Experimental Study on Drag Reduction Effects of New Non-Ionic Surfactants

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Key words: Drag reduction, Heat transfer efficiency reduction, Surfactant, Pressure drop

ABSTRACT: The drag reduction (*DR*) and heat transfer efficiency reduction (*ER*) of non-ionic surfactant were investigated as a function of fluid velocity, temperature, and surfactant concentration. An experimental apparatus consisting of two temperature controlled water storage tanks, pumps, test specimen pipe and the piping network, two flow meters, two pressure gauges, a heat exchanger, and data logging system was built. From the experimental results, it was concluded that existing alkyl ammonium surfactant (CTAC Cethyl Trimethyl Ammonium Chloride) had *DR* of 0.6~0.8 at 1,000~2,000 ppm concentration with fluid temperature ranging between 50~60℃. However, the *DR* was very low when the fluid temperature was 70~80℃. The new amine oxide and betaine surfactant (SAOB Stearyl Amine Oxide + Betaine) had lower *DR* at fluid temperatures ranging between 50~60℃ compared with CTAC. However, with fluid temperature ranging between 70~80℃ the *DR* was 0.6~0.8 when the concentration level was 1,000~2,000 ppm.

Nomenclature

AO	: amine-oxide
CTAC	: cethyl trimethyl ammonium chloride
DR	: drag reduction
ER	: efficiency reduction
P	: pressure [N/m^2]
SAOB	: stearyl amine oxide + betaine

Greek symbols

Δ	: difference
η	: heat transfer efficiency

Subscripts

A	: with surfactant
W	: without surfactant

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1. Introduction

The rapidly increasing demand for energy in cooling and heating applications has led to renewed focus in developing energy efficient sustainable technologies. To this end, district heating systems are considered as one of the prime candidate for space heating and cooling applications. These systems are regarded as alternative energy systems with significant potential for energy saving.[1] The most commonly used heat transmission method converts recovered heat into hot water and cool water and uses district supply pipeline to transmit the water. Transmission of hot water and cool water requires large amounts of pumping power. Especially, when transmission distance is long or when transmission volume is high, energy savings in fluid transmission become an important issue. In this regard, drag reduction in fluid transport processes has received considerable attention. Drag reduction is achieved by adding small volume of surfactants in the turbulent flow field thereby accelerating the fluid flow and reducing the drag more compared to conventional methods involving the use of solvents. An overview of drag reducing surfactants and their characteristics is covered by Zakin et al.(2) Reduction of flow resistance using water-soluble high molecule materials to reduce water drag has been researched for a long time.(3-4) In reference,(5) physicochemical properties and rheological behaviour of surfactants is studied. The results show that rodlike micelles are formed above a characteristic concentration. The drag reduction occurs because the rodlike micelles align in the direction of flow and hence contribute to drag reduction. Hu et al.(6) studied the shear thickening in low concentration surfactant solutions by investigating the properties such as slip, fracture and stability in the shear induced phase. Gasljevic et al.(7) described the phenomenon of micellar structure break-up and recovery in turbulent flows in a drag reducing surfactant solution.

From the applications point of view, Myska and Chara(8) have presented experimental results involving the use of drag reducing surfactants in a small house heating system. They reported no significant reduction in heat transfer. However, they recommend proper precautions be taken concerning bio-degradation of surfactant in long operation heating systems. In another study, a field performance was carried out in Denmark. To achieve economic viability by way of reducing the initial cost, one pipe pulsating system consisting of 7.5 km long pipeline using friction reducing additives was designed and constructed. Results showed that the overall economy is better than the conventional double pipe system.(9)

Since then, many studies on reduction of flow resistance, using cationic alkyl ammonium surfactants have been conducted. However, cationic alkyl ammonium surfactants have been found to have higher environmental load and their use has been declining over the years. To overcome this issue, new surfactants have been developed and basic research on these materials is being conducted. In Japan, research on synthesis of cationic amine-oxide surfactants with low environmental load, evaluation on *DR* effect, and mechanism of correlation between micelle structure and *DR* (Drag Reduction) effect have been recently examined by the Ministry of Economy, Trade and Industry. Based on this, basic synthesis experiment was carried out for full-fledged production of DRC-6 and DRH-4 based surfactants, and conditions for manufacturing these two materials were developed.(10)

Although research on generation of micelle related with cationic surfactants and nonionic surfactants has been conducted, the stability and *DR* characteristics have not been examined. In this study, we will present experimental results involving the use of new surfactants. These surfactants were synthesized anew to develop nonionic amine-oxide + betaine surfactants which have the lowest effect on environment. For these reasons, we are interested in examining their drag reduction (*DR*) and associated heat transfer efficiency reduction (*ER*) characteristics under various operating conditions.

2. Drag reduction surfactants

2.1 Background and the concept

The rate of micelle generation is one of the important properties of surfactants. Ideally each surfactant should be able to generate stable micelle at an optimal rate. However, usually this is not the case. Therefore, it is necessary to develop intervention strategies to enhance the rate of micelle generation. To this end, chemical composition and structure of conventional surfactants are controlled to ensure generation of stable micelle. Low-toxic and environment-friendly amine-oxide, betaine, sugar and glucamide surfactants have been studied. However, a broad evaluation of *DR* effect regarding the structure and chemical transformation of surfactants has not been addressed. The formation of a single cylindrical micelle requires that size of hydrophilic head group and size of oleophilic tail group should be kept constant. In order to keep hydrophilicity relatively high to maintain stability of micelle in high temperature area, we increased the size of head group or used the method of forming combined micelle using different-sized surfactants. Through analysis of the structure and composition of stable micelle in their formation stage, it was reasoned that if nonionic surfactants, which belong to C12 scope and have relatively small size of head group, are applied in addition to the ordinarily used main surfactants belonging to C16 scope, stable micelle would be generated.

2.2 Types of surfactants

The *DR* and *ER* performances of one alkyl ammonium surfactant (CTAC) and non-ionic Stearyl Amine Oxide + Betaine (SAOB) surfactants listed below were experimented.

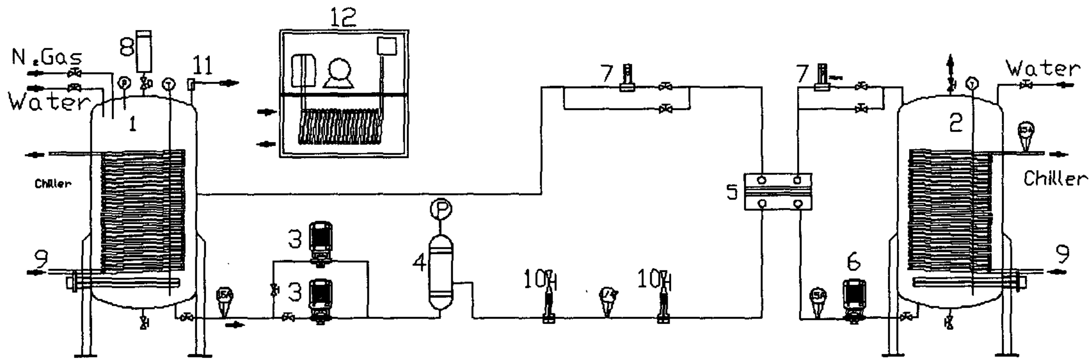
- CTAC; Cethyl Trimethyl Ammonium Chloride + Na-Salicylate (1 : 1).
- SAOB; Stearyl Amine Oxide + Betaine (1 : 1).

3. Experiments on drag and heat transfer efficiency reductions

3.1 Experimental Apparatus

The experimental setup used herein to study the performance of surfactants, in terms of drag reduction and heat transfer efficiency reduction, is depicted in Fig. 1. Figure 1 also shows the location of all measuring sensors. The experimental setup comprises of one sealed main storage tank (60 liter), one open-ended auxiliary storage tank (60 liter), two pumps, a test tube specimen for measuring drag reduction, a heat exchanger and two flow meters (accuracy: ±0.5 %FS). It also has a chiller (2 RT), two electric heaters (5 kW each), a temperature controller, two pressure sensors (Sensys, Model: PSCD-0002KAAG, range: 0~2 kgf/cm^2, output: 1~5 VDC, accuracy: ±0.5%FS) and a data logger (Agilent, Model No. 34970A).

Each storage tank contains a cooling coil connected to the chiller and an electric heater for temperature control. Especially, the sealed main



1. Main tank (60 L) 2. Auxiliary tank (60 L) 3. Pump 4. Air chamber
5. Heat exchanger 6. Pump 7. Flowmeter 8. Inlet of drag reduction additives
9. Cooling coil 10. Pressure sensor 11. Relief valve 12. Chiller (2 RT)

Fig. 1 Schematic diagram of experimental apparatus.

storage tank is designed to keep nitrogen atmosphere to prevent contact with oxygen. Water is pumped from storage tank into specimen tube, and any air that may be generated in this process is removed by an air vent. The experimental straight-tube test specimen comprises of 2 m long SUS tube of 4.2 mm diameter. The test tube is designed to keep constant fluid flow conditions as the fluid passes through it. Pressure sensors are installed to measure the pressure drop across the test specimen. This will enable determination of drag under various operating conditions.

In addition, a frequency inverter is installed to adjust the speed of the centrifugal pump and thus measure the effect of change in flow rate on drag reduction properties of surfactants. To measure the heat transfer performance, a plate-type heat exchanger (capacity: 20,000 kcal/h) is installed. Four T-type thermocouples (accuracy: ±0.5℃) are installed, which are located at inlet and outlet of hot and cold water side of heat exchanger. Circulating water pumps are installed for water flow from both storage tanks at different water temperature and measure the performance on the basis of changes in the fluid temperature, surfactant concentration and flow velocity. Drag and heat transfer performance characteristics as a function of fluid temperature, types and concentration of surfactants, and flow velocity were analyzed.

3.2 Experimental procedures

Experiments were conducted by using one alkyl ammonium surfactant and one low-toxic betaine synthetic surfactant, at fluid temperature settings of 50℃, 60℃, 70℃ and 80℃. At each temperature, four surfactant concentrations were tested: 500 ppm, 1,000 ppm, 1,500 ppm and 2,000 ppm with flow velocities ranging between 0.5~4.0 m/s.

In each test, the surfactants were added to the main tank using an injecting device shown in Fig. 1. The heaters were turned on and at the same time, the circulation pumps were turned on to initiate fluid flow in the pipes and the surfactant was added to the water. A measured quantity of surfactant was added such that the desired ppm ratio was achieved. The heater was controlled to maintain the fluid temperature at the desired setting value. Once steady state conditions were reached, measurements were made of fluid flow and temperatures of the primary fluid (with surfactant) and secondary fluid (water as heat transfer medium) across the plate heat exchanger. Also, under steady state conditions, measurements were made of pressures at the inlet and outlet of the test tube specimen to be used for drag reduction analysis. These readings were used in computing the heat transfer efficiency and drag reduction properties.

The cooling coil and refrigeration system used in the secondary circuit enables in rejecting the heat gained by the secondary fluid. Also, the cooling coil in the primary circuit was used to bring the tank temperature to the required initial conditions through mechanical refrigeration in order to reduce the time needed to establish the initial temperature conditions.

3.3 Uncertainty in measured data

In addition to the uncertainties associated with accuracy of sensors, other sources of uncertainties include the temperature deviations from steady state, and the response characteristics of the temperature control system. Taking into consideration the accuracy of the sensors stated above, the overall uncertainty in the measurements is estimated to be less than ±2%.

3.4 Performance analysis

The heat transfer performance was analyzed as a function of fluid temperature, types and concentration of surfactants and fluid flow rate.

In addition, the measured performance characteristics were compared with those obtained using filtered water without drag reducing surfactants. The drag resistance reduction ratio (DR) and heat transfer efficiency reduction ratio (ER) were defined as follows.

$$DR=\left(1-\frac{\Delta P_A}{\Delta P_W}\right),\quad ER=\left(1-\frac{\eta_A}{\eta_W}\right)$$

where, ΔP_W is pressure drop without surfactant, ΔP_A is pressure drop with surfactant, η_W is heat transfer rate without surfactant and η_A is heat transfer rate with surfactant.

4. Results and discussion

To compare the DR and ER performance of the newly developed nonionic Stearyl Amine-Oxide + Betaine surfactant (SAOB), synthesis solution combining CTAC (Cethyl Trimethyl Ammonium Chloride) and Trimethyl Ammonium Chloride and Na-Salicylate was used as a performance-proven cationic alkyl ammonium drag-reducing surfactant. The results of analysis of CTAC's DR and ER performances as a function of flow velocity, temperature and concentration are shown in Fig. 2. Note that the surfactant with less than 1,000 ppm concentration showed a drastic reduction in DR as the fluid velocity and temperature were increased. For this reason, concentration levels less than 1,000 ppm are considered as not appropriate. The DR ratio exceeded 60% for surfactant concentration over and above 1,000 ppm at fluid temperature 50℃. The DR ratio ranged between 60% to 80% at all flow velocities up to 4.0 m/s and the surfactant concentration ranging between 1,000

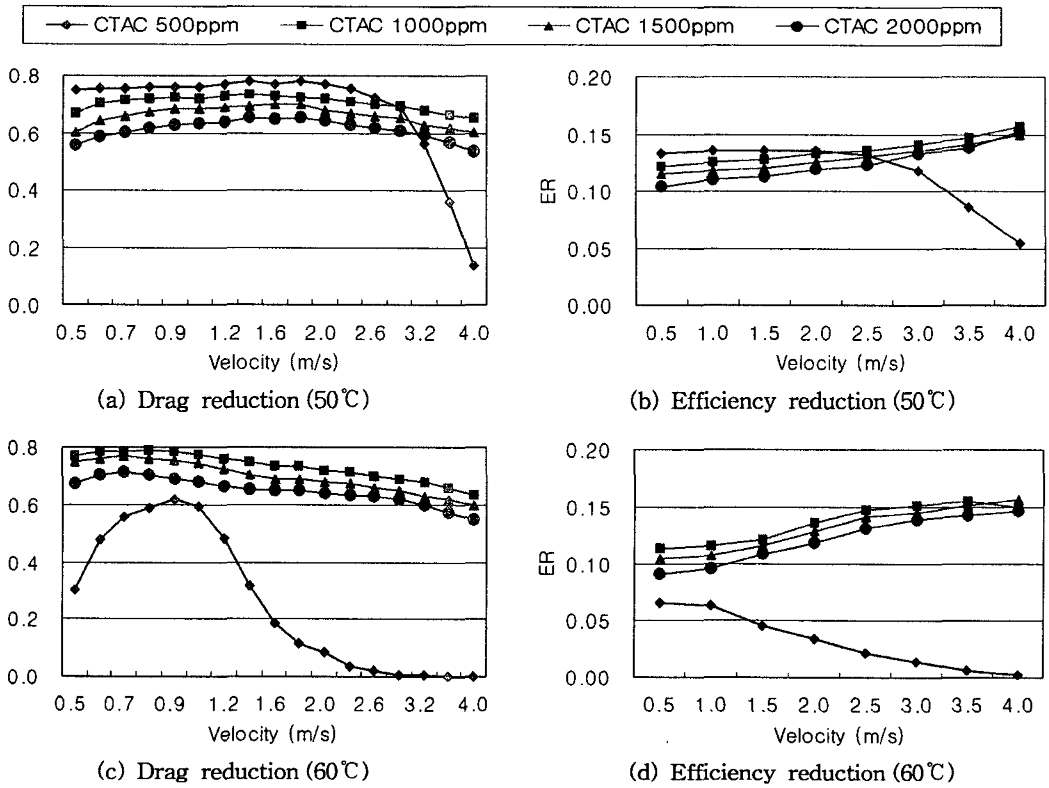


Fig. 2 DR and ER of CTAC surfactant.

ppm to 2,000 ppm with the fluid temperatures up to 60℃. However, the *DR* ratios showed sharp decrease and were very low (near zero) for accurate measurement regardless of surfactant concentration as the fluid temperature was increased to over 70℃. This result shows that there is a critical temperature limit for CTAC surfactants beyond which structural break-up of micelles occurs and therefore drag reduction decreases sharply beyond this critical temperature.

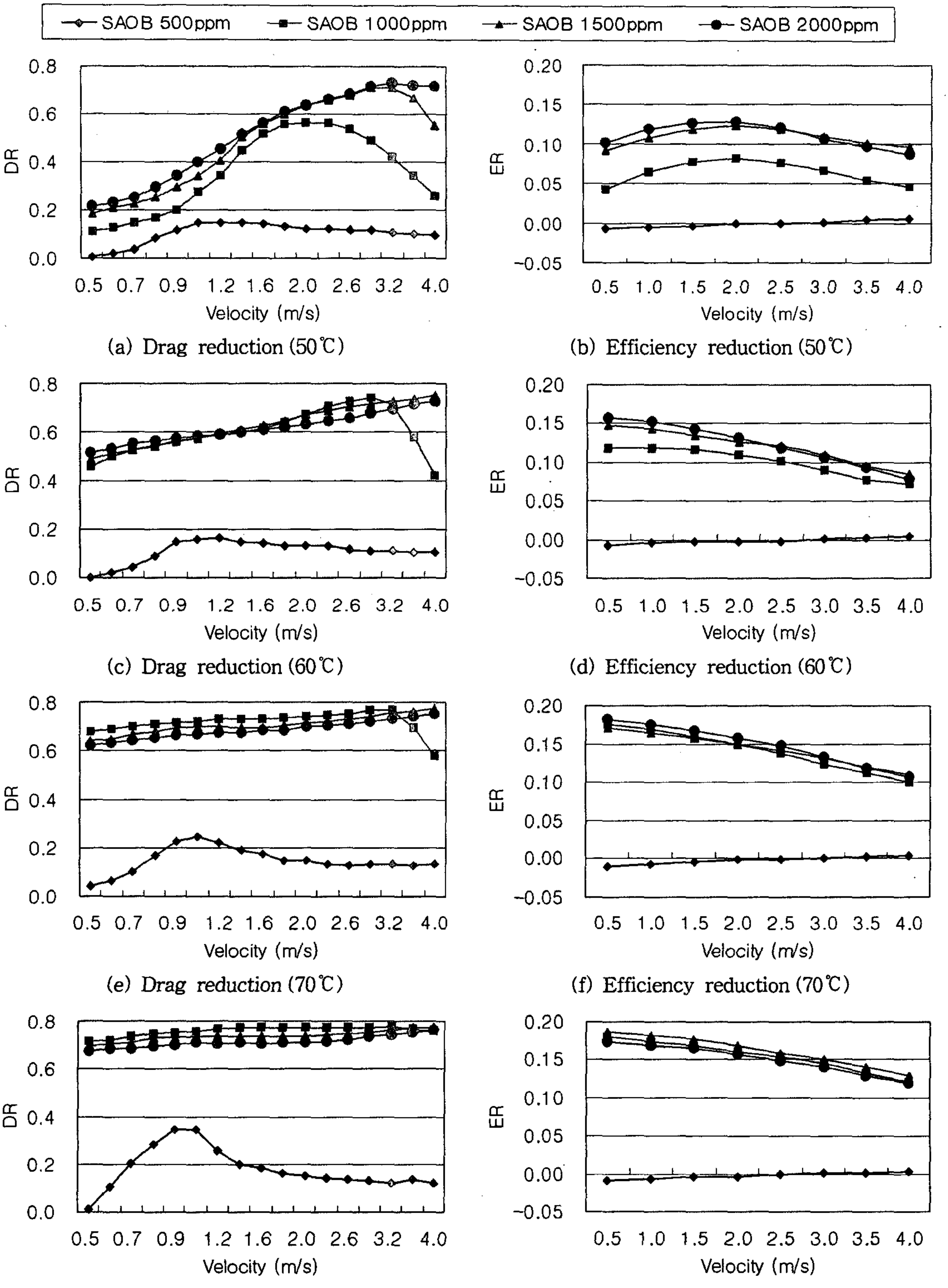
The *ER* ratio was between 10~15% regardless of surfactant concentration when the fluid temperature was 50℃ except for 500 ppm concentration level. When the fluid temperature was increased to 60℃, the *ER* ratio was no more than 7% at 500 ppm concentration, the point at which the *DR* rate showed a large drop. A 10~15% *ER* ratio was recorded for all concentration levels ranging between 1,000~2,000 ppm and the corresponding *DR* ratio was good. These results were compared with six new and environment-friendly amine-oxide + betaine surfactants. The experiments showed that SAOB (Stearyl Amine Oxide + Betaine) had the best performance of all the surfactants.

The *DR* and *ER* performances of SAOB are shown in Fig. 3. Very low *DR* ratios were recorded regardless of fluid temperature when surfactant concentration was 500 ppm. It was found that for concentration levels 1,000 ppm or greater as the fluid temperature was increased, the *DR* ratio increased as well. For example, from the results depicted in Fig. 3, we note that for surfactant concentration levels ranging from 1,000 ppm to 2,000 ppm as the fluid temperature is increased to over 60℃, the *DR* ratio increased as well. From economic point of view, the surfactant concentration should be as low as possible in real application, therefore, the concentration level of 1,000 ppm is considered as appropriate. When surfactant concentration is not less than 1,000 ppm and fluid temperature is held at 50℃, the *DR* values showed sharp decrease as the flow rate was increased. However, as the fluid temperature was increased, the *DR* values did not change with the flow rate. In general, based on the experiments conducted, we note that the *DR* values ranged between 60% to 80% regardless of the flow rate when the surfactant concentrations were between 1,000~2,000 ppm and fluid temperature was over 70℃, showing slight improvement in the *DR* performance compared to the CTAC performance (Fig. 2, at 60 ℃). Compared to CTAC, the *DR* is slightly lower in the case of SAOB at fluid temperature of 60℃ when surfactant concentration remained between 1,000 ppm and 2,000 ppm. However, when the fluid temperature was increased to 70~80℃, the *DR* values were much better. This result points to the fact that the *DR* is not significantly influenced by the temperature increase which is attributed to the fact that micelle generation in SAOB surfactant at higher temperatures is stable and thus contributing to drag reduction at higher temperatures.

As far as the heat transfer reduction is concerned it was noted that the *ER* values were near zero regardless of fluid temperature and flow rate when surfactant concentration was 500 ppm. As the fluid temperature increased, *ER* values increased as well. The *ER* values were 10~18% at fluid temperature of 70℃ and surfactant concentration over 1,000 ppm. When the fluid temperature was increased to 80℃, the recorded values of *ER* were between 12~19%.

From Fig. 3, it can be noted that the *DR* and *ER* ratios show very little differences based on concentration levels when the fluid temperature is over 70℃. Nonionic surfactants other than SAOB show the *DR* performance inferior to that of SAOB. As shown above, the *DR* and *ER* effects were analyzed by using the newly developed drag reducer for high-temperature water.

A major contribution of this study is that



(a) Drag reduction (50℃)

(b) Efficiency reduction (50℃)

(c) Drag reduction (60℃)

(d) Efficiency reduction (60℃)

(e) Drag reduction (70℃)

(f) Efficiency reduction (70℃)

(g) Drag reduction (80℃)

(h) Efficiency reduction (80℃)

Fig. 3 *DR* and *ER* of SAOB surfactant.

through experiments and analysis we have developed a technique for stabilizing the microstructure of micelle and obtained the composition of components of drag reducers showing optimal *DR* effects in high-temperature water.

Unlike the conventional drag reducers, the newly developed surfactants show good *DR* performance in the temperature range exceeding 70℃. Therefore, the developed surfactants are excellent candidates for use in high-temperature hot water systems.

5. Conclusions

Nonionic Amine-oxide + Betaine surfactants were studied as additives for reducing friction loss in the flow of water in pipes. Experiments were conducted to evaluate the performance of surfactants in terms of drag reduction and heat transfer efficiency reduction. Based on the experimental results, we offer the following conclusions.

(1) CTAC, which is a conventional cationic surfactant, recorded a *DR* performance of about 60~80% when fluid temperature was 50~60℃ and surfactant concentration 1,000~2,000 ppm. However, the *DR* values were very low regardless of surfactant concentration when the fluid temperature exceeded 70℃.

(2) The *DR* performance of the nonionic Amine-oxide + Betaine SAOB developed herein shows similar values compared to CTAC at fluid temperature 60℃ and surfactant concentration 1,000~2,000 ppm.

(3) Since the surfactant concentration should be as low as possible from the environmental and economic point of view, the results confirm that a concentration level of 1,000 ppm is most appropriate.

(4) The *DR* values of SAOB ranged between 60% to 80% regardless of flow rate when the surfactant concentrations were 1,000~2,000 ppm and fluid temperature was higher than 70℃, showing a slight improvement in *DR* performance in comparison with CTAC.

(5) Unlike conventional drag reducers, the newly developed surfactants showed good *DR* performance in the temperature range exceeding 70℃. Therefore, the developed surfactants are excellent candidates for use in high-temperature hot water systems.

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