Drag Reduction of Non-Newtonian Fluids in a Circular Pipe with a Highly Water-Repellent Wall

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With a highly water-repellent wall pipe in the drag reduction of polymer solutions, a flow system in which drag reduction is obtained in both laminar and turbulent flow ranges was realized. Experiments were carried out to measure the pressure drop in pipes with a highly water-repellent wall and an acrylic resin wall by a pressure transducer. The basic material of the highly water-repellent coating is fluorine-alkane-modified acrylic resin with added hydrophobic silica, which was left overnight in air after it was coated to the pipe wall. The diameter of the pipe was 6 mm. The polymer solutions tested were PEO15 aqueous solutions in the concentration range of 30~1,000 ppm. The drag-reduction ratio for laminar flow was about 11~15%. To understand this effect, the pressure drop was measured by using surfactant solutions and degassed water, and by pressurizing tap water in the pipeline. The laminar drag was not reduced in surfactant solutions, although degassed water and pressurizing tap water in the pipeline had no effect on the reduction. In the laminar flow range, the friction factor of a power-law fluid with fluid slip was analyzed by applying the modified boundary condition on fluid slip at the pipe wall, and the analytical results agreed with the experimental results in the low Reynolds number range.

Introduction

The reduction of fluid frictional drag is one of the important hydrodynamic problems from the point of view of practical applications, and many studies on drag reduction have been done over the years. It is well known that polymer solutions undergo drag reduction in the turbulent flow range, which was first observed in a circular pipe by Toms (1948). Thereafter, many studies related to the Toms effect have been reported. Drag reduction has been realized using such additives as fiber, fine solid particles, and surfactant solutions, and by changing the shape of the solid surface, such as using the riblet. As is generally known, the aforementioned cause drag reduction in the turbulent flow range by reducing the disturbance; however, they do not reduce frictional drag compared with the value obtained when only solvent is used in the laminar flow range.

On the other hand, if fluid slip occurs at the solid boundary, a new drag reduction can be obtained. Watanabe et al. (1996) were the first to report drag reduction in the laminar flow range of Newtonian fluids flowing in square and rectangular ducts with highly water-repellent walls by measuring the pressure drop. However, this type of drag reduction does not occur in the turbulent flow range, although the precise mechanism is unknown at present. Similar laminar drag-reduction phenomena have been observed in a circular pipe (Watanabe et al., 1999), an enclosed rotating disk (Watanabe and Ogata, 1998), and two concentric rotating cylinders (Watanabe and Akino, 1999), all with highly water-repellent walls.

Furthermore, for a duct (Watanabe et al., 1998) and a circular pipe with highly water-repellent walls, the velocity profiles of Newtonian fluids suggested that the velocity did not become zero at the wall and that the finite velocity at the wall could be the slip velocity. The friction factor with fluid slip at the wall has been obtained analytically, and agrees qualitatively with the experimental results.

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Therefore, if a highly water-repellent wall pipe were applied in the drag reduction of polymer solutions, a flow system with drag reduction in both laminar and turbulent flow ranges could be obtained.

The purpose of this study is to estimate the effect of drag reduction in both laminar and turbulent flow ranges by measuring the pressure drop of polymer solutions in a pipe with a highly water-repellent wall. In order to clarify the influence of the physical characteristics of the wall surface on laminar drag reduction, we measured the pressure drop of surfactant solutions, degassed water, and pressurized water. Furthermore, we analyzed the friction factor with fluid slip at the wall for a power-law fluid, and compared the results with the experimental results.

Experimental Apparatus and Method

Figure 1 shows the experimental pipeline system. As indicated in the figure, the test fluids in the pressure tank were forced through the pipe by a compressor. Fully developed steady flow was obtained in the test section. The flow rate was controlled by valves installed at the pressure tank exit and the pipeline exit, and was measured with a digital counting scale. Polymer solutions passed once through the pipeline were discarded to avoid the effect of the degradation on the pressure measurement value. For measurements of surfactant solutions, the test fluids were circulated in the same pipeline by a centrifugal pump installed in the pipeline.

The circular pipe with a highly water-repellent wall that was tested was 6 mm in diameter and 430 mm in length. The basic material of the highly water-repellent coating is fluorine-alkane-modified acrylic resin with added hydrophobic silica, which was left overnight in air after it was coated to the pipe wall. The thickness of the water-repellent coating was about 10 μm, and the diameter was determined to be the mean value of the inlet and outlet diameters of the test pipe, as measured by a micrometer. Furthermore, a smooth-walled pipe of the same dimensions, and with an acrylic resin wall, was used for comparison with the experimental results under no-slip conditions.

The pressure drop in the test section was measured by means of a pressure transducer and a U-tube manometer; the diameter of the pressure hole was 1 mm. Measurement was repeated several times. The reported value is the best estimate of the result, and with a 95% confidence limit, the true value is believed to lie within $\pm 3.15\%$ of the estimated value in the laminar flow range.

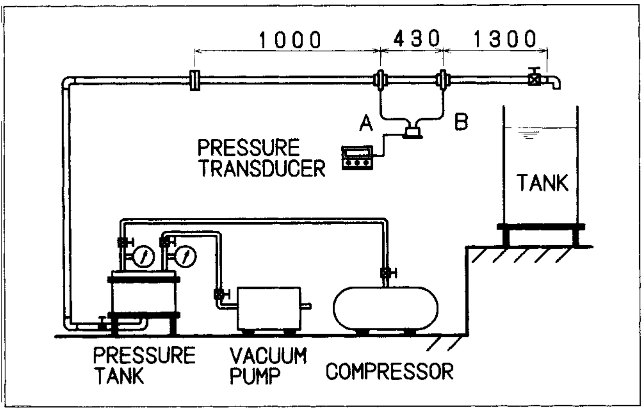

Figure 1. Experimental pipeline system.

The test fluids were PEO15 aqueous solutions in a concentration range of 30 ppm ~ 1,000 ppm as the polymer solutions, and Ethoquad O/12 aqueous solutions in the concentration range of 27 ppm ~ 109 ppm as the surfactant solutions. The Ethoquad O/12 solutions contained equimolar amounts of counterions (sodium salicylate). The solutions were mixed in the solvent (tap water) with gentle stirring, and used three days later. The physical properties of the PEO15 solutions were determined from the flow curves obtained using a tube viscometer, and kinematic viscosity was measured with a Ubbelohde viscometer in the case of the 30 ppm ~ 200 ppm concentration range.

Degassed water was used in order to examine the effect of air in tap water on the laminar drag reduction. Tap water in the pressure tank was degassed by a vacuum pump and the test fluids were held for about 6 h in vacuum. Subsequently, the test fluids were forced through to the pipe by a compressor under constant pressure. Two test fluids, set at −300 mmHg and −600 mmHg in a vacuum tank, were used. For measurements using pressurized water, tap water was pressurized after filling the pipeline. The flow rate was controlled by a valve installed at the pipeline exit. Two test fluids, set at 0.1 MPa and 0.2 MPa, were used.

Figure 2 shows a micrograph of the surface of a highly water-repellent wall. The existence of many fine grooves on the surface increases water repellency. The width of the grooves is about 10 μm.

Figure 3 shows the comparison of droplets on the test highly water-repellent wall. PEO15 solutions have the same contact

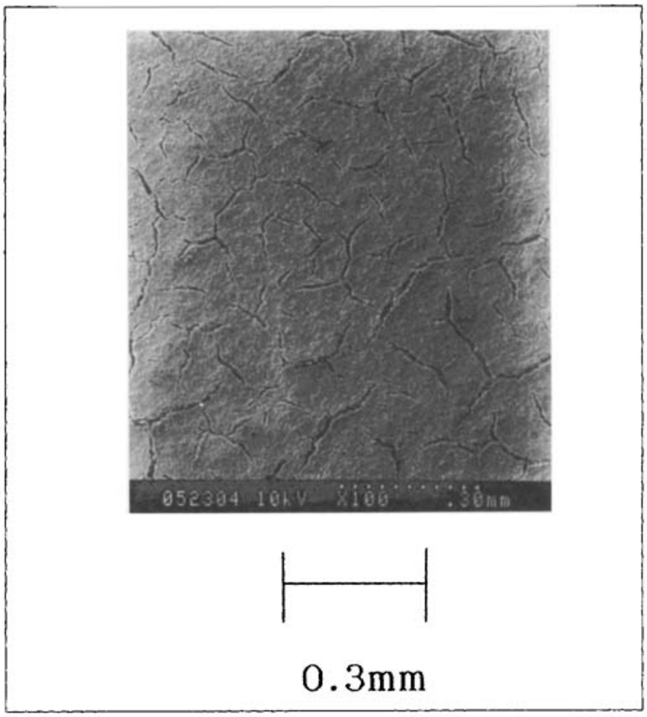

Figure 2. Surface condition of test highly water-repellent wall.

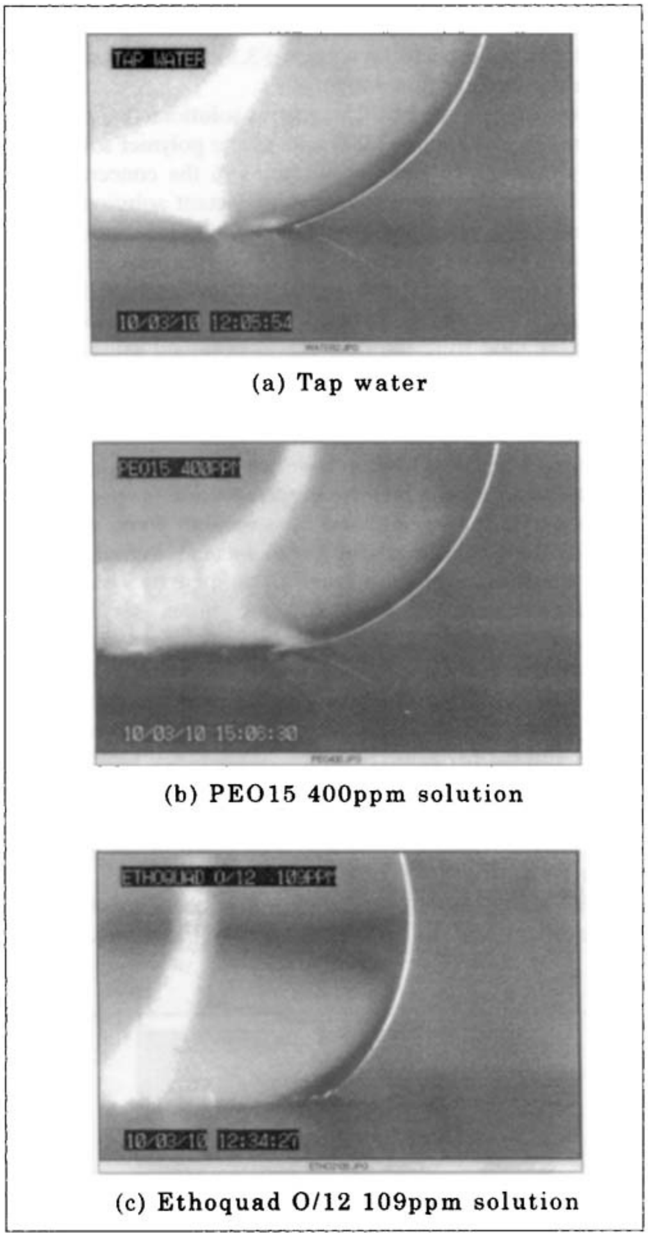

Figure 3. Comparison of droplets on the test highly water-repellent wall.

angle of about 140° as tap water. On the other hand, the contact angle of the Ethoquad O/12 solutions was decreased compared with that of tap water, because of the decrease in surface tension. In general, the largest contact angles recorded for a smooth surface are 112°–115° (Moilliet, 1963), and the effect of the fine grooves does not occur on the repellency for the surfactant solutions.

Results and Discussion

The experimentally determined friction factors of PEO15 solutions are shown in Figures 4 and 5. In these figures, the solid lines indicate $\lambda = 64/Re$ for laminar flow, the Blasius equation, $\lambda = 0.316 Re^{-0.25}$ for turbulent flow, and Virk's

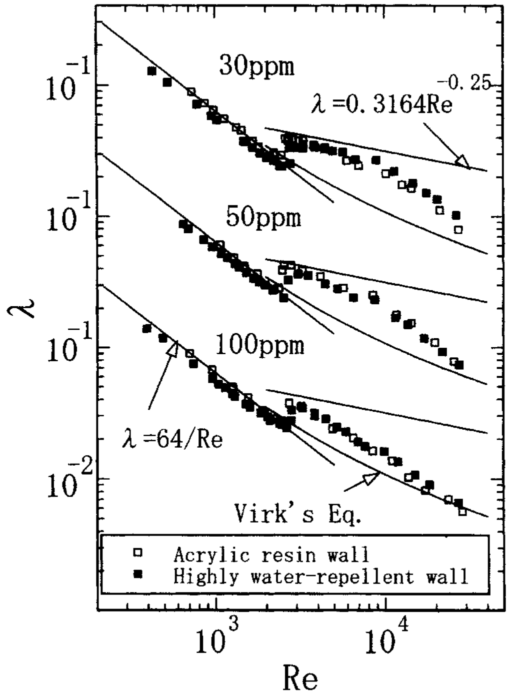

Figure 4. Experimental values of λ for dilute PEO15 solutions.

equation (Virk, 1975) for maximum drag reduction of polymer solutions. It was confirmed that the experimental data for tap water in the acrylic resin wall pipe fit the $\lambda = 64/Re$ value and the Blasius equation in the laminar and turbulent flow ranges, respectively. Drag reduction in the laminar flow

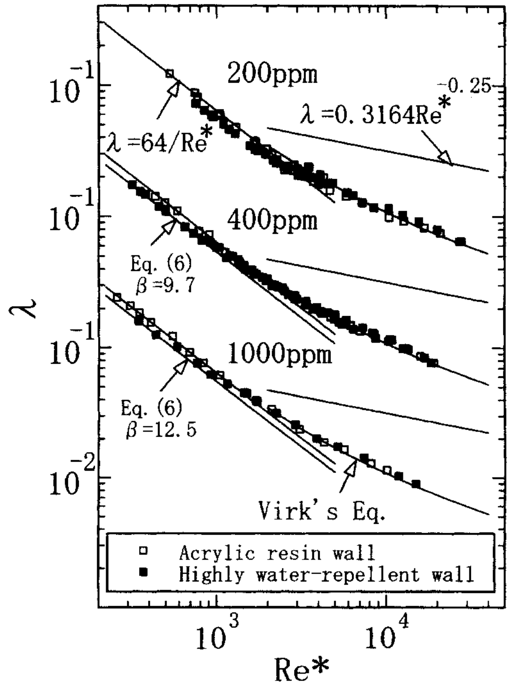

Figure 5. Experimental values of λ for concentrated PEO15 solutions.

range was observed in the highly water-repellent wall pipe, but not in the acrylic resin wall pipe.

On the other hand, no difference was recognized between the experimental results for the acrylic resin wall pipe and those for the highly water-repellent wall pipe in the turbulent flow range, but turbulent drag reduction occurred for all solutions, known as the Toms effect. The friction factors of high-concentration solutions fit the Virk's equation according to the increase in the Reynolds number, *Re*.

Figure 6 shows the relationship between *Re* and $\lambda \cdot Re$. For low-concentration solutions of 30 ppm ~ 100 ppm, the transition Reynolds number of the pipe with a highly water-repellent wall increases slightly. This tendency has also been observed for Newtonian fluids. However, this delay in transitions was not observed for solutions with concentrations higher than 200 ppm. For Newtonian fluids, the friction factor λ of the highly water-repellent wall pipe decreased parallel to the λ of the acrylic resin wall pipe; however, this is not observed for polymer solutions of any concentration. The laminar drag-reduction ratio decreased with an increase in *Re*. This tendency was especially noted with high-concentration solutions of 400 ppm and 1,000 ppm. The probable reason is explained as follows. Fluctuation of static pressure was observed in the laminar flow range for PEO solutions, and as a result, laminar flow could easily become unstable compared with Newtonian fluids. This fluctuation cannot be neglected for slip velocity at the wall and the effect probably appears, because the experimental results for the acrylic resin wall pipe almost agree with $\lambda = 64/Re$.

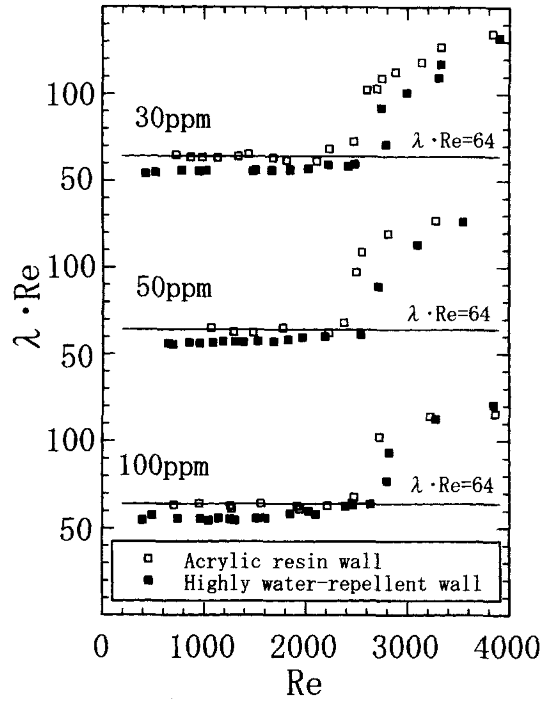

Figure 6. Comparison of ($\lambda \cdot Re$) for dilute PEO15 solutions.

The laminar drag-reduction ratio is defined as

$$DR = \left| \frac{\lambda_r - \lambda_a}{\lambda_a} \right| \times 100(\%), \qquad (1)$$

where λ_r and λ_a are the friction factors of pipes with highly water-repellent wall and an acrylic resin wall, respectively. The laminar drag-reduction ratio was about 11 ~ 15%, and increased slightly with increasing concentration.

From Figures 4 and 5, it is seen that polymer solutions with concentrations lower than 200 ppm are effective for obtaining laminar drag reduction in the pipe with a highly water-repellent wall. On the other hand, high-concentration solutions can be used to obtain higher laminar drag-reduction ratios in the low Reynolds number range, but not in the high Reynolds number range.

Figure 7 shows the relationship between the viscosity and the laminar drag-reduction ratio. In this figure, the experimental results for Newtonian fluids are also shown for comparison. For solutions with concentrations lower than 200 ppm, the laminar drag-reduction ratio is the range average of up to $Re = 1{,}600$. For the 400 ppm and 1,000 ppm solutions, it was difficult to determine the average, and values at $Re =$ 730 and 430, respectively, were obtained. When Newtonian fluids and non-Newtonian fluids of the same order of viscosity were compared, a higher drag-reduction ratio was observed for the former.

For non-Newtonian fluids, the drag reduction ratio increases gradually with an increase in viscosity, and finally plateaus. This result suggests that there is a limit to the drag-reduction ratio in the case of laminar drag reduction in a pipe with a highly water-repellent wall.

If we consider the non-Newtonian viscosity of polymer solutions, analysis applying the power-law fluid would be of significance in engineering calculations. In this study, we analyze the friction factor for the power-law fluid with fluid slip at the pipe wall.

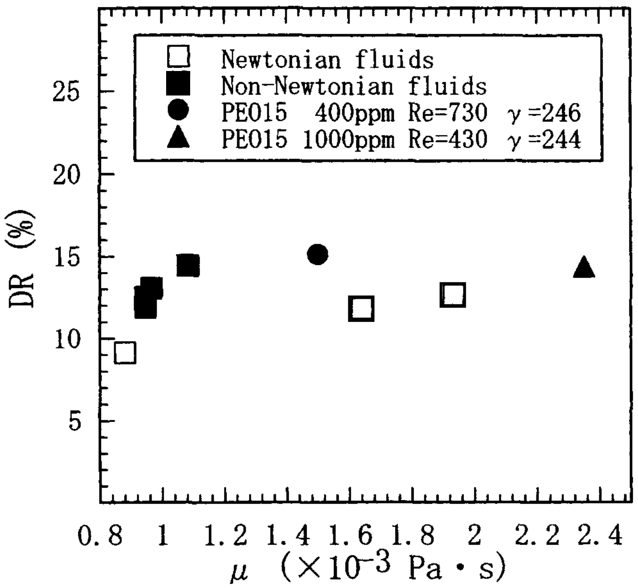

Figure 7. Comparison of drag-reduction ratio for viscosity.

For the case of a steady and fully developed flow in a circular pipe, the equation of motion is given as follows:

$$\frac{1}{r}\frac{d}{dr}(r\tau_{rz}) = -\left(\frac{dp}{dz}\right), \tag{2}$$

where τ_{rz} is the shear stress.

Inserting the power-law fluid model $\tau_{rz} = K(-du/dr)^n$ into Eq. 2, and integrating under the following boundary condition, we obtain Eq. 3:

$r = 0$: u is finite

$r = R$: $u = U_s$

$$u = \left(-\frac{dp}{dz}\right)^{1/n} \frac{nR^{(n+1)/n}}{2^{1/n}K^{1/n}(n+1)}\left\{1-\left(\frac{r}{R}\right)^{(n+1)/n}\right\} + U_s. \tag{3}$$

The slip velocity U_s is determined in order to modify Navier's hypothesis (Navier, 1816), which proposes that the wall shear stress is proportional to the slip velocity. Thus, we assume it as the following equation:

$$\tau_w = \beta u_s^N. \tag{4}$$

Then, the velocity profile is obtained as follows:

$$u = \left(\frac{\Delta p}{2KL}\right)^{1/n} \frac{nR^{(n+1)/n}}{n+1}\left\{1-\left(\frac{r}{R}\right)^{(n+1)/n}\right\} + \left(\frac{R\Delta p}{2\beta L}\right)^{1/N}, \tag{5}$$

where $(\Delta p/L)$ is the pressure gradient, and is equal to $(-dp/dz)$.

Based on the measurement results of torque acting on an inner rotating cylinder with a highly water-repellent wall, it was found that N in Eq. 4 is almost equal to n of the power-law fluid model (Watanabe and Akino, 1999). Thus, if we assume $N = n$, the friction factor λ is obtained as follows:

$$\lambda = \frac{64}{Re^*}\frac{1}{\left[1+\dfrac{(3n+1)K^{1/n}}{nR\beta^{1/n}}\right]^n}, \tag{6}$$

where Re^* is the generalized Reynolds number, and is defined as

$$Re^* = \frac{8n^n \rho d^n \bar{u}^{2-n}}{2^n(3n+1)^n K}. \tag{7}$$

Here, λ of Newtonian fluids is equal to the following equation if we insert $n = 1$ into Eq. 6:

$$\lambda = \frac{64}{Re}\frac{1}{\left(1+\dfrac{4\mu}{R\beta}\right)}. \tag{8}$$

If the flow does not exhibit fluid slip, Eq. 6 gives $\lambda = 64/Re^*$ on substituting $\beta = \infty$ into the equation.

In order to calculate the friction factor using Eq. 6, it is necessary to determine the value of the sliding coefficient β. Therefore, we determined β by substituting the experimental results of λ into Eq. 6.

Figure 5 shows the results of Eq. 6, calculated by substituting the value of β. The results agree with the experimental results at Reynolds numbers less than 800 for a PEO15 solution of 400 ppm. With an increase in the concentration, the experimental results deviate from the analytical result in the low Reynolds number range. Thus the relationship between the wall shear stress and the slip velocity for non-Newtonian fluids can be approximated to the power law in this range.

Figure 8 shows the relationship between the viscosity and β. In this figure, the experimental results for Newtonian fluid in pipes of $\phi 6$ and $\phi 12$ are also shown for comparison; β is the experimental value for $\phi 12$ and the inferred value for $\phi 6$. Here β is not of the same order of magnitude for the same fluid when pipes of $\phi 6$ and $\phi 12$ are compared. Moreover, β increases with an increase in viscosity for all fluids. For a pipe of $\phi 6$, however, the increase in β of non-Newtonian fluids is gradual compared with that of Newtonian fluids.

To understand the mechanism of the occurrence of fluid slip at the highly water-repellent wall, observations from a microscopic viewpoint are necessary, because the wall has many fine grooves on its surface, as shown in Figure 2. If the occurrence of fluid slip is due to the existence of the gas phase in the fine grooves, the effect may be clarified by testing surfactant solutions and degassed water, and by pressurizing tap water in the pipeline.

The experimental results of the friction factor of surfactant (Ethoquad O/12) solutions are shown in Figure 9. The viscosity of water was used to calculate Re. For surfactant solutions, the difference in the friction between the acrylic resin wall pipe and the highly water-repellent-wall pipe is not recognized in both laminar and turbulent flow ranges, so that the laminar drag reduction does not occur.

The reason is thought to be as follows. From the microscopic viewpoint, the main reason for the fluid slip is the reduced molecular attraction between the liquid and the solid surface. Because the free surface energy of the solid is very

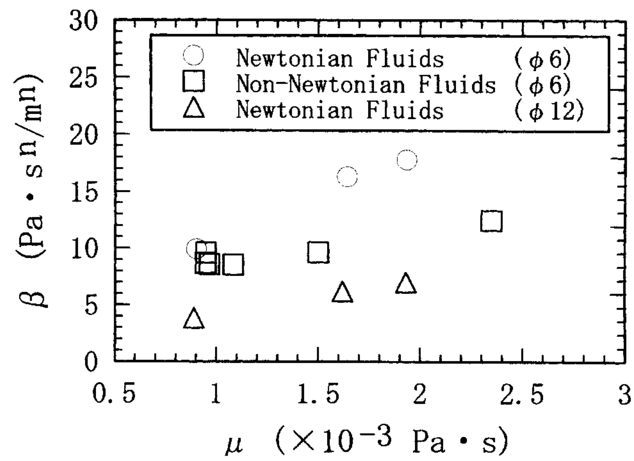

Figure 8. Comparison of sliding coefficient for viscosity.

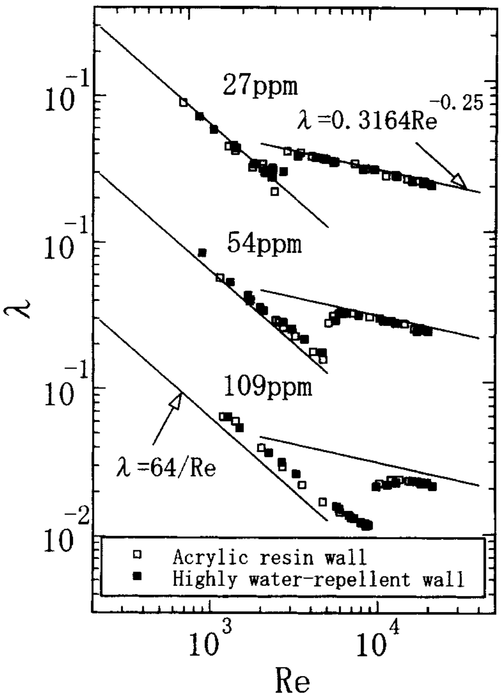

Figure 9. Experimental values of λ for Ethoquad O/12 solutions.

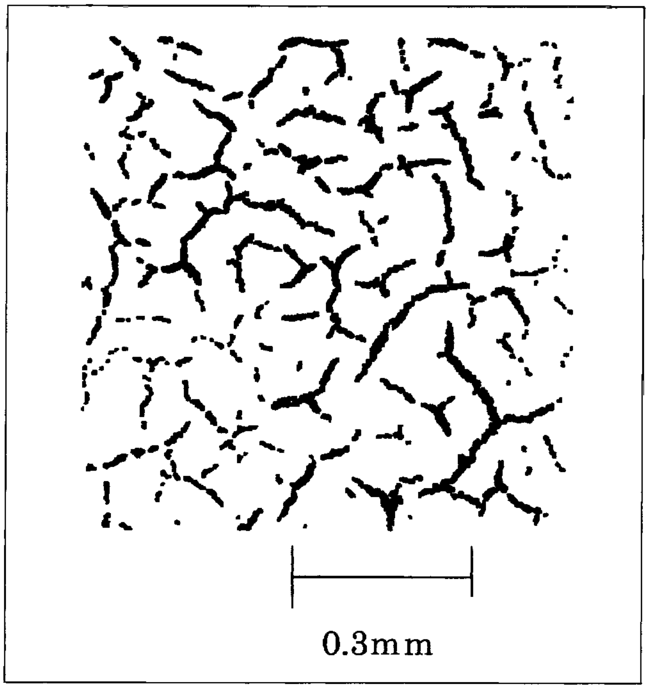

Figure 10. Normalized picture of highly water-repellent wall.

low, the contact area of the liquid is decreased compared to that of a conventional smooth surface due to the presence of the many fine grooves on the solid surface. It can be considered that air is trapped in the fine grooves, and that air plays an important role in the occurrence fluid slip. Liquids such as surfactant solutions fill the fine grooves when the surface tension decreases. Figure 3 shows that the contact angle is decreased, and that the high water repellency was not observed for surfactant solutions. As a result, fluid slip does not occur and laminar drag reduction cannot be recognized.

The result of Figure 2 normalized for the area of the grooves by means of a digital computer is shown in Figure 10. In the figure, the dark parts indicate that groove. The ratio of the groove area for the total wall area is about 12.8%. The laminar drag-reduction ratio is about 11~15%. Although we cannot simply conclude by comparing only these values, it also can be considered that the groove plays an important role in the occurrence of fluid slip.

The experimental results of the friction factor of degassed tap water are shown in Figure 11. In this figure, the results at atmospheric pressure indicate the results for nondegassed tap water. The values measured under the three conditions almost agree, and drag reduction is observed in the laminar flow range. Thus, it can be concluded that degassing the water has no effect on drag reduction.

The experimental results of the friction factor of pressurized tap water in the pipeline are shown in Figure 12. The values measured under the three conditions almost agree, and drag reduction is observed in the laminar flow range. Thus, it can be concluded that compressing the air trapped in the fine grooves by increasing the pressure in the pipe in this pressure range has no effect on drag reduction.

Conclusions

Polymer solutions flowing in a circular pipe with a highly water-repellent wall were experimentally investigated. The basic material of the highly water-repellent coating is fluorine-alkane-modified acrylic resin with added hydrophobic silica. There are many fine grooves on the highly water-repellent wall. The polymer solutions were PEO15 aqueous solutions in the concentration range of 30 ppm~1,000 ppm.

Laminar drag reduction of polymer solutions was verified. However, no difference in the friction factor between an

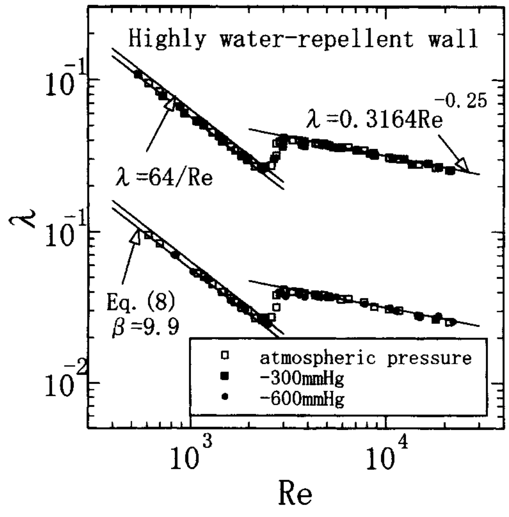

Figure 11. Experimental values of λ for degassed tap water.

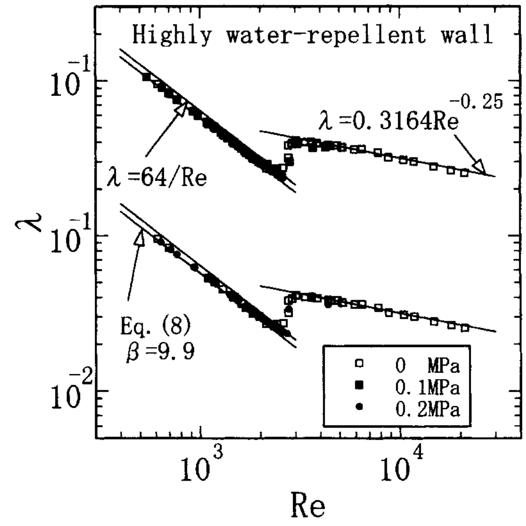

Figure 12. Experimental values of λ for tap water with pressurizing pipeline systems.

acrylic resin wall pipe and a highly water-repellent wall pipe was recognized in the turbulent flow range. That is, we can obtain drag reduction in both the laminar and turbulent flow range for polymer solutions in the highly water-repellent coating pipe.

It can be seen from the macroscopic viewpoint that laminar drag reduction occurs by fluid slip at the pipe wall, and the analytical results for power-law fluids with fluid slip agree qualitatively with the experimental data in the small Reynolds number range. Since no difference in the friction factor between an acrylic resin wall pipe and a highly water-repellent wall pipe was found either in the laminar flow or turbulent flow range for surfactant solutions, such as laminar drag reduction does not occur in surfactant solutions, this fact suggests that air is trapped in the fine grooves of the pipe filled with a liquid, and that this plays an important role in the occurrence of fluid slip.

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Notation

K = power-law coefficient, Pa·s^n
L = length of test section, m
n = power-law exponent
P = pressure, Pa
Δp = pressure drop, Pa
R = radius of pipe, m
Re = Reynolds number
Re^* = generalized Reynolds number
U = velocity in the z-direction, m/s
U_s = slip velocity at pipe wall, m/s

Greek letters

β = sliding coefficient, Pa·s/m
γ = shear rate, 1/s
λ = friction factor
μ = viscosity, Pa·s
ν = kinematics viscosity, m^2/s
ρ = density, kg/m^3
τ_w = wall shear stress, Pa
r, θ, z = cylindrical coordinates

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