the pseudo-laminarization effect of several types of dilute (100 ppm) and ultra-dilute (<100 ppm) polymer solutions on the properties of flow in a narrow pipe (inner diameter: 125–680 μm).

2. Experimental setup

2.1. Experimental apparatus

The experimental apparatus is shown schematically in Fig. 1(a). A syringe pump supplies test fluid to an acrylic channel that leads to a narrow pipe (capillary). In general, the pressure drop in a flow is defined by the pressure difference between two different points in the flow direction. However, in this experiment we attached the pipe to the acrylic channel because it would have been too difficult to machine pressure holes in the pipe itself. This approach is similar to one that we have used previously [8]. Because the validity of the experiment by this method may be questioned, another experimental apparatus (Fig. 1(b)) was used. Details of each element of the experimental apparatus are given below.

2.1.1. Syringe pump

Flow of the test fluid was driven by a syringe pump (JP-H5; Furue Science Co., Ltd., Japan). The flow rate Q was changed by choosing the syringe (17, 100, 200, or 400 mL) according to the speed of the piston. The part of the pump in contact with the test fluid was made of SUS304 stainless steel, and a hard rubber ring was used to prevent leakage. We checked the accuracy of the pump periodically and confirmed that any variability in the flow rate was less than 5%.

2.1.2. Acrylic channel

A cylindrical acrylic channel was used because it would have been difficult to machine pressure holes in the capillary itself. The channel had an inner diameter of 25 mm, an outer diameter of 58 mm, and was 180 mm long.

2.1.3. Pressure transducers

Differential pressure transducers (SPX-D, SPD-12; Tsukasa Sokken Co., Ltd., Japan) were used to measure the pressure drop Δp. The order of the pressure drop was 100 or 500 kPa depending on the magnitude of the differential pressure to be measured. The accuracy of the pressure transducers was studied previously [9] and was found to be better than

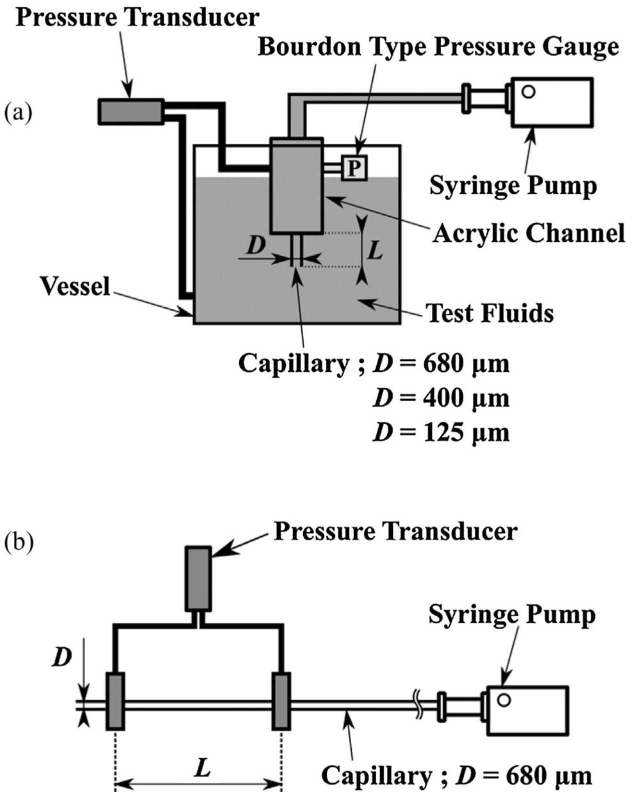

Fig. 1. Schematic views of the sets of experimental apparatus used to measure pressure drop for (a) a constant flow rate. (b) For D = 680 μm only, both sets of experimental apparatus were used to measure viscosity.