

Temperature and diameter effect on hydrodynamic characteristic of surfactant drag-reducing flows

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(Received May 20, 2005; final revision received October 28, 2005)

Abstract

Hydrodynamic characteristic of surfactant drag-reducing flows is still not fully understood. This work investigated the temperature and diameter effect on hydrodynamic characteristic of cationic surfactant drag reducing flows in pipes. Solution of oleyl bishydroxyethyl methyl ammonium chloride (Ethoquad O/12), 900 ppm, as a cationic surfactant and sodium salicylate (NaSal), 540 ppm, as a counter-ion was tested at 12, 25, 40, and 50°C in pipes with diameter of 13, 25, and 40 mm. Drag reduction effectiveness of this surfactant solution was evaluated in 25 mm pipe from 6 to 75°C. Rheological characteristic of this solution was measured by stress control type rheometer with cone-and-plate geometry. Scale-up laws proposed by previous investigators were used to evaluate the flow characteristic of the solution. It was found that this surfactant solution has clear DR capability until 70°C. Result of this work suggested that temperature has a significant influence in changing the hydrodynamic entrance length of surfactant drag reducing flows. From rheological measurement, it was found that the solution exhibits Shear Induced Structure at all temperatures with different degree of peak viscosity and critical shear rate.

Keywords : drag reduction, cationic surfactant, temperature and diameter effect, shear induced structure

1. Introduction

Decreasing of fossil fuel reservation forces scientists and engineers to build energy-saving systems. Small amount of certain surfactants added into water can reduce friction factor below that of the solvent in turbulent flow. Drag Reduction (DR) is defined as a ratio of friction factor difference between solvent and solution to the solvent friction factor. The maximum DR in surfactant solutions can reach larger than 80%; it is a significant value to reduce pumping power. Many drag-reducing solutions are non-Newtonian fluids with strong viscoelasticity and high ratio of extensional viscosity to shear viscosity (Zhang *et al.*, 2005). Bewersdorff (1990) suggested that Shear Induced Structure (SIS) is responsible for DR. However, cationic-surfactant drag-reducing systems do not necessarily show SIS (Lin *et al.*, 2001; Myska and Stern, 1998). Recent investigation by Lu *et al.* (1997) using cationic surfactant system, found that a non-viscoelastic fluid also has a good drag-reducing ability. They suggested that extensional viscosity appears to be the key property controlling drag-reducing flows. Li *et al.* (2004) found that elongational viscosity of his CTAC/NaSal solution has no visible difference from that

of water, even though the DR can be seen clearly in his work. It is not completely understood which rheological behaviour is responsible for the DR occurring in turbulent shear flows of surfactant solutions (Bewersdorff, 1996). Anyway, the existence of thread-like micelles seems to be necessary for DR effectiveness. The microstructure of thread-like micelle directly observed by cryo-TEM in ethylene glycol/water can be well correlated with the DR effectiveness of surfactant solutions (Zhang *et al.*, 2005).

In the case of drag-reducing flows by surfactant additive, friction factor is normally plotted against Reynolds number based on solvent (Newtonian) viscosity (Gyr and Bewersdorff, 1995). At SIS, viscosity increase of surfactant solution is a function of slit width of viscometer (Bewersdorff, 1990). Due to the time-dependent rheological material properties in the SIS, it is very difficult to predict the proper viscosity from rheometric measurement for these solutions in turbulent flows (Bewersdorff, 1996). In this work, Reynolds number was calculated based on solvent (Newtonian) viscosity.

Researchers have proposed some scale-up laws for polymeric and surfactant drag-reducing flows. The scale-up laws will be used to evaluate hydrodynamic characteristic of surfactant solution used in this work. Based on argument that constant friction velocity in non-Newtonian flow implies constant rheological properties and leading to a constant of

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velocity increase beyond Newtonian value, Wilson (1989) proposed scale-up law for polymeric fluids as follow:

$$\left[\frac{V}{u^*}\right]_2 = \left[\frac{V}{u^*}\right]_1 + 2.5 \ln\left[\frac{D_2}{D_1}\right] \quad (1)$$

$$\left[\frac{\rho u^* D}{\eta}\right]_2 = \left[\frac{\rho u^* D}{\eta}\right]_1 \left[\frac{D_2}{D_1}\right] \quad (2)$$

where V is mean velocity, u^* is friction velocity, D is diameter, ρ is density, η is solvent viscosity, whereas subscript 1 and 2 refer to the different pipe-diameter. This scale-up law was applied for turbulent flow of dilute polymer solution at pipe-diameter of 2.92, 8.46, and 32.1 mm. Gasljevic (1995) proposed DR of surfactant solution expressed as a function of bulk fluid velocity. One of the present authors proposed bulk velocity or wall shear stress as a unique parameter to define DR, and proposed critical wall shear stress (at critical Reynolds number) as the upper bound of DR effectiveness for surfactant drag-reducing systems (Usui, 1998). This finding is similar to that of Bewersdorff (1990) who concluded critical wall shear stress is independent of pipe diameter.

There are three conclusions from recent investigation on diameter scaling by Gasljevic *et al.* (2001): firstly, the earlier scaling procedure (DR against V) appears to work well for some surfactant solutions (that exhibit 3-layers velocity profiles). Secondly, a nonionic surfactant solution they studied (that exhibit fan-type pattern of temperature profile) can be scaled well with another scaling procedure, namely τ_w versus V . Finally, another fluid, a highly-concentrated but degraded polymer solutions exhibited scaling that was not correlated as well as the other fluids by either approach, and may belong to an intermediate category.

From the above explanation, it seems there is no single scale-up law applicable to all fluids at various conditions. That complexity increases with the thesis that friction factor of viscoelastic fluid flow in pipe is also depend on position (x/D) and Weisenberg number (tV/D), where t is characteristic time obtained from shear-stress relation model of non-Newtonian fluid, V is mean velocity, and D is diameter (Cho and Hartnett, 1985). But, Gasljevic *et al.* (1999) proved from his scale-up law of surfactant solutions that Weisenberg number was not a key factor for DR scale-up law. For polymeric fluid, it is believed that hydrodynamically fully developed flow region can be obtained at x/D more than 100 (Cho and Hartnett, 1985), whereas for surfactant solutions, Gasljevic *et al.* (1997) found that the friction factor and Nusselt number are still changing at the same rate at 300 diameters after a conical entry. It can be seen from his figure that the change is small after 140 diameters. Pollert *et al.* (1996) used at least 150 diameters to ensure that turbulent flow of surfactant solution was fully developed. However, Suzuki *et al.* (2004) predicted that the entry length of 1000 to 2000 times hydraulic diam-

eter is required for fully developed surfactant solution flow. Study on fully developed flow of drag reducing fluid after piping elements was rare. For polymeric (polyacrylamide) solution flow after sudden expansion, Pak *et al.* (Gasljevic *et al.*, 1997) explained it took 25 to 50 diameters for the pressure drop per unit length to achieve again the fully developed value. Tagoku *et al.* (2004) showed that friction factor of surfactant (Ethoquad O/12) solution after branch is higher than that before the branch. It may be caused by high shear stress responsible for destroying the super-ordered thread-like micelle.

In this work, temperature and diameter effect were investigated by flowing cationic surfactant solutions in pipe with three kind of diameters, i.e. 13, 25, and 40 mm; each at 12, 25, 40, and 50°C. DR effectiveness of this surfactant solution was measured in 25 mm pipe from 6 to 75°C. It was reported by Smith that cationic surfactant Ethoquad O/12 with excess NaSal is DR effective in water in a wide range from 2 to 80°C (Zhang *et al.*, 2005). The previous scale-up laws were used to evaluate the experimental results. Rheological behaviour was studied by measuring shear viscosity of the solutions at 12, 25, 32.5, 40, and 50°C.

2. Experiments

A closed circulating flow loop shown in Fig. 1 was used to measure the relationship between flow rate and pressure drop of straight pipe flow. Experimental apparatus includes a variable speed pump, a fluid storage tank, a heating and cooling facility with a temperature controller, an electromagnetic flow meter, two manometers, and two pressure transducers. High temperature resisting PVC pipes were used to construct the flow loop and the test section. Three kinds of horizontal test pipes, 13, 25, and 40 mm in diameter, were used in this study.

The pressure holes were located at $L/D = 231.5$ and 254.5 for 13 mm pipe, 130.8 and 210.6 for 25 mm pipe, 56 and 113.5 for 40 mm pipe (L is defined as the length measured from piping element (elbow or pipe-reducer) to the pressure hole). Additional stainless-steel pipe with diameter of 13

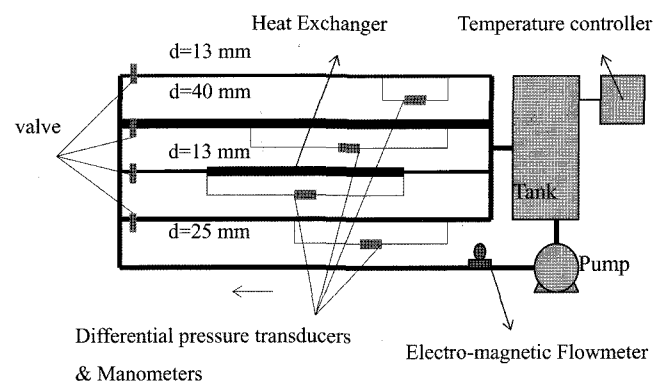


Fig. 1. Schematic picture of experimental installation.

mm and pressure holes position at $L/D = 119$ and 314 was used as comparison. To assure that the installation works properly, before and after the experiments the installation was calibrated by measuring water friction factor in turbulent flow. The water friction factors were in a good agreement with the Blasius equation. For drag reducing system by surfactant used in this study, Chou *et al.* (1989) reported that the optimum molar ratio of surfactant to counter-ion is 1:1.5. In this work, oleyl bishydroxyethyl methyl ammonium chloride ($C_{18}H_{35}N(CH_3)(C_2H_4OH)_2Cl$) 900 ppm was used as the surfactant. Sodium salicylate (HOC_6H_4COONa) 540 ppm was added as the counter ion. In this experiment, the solution was tested at 12, 25, 40, and 50°C.

Electronic differential pressure transducers were calibrated by CCl_4 manometer, while electromagnetic flow meter was calibrated by conventional method using a bucket and stopwatch. Surfactant and counter ion was mixed with warm de-ionized water to ascertain that all additive dissolve completely in water. After pouring the solution into the tank, the solution was forced to flow in all section of the installation for about 1 hour to assure homogeneity of the fluid.

3. Experimental results and discussions

3.1. Shear viscosity

Shear viscosity was measured by using a stress control type rheometer, i.e. SR-5 from Rheometric Scientific Co. Ltd. with cone-and-plate geometry. The measurement was conducted by increasing shear stress from 0.01 to 15 – 20 Pa. To ensure repeatability of the result, 2 – 3 samples were used for every measurement. Before running each experiment, each sample was left in the cone-and-plate about 1 minute to assure thermal equilibrium of the sample. Fig. 2 shows shear viscosity as a function of shear rate and temperatures.

It can be seen in Fig. 2 that SIS is occurs in the solution

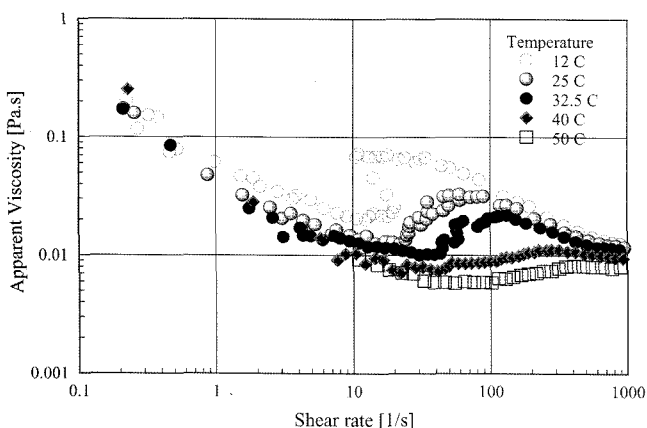


Fig. 2. Shear viscosity of Ethoquad O/12 900 ppm + NaSal 540 ppm at various temperature.

at all temperatures. It is common to conclude the SIS occurrence in surfactant solution by evaluating the relationship between apparent viscosity and shear rate (see Bewersdorff and Ohlendorf, 1988; Gyr and Bewersdorff, 1995; Lu *et al.*, 1988; Lin *et al.*, 2001; Zhang *et al.*, 2005). Lin *et al.* (2001) worked with Ethoquad O/12; and they found that shear instability only occur at very high concentration of surfactant and counter-ion, i.e. 100/250 mM. In their explanation, they quoted possibility that elastic instability may responsible for dramatic rise in the shear stress and in the first normal stress difference after start-up of shear. However, for low concentration of surfactant and counter-ion (similar with author used in this work), the instability did not occur.

It can be seen in Fig. 2 that critical shear rate for SIS increases by temperature, i.e. about 20/s at 12°C and 100/s at 50°C, whereas peak value of viscosity in SIS is decreases by temperature; this phenomena are consistent with those found by Bewersdorff (1990). Critical shear rate increasing and peak-viscosity decreasing in SIS were also obtained by increasing surfactant concentration and lowering gap of couette-type viscometer (Bewersdorff, 1996). There is a certain relation between critical shear rate and peak viscosity in SIS: when critical shear rate is high, peak value of viscosity is low and vice versa. From light scattering and electrical birefringence, Bewersdorff (1996) found that length of the micelle in surfactant solution increases when the temperature decreases. It is understandable that longer rod has larger surface area and receiving bigger force from fluid flow than the shorter one. That is why the longer rod is aligned at lower critical shear rate. Longer rods will also develop larger super-ordered structure in SIS. This results in higher peak value of viscosity.

3.2. Pressure drop

The result can be presented in relationship between friction factor and Reynolds number. The Reynolds number is defined as:

$$Re = \frac{\rho V D}{\eta} \quad (3)$$

where ρ is fluid density, V is mean fluid velocity, D is pipe diameter, and η is solvent viscosity.

Whereas friction factor is:

$$f = \frac{\tau_w}{(1/2)\rho V^2} \quad (4)$$

where τ_w is wall shear stress.

Blasius equation correlates friction factor and Reynolds number in turbulent flow, i.e. (McComb, 1990):

$$f = 0.0791 Re^{-0.25} \quad (5)$$

where f is friction factor, and Re is Reynolds number. Maximum Drag Reduction Asymptote (MDRA) limits

the maximum DR that can be achieved by a drag reducing fluid. The well-known MDRA for dilute polymer solutions is that proposed by Virk. A fairly good power law approximation to this implicit equation is given by (Aguilar *et al.*, 2001):

$$f = 0.58Re^{-0.58} \quad (6)$$

This asymptotic correlation has been confirmed by a great amount of experimental data with regard to dilute polymer solutions, and it has shown to be independent of pipe diameter, concentration, molecular weight, coil size, etc.

There is almost an unanimous consensus that the MDRA for surfactants should be higher than that of polymers (Aguilar *et al.*, 2001). Zakin *et al.* (1996), proposed a new MDRA for surfactants. This MDRA is approximately valid in the range between $4000 < Re < 130,000$:

$$f = 0.315Re^{-0.55} \quad (7)$$

DR effectiveness of Ethoquad O/12 900 ppm + NaSal 540 ppm was evaluated by measuring pressure drop and flow rate of the solution from 6 to 75°C in 25 mm pipe. The results are shown below.

It can be seen from Fig. 3 that the surfactant solution has DR capability until temperature about 70°C. At 75°C, DR capability disappears completely. It seems that the critical temperature (at maximum DR) of this solution is located somewhere between 60 and 65°C, while lowest DR is recorded at 6°C. It is believed that solubility problem is responsible for small DR at low temperature, while destroying of super-ordered thread-like micelle at high temperature causes disappearing of DR capability at 75°C. Zhang *et al.* (2005) noticed a clear relation between micellar network occurrence and DR. It means that thread-like micelle is responsible for DR. Some researchers found that condition of thread-like micelle in surfactant solution is influenced by temperature (Bewersdorff, 1996): by light

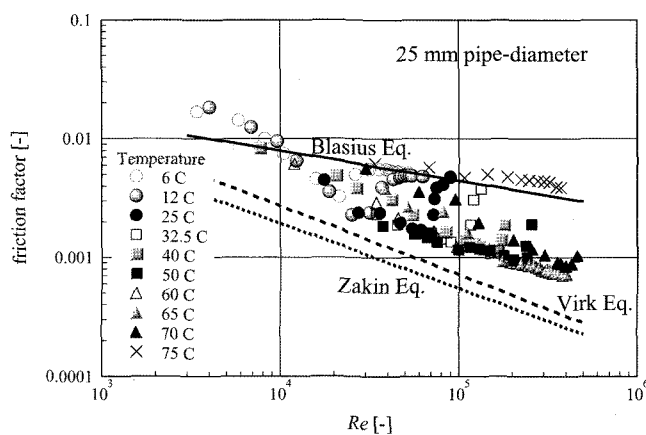


Fig. 3. Relationship between friction factor and Reynolds number of Ethoquad O/12 900 ppm + NaSal 540 ppm in 25 mm pipe at various temperature.

scattering and electrical birefringence method, Lu *et al.* (1997): by birefringence method). At high temperature, the length of thread-like micelle is shorter (Bewersdorff, 1996), or resulted in weak birefringence (Lu *et al.*, 1997). It can be concluded that at 75°C the super-ordered thread-like micelle in surfactant solution used in this work was destroyed. At low temperature (2°C), Zhang *et al.* (2005) also recorded small DR in their surfactant solution. This phenomenon may be related with solubility decrease of surfactant. By added ethylene glycol into water, surfactant solubility at low temperature is improved, and then DR is increased.

Relationship between friction factor and Reynolds number in the three pipes can be seen at the following figure.

It can be seen from Fig. 4 that there exists a clear diameter effect on the curves of friction factor against Reynolds number. It is interesting to note that critical Reynolds numbers in all pipes are moved to the higher values with respect to temperature. Decreasing solvent viscosity is responsible for the increasing of critical Reynolds number. Surprisingly, at 40 and 50°C, the critical Reynolds number of 25 and 40 mm pipe passes that value of 13 mm pipe. At 25°C, the critical Reynolds number for all pipes is the same: this is the cross-point temperature. Below the cross point, critical Reynolds number of 25 and 40 mm pipe are less than that of 13 mm pipe, and above the cross point, the critical Reynolds number of 25 and 40 mm pipe are bigger than that of 13 mm pipe. Comparing the curves in Fig. 4 with previous study on diameter effect of drag reducing flows, it can be inferred that similar pattern with previous works only occurs at high temperature. For example, result from Bewersdorff and Ohlendorf (1988) studied on diameter effect of $C_{16}TASal$ solution in tap water at 25°C has a comparable pattern with the curves at 50°C in Fig. 4. Bewersdorff and Ohlendorf (1988) used sufficiently long entrance length of $L/D \approx 280$ to ensure a fully developed turbulent flow in the measuring section. At low temperature, the pictures in Fig. 4 were significantly different from that of Bewersdorff and Ohlendorf (1988).

Temperature effect on the friction factor of each pipe can be seen in the following figure.

Gasljevic (1997) found that DR of surfactant solution increases slowly from $L/D = 200$ to 300. In this study, the location of pressure-drop measurement was fixed, while temperature of surfactant solution was changed. By considering the location of pressure-drop measurement of 13 mm pipe ($L/D = 231.5$ and 254.5), it is understandable that by increasing temperature, minimum friction factor in the pipe decreases slowly (see Fig. 5). On the other hand, pressure-drop measurements in 25 and 40 mm pipe were carried out at much shorter L/D than in 13 mm pipe. By increasing temperature, minimum friction factors of 25 and 40 mm pipe decrease significantly than that of 13 mm pipe. That is why friction factor curves of 25 and 40 mm pipe

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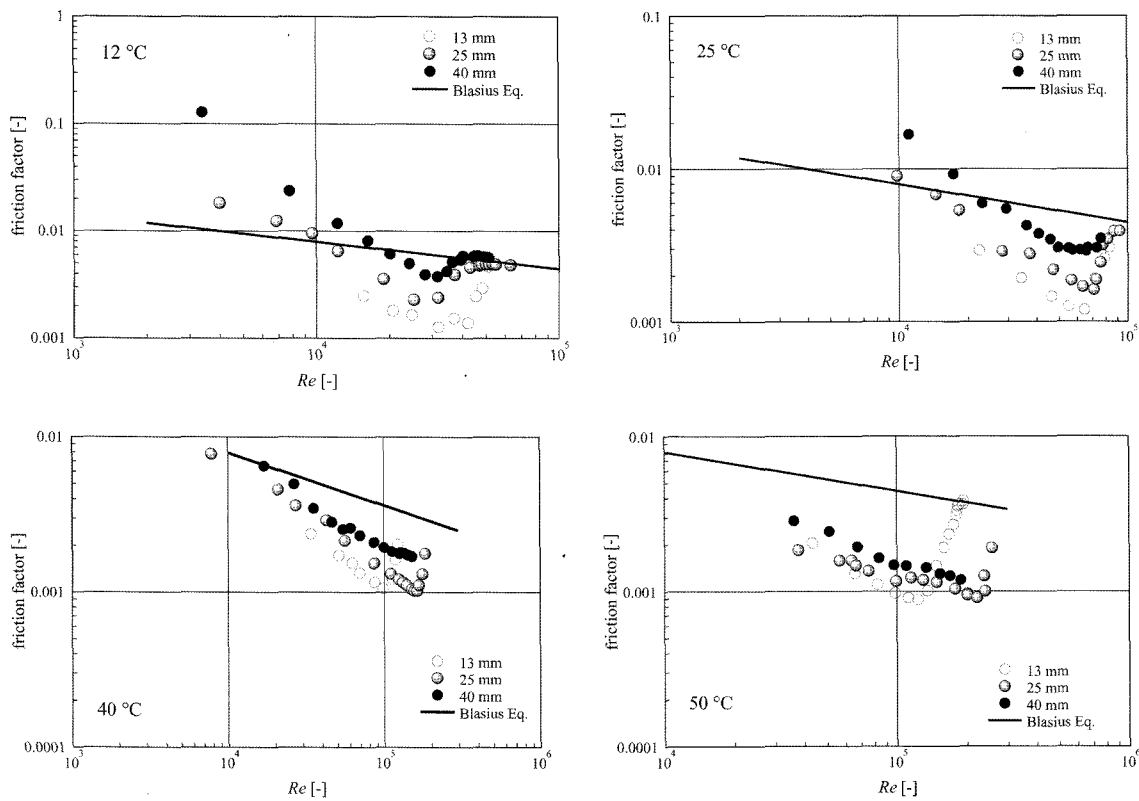


Fig. 4. Relationship between friction factor and Reynolds number of Ethoquad O/12 900 ppm + NaSal 540 ppm at various temperature.

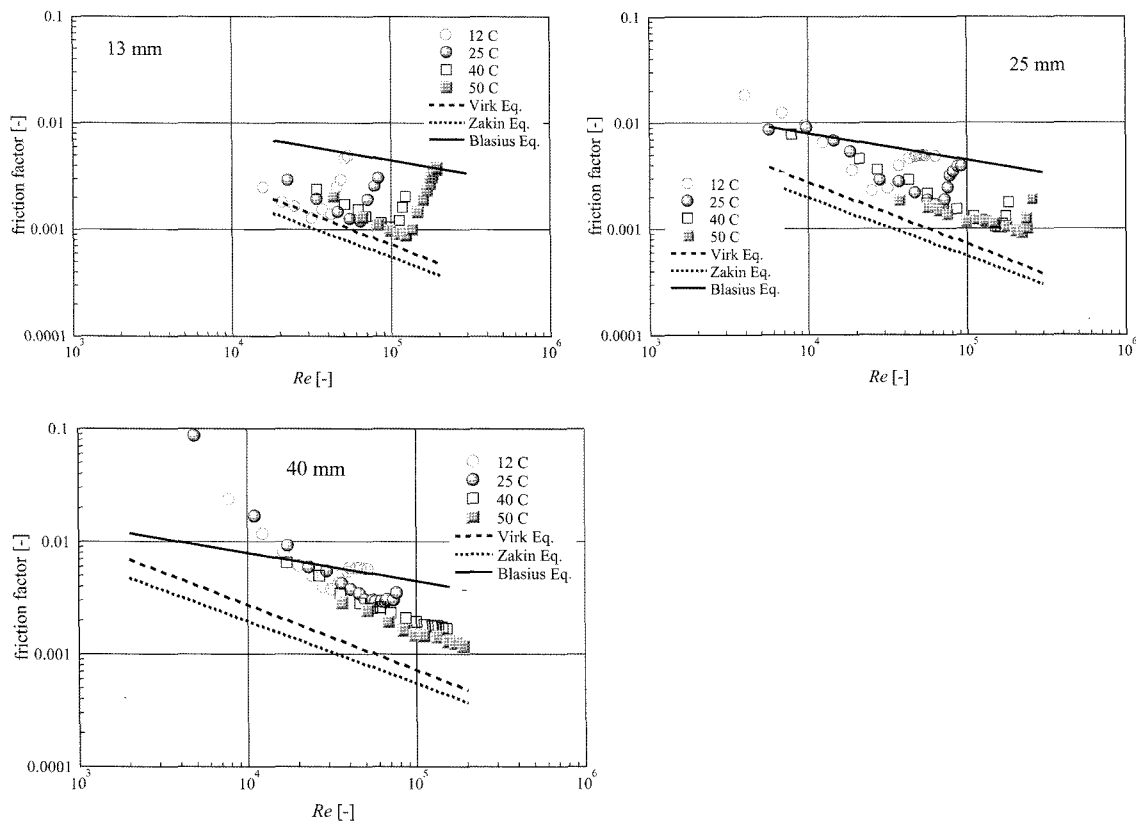


Fig. 5. Relationship between friction factor and Reynolds number at various temperature and pipe-diameter.

passes the curves of 13 mm pipe at 40 and 50°C.

3.3. Scale-up law evaluation

Result of this work has a similar pattern with previous investigation by others researchers only at high temperature. So it is predicted that the previous scale-up laws only applicable at high temperature. For simplicity reason, only data at 25°C and 50°C will be shown below.

Scale-up law as Eq. (1) and (2)

The scale-up law in Eq. (1) is plotted as a function of friction velocity, u^* , instead of Reynolds number corresponding to Eq. (2).

Scale-up law: τ_w versus V

Curves show relation between τ_w and V at temperature of 25 and 50°C are shown below.

Scale-up law: Drag reduction versus V

Curves show relation between drag-reduction versus mean velocity are given below.

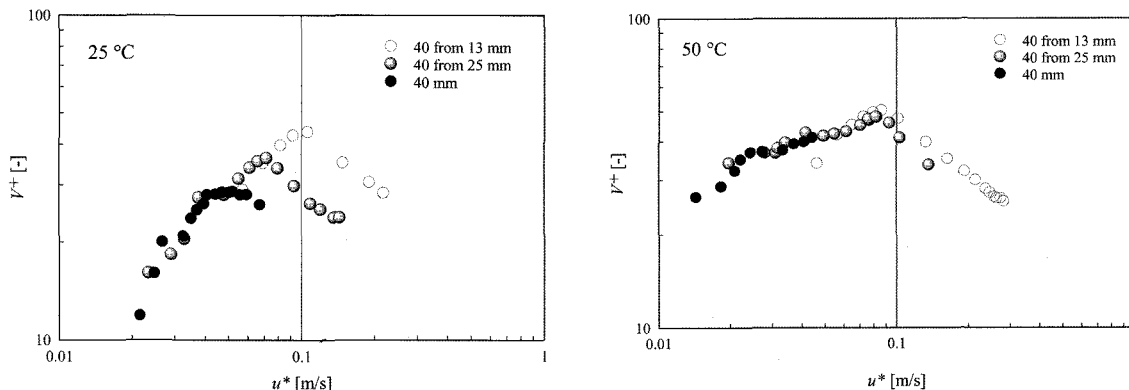


Fig. 6. Application of scale-up law proposed by Wilson as in Eqs. (1) and (2) for solution at: 25 and 50°C. In this figure, V^+ is defined as V/u^* .

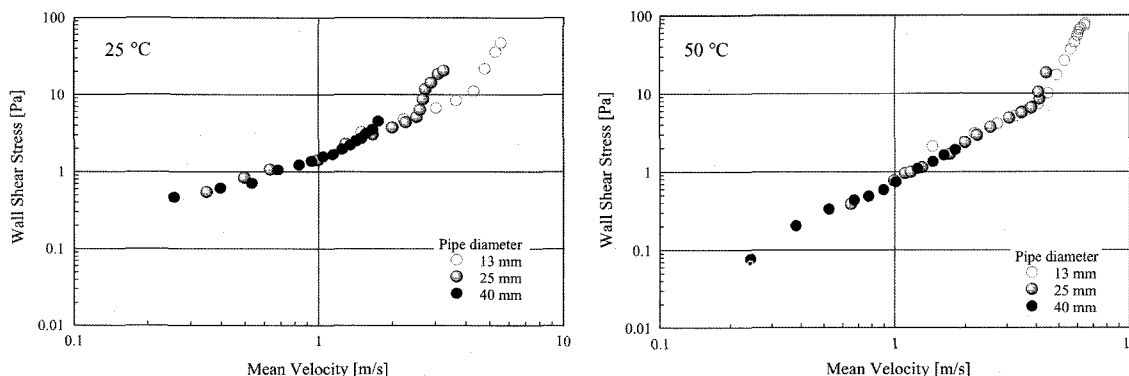


Fig. 7. Relation between wall shear stress and mean velocity of the solution at 25 and 50°C.

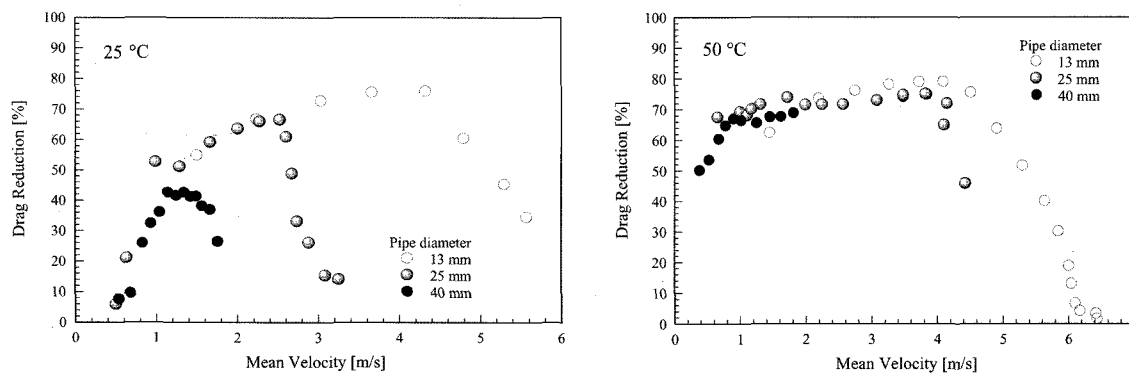


Fig. 8. Drag reduction as a function of mean velocity of the solution at 25 and 50°C.

It seems from Figs. 6-8 that the scale-up laws are well applicable at 50°C, and poor at the lower temperatures. Generally, the scale-up laws were built based on fully developed region of turbulent drag reducing flows. By evaluating the position of pressure-drop measurement at each pipe, it is clear that flow in 13 mm pipe was more developed than that in 25 and 40 mm pipe. By increase the temperature, it can be seen at Figs. 6-8 that the scale-up laws can be applied for all pipes (mainly for 13 and 25 mm pipe). There is a possibility that the applicability of the scale-up laws at 50°C maybe caused by the change of hydrodynamic entrance length in larger pipes. In general, it can be said that temperature may influence hydrodynamic entrance length of drag reducing flows. To support this argument, additional experiments were conducted in stainless-steel pipe with diameter of 13 mm. Experiments were conducted at 25 and 40°C. The data was compared with previous result of 13 mm PVC pipe in the following figure.

It can be seen from Fig. 9 that there is difference on critical Reynolds number at 25°C between both pipes. To ensure the result, the experiments were repeated, and the results are the same. On the other hand, at 40°C, both curves were coincided. Considering fully developed criteria proposed by previous investigators, it is clear that upstream pressure holes position for stainless-steel pipe was in developing flow region (i.e. $L/D = 119$ for stainless-steel and 231.5 for PVC pipe), but it should be noted that downstream pressure hole position of the stainless-steel pipe was farer (i.e. $L/D = 314$ for stainless-steel and 254 for PVC pipe). That is why the difference in critical Reynolds number between both pipes at 25°C was not large. From this supporting data, it can be concluded that temperature may responsible for changing the hydrodynamic entrance length of surfactant drag reducing flows.

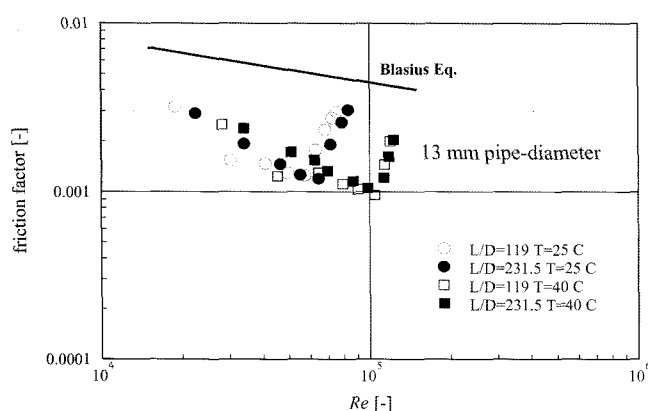


Fig. 9. Relationship between friction factor and Reynolds number at 13 mm pipe-diameter with different location of pressure holes as a function of temperature.

4. Conclusions

Temperature and diameter effects on hydrodynamics characteristic were investigated by conducting experiments on drag reducing fluid flows in three kinds of pipe diameter, i.e. 13, 25, and 40 mm at various temperatures (12, 25, 40, and 50°C). Additional stainless-steel pipe with diameter of 13 mm was used to compare the results of 13 mm PVC pipe. Ethoquad O/12 900 ppm was used as surfactant, whereas NaSal 540 ppm was used as counter-ion. Molar ratio between surfactant to counter-ion is 1:1.5. Effectiveness of the surfactant solution was evaluated by measured pressure drop and flow rate of this solution in 25 mm pipe from temperature of 6 to 75°C.

From rheological measurement, it is found that SIS occurs in the solution at 12, 25, 32.5, 40, and 50°C with different degree of peak-viscosity and critical shear rate of SIS. Critical shear rate increases whereas peak-viscosity decreases by temperature. It is believed that length changing of the rod-like micelle is responsible for the variation of peak viscosity and critical shear rate of SIS by temperature.

It is found that this surfactant solution is drag reduction effective until temperature about 70°C. At low temperature, results of this work have no similar pattern with others investigation conducted by previous researchers. But at 50°C, the similarity appears. It seems that all scale-up laws used in this work are well applicable at 50°C. The changing of hydrodynamics entrance length in 25 and 40 mm pipe by temperature may responsible for the applicability of the scale-up laws at 50°C. Additional experiments conducted in stainless-steel pipe reinforce that conclusion. It seems that temperature has significant influence in changing of hydrodynamic entrance length of surfactant drag reducing flows.

To obtain a good correlation for scale-up of DR system, we have to do the experiments at fully developed region. Because of very long entrance length is required to get fully developed condition in larger pipe diameter flow system, our experimental facility was not enough to get fully developed condition. We must be careful, however, to evaluate the scale-up law in surfactant DR. Pipe with sufficiently long hydrodynamic entrance length should be used to ensure the fully developed condition in the test section.

List of symbols

D	= Pipe diameter [m]
f	= Fanning friction factor [-]
L	= Length [m]
Re	= Reynolds number [-]
u^*	= Friction velocity [m/s]
V	= Mean Velocity [m/s]
V^+	= Dimensionless velocity [-]

- ρ = Density [kg/m³]
 η = Viscosity [Pa.s]
 τ_w = Wall Shear Stress [Pa]

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