Application of a Drag Reduction Phenomenon Caused by Surfactant Solutions

Takashi SAEKI

Department of Environmental Science and Engineering,
Graduate School of Science and Engineering,
Yamaguchi University,
2-16-1, Tokiwadai, Ube-shi, Yamaguchi 755-8611, Japan

Keywords*:* Air Conditioning System, Cooling Operation, Drag Reduction, Heat Transfer, Analogy

In 1994, the first commercial application of surfactant drag reduction was conducted in Japan for the air conditioning system in the Shunan Regional Industry Promotion Center building. A commercially available drag-reducing additive (LSP-01) based on the mixture of a cationic surfactant, a counter ion, and corrosion inhibitors was developed based on the results of the project. Since 1995, LSP-01 has been used at more than 180 sites in building air conditioning systems throughout Japan. The drag-reducing technique was adopted recently for an air conditioning system in a skyscraper in Tokyo. Here, I measured the drag reduction and heat transfer characteristics during the cooling operation of a heat exchanger for a surfactant and a counter ion system, Ethoquad O/12 and NaSal. The analogy between the momentum and heat transfer for the drag-reducing flow is also discussed.

Introduction

Many studies of surfactant drag reduction have been conducted since the 1980s, including investigations of the selection and optimization of additives, drag reduction flow properties, the mechanisms of drag reduction, and more. It is known that certain cationic quaternary ammonium surfactants with certain counter ions display significant drag reduction qualities for water. It is necessary to evaluate a surfactant according to not only the drag-reducing effect, but also the solubility in a lower temperature range (5–15°C) and the obstruction caused by some ions dissolved in water for practical use. Yamaguchi University, the Shunan Regional Industry Promotion Center, and the LSP Cooperative have collaborated to adopt a drag-reducing technology for practical use. Our group has acquired two basic patents in Japan which propose the use of cationic quaternary ammonium surfactants to reduce the energy consumption of water transportation (Usui and Tokuhara, 1992; Tokuhara and Usui, 1995) and we developed a commercial drag-reducing additive product (named LSP-01) based on the mixture of a cationic surfactant (oleylbishydroxy–ethylmethyl ammonium chloride), sodium salicylate, and corrosion inhibitors. Osaka Gas Co. selected oleyltrihydroxyethyl-ammonium chloride as an alternative quaternary ammonium cationic surfactant, and they developed another commercial drag-reducing additive product (named Eco-micelle).

Drag reduction caused by surfactant solutions is considered an effective way to reduce the pumping power in closed-loop district heating and cooling systems. In 1994, the first commercial application of surfactant drag reduction was conducted in Japan by our group for the air conditioning system in the Shunan Regional Industry Promotion Center building. The building has two stories with a total floor space of 2490 m^2, and the water capacity of the air conditioning system is 5 m^3. Since 1995, LSP-01 has been used at more than 180 sites in building air conditioning systems throughout Japan, including office buildings, hotels, hospitals, supermarkets, airport facilities, and industrial factories (Saeki *et al.*, 2002). Almost all of our drag-reducing projects showed more than a 20% reduction in the pumping power required for circulating water, and some air conditioning systems have obtained up to 60% energy savings (AIST, 2008). The water capacities of these systems were at most dozens of m^3. Recently, commercial applications of drag reduction using LSP-01 has been conducted for the air conditioning systems of very high buildings (skyscrapers) in metropolitan areas, the water capacity values of which are more than a hundred m^3. These projects demonstrate the remarkable development of this technology. However, not a few researchers have pointed out that heat transfer reduction occurs simultaneously for drag-reducing flows (Aguilar *et al.*, 2001; Inaba *et al.*, 1995, 1997; Nobuchika *et al.*; 2000; Qi *et al.*; 2001, 2003; Steiff *et al.*, 1998; Usui and Saeki, 1993). It is not easy to measure the exact heat transfer reduction for practical air conditioning systems; however, in all of the abovementioned projects with LSP-01, no predicted serious problems of heat transfer has been detected. Our group measured the heat transfer characteristics during heating operation for two types of cationic surfactant (Saeki *et al.*, 2013). Based on the results obtained under a constant heat flux condition, we proposed a suitable concentration of the surfactant which showed lower heat transfer reduction inside the heat exchanger. Since the heat transfers under the cooling operation of most air conditioning systems are conducted under constant-wall temperature conditions, the cooling ability might be reduced when heat transfer reduction occurs. Therefore, it is also necessary to show heat transfer characteristics during a cooling operation together with drag reduction effects.

Here, I present a recently developed drag-reducing technique adopted for an air conditioning system in a skyscraper in Tokyo, the water capacity of which is 140 m^3. The heat transfer data measured during the cooling operation of a heat exchanger is also shown in order to consider the heat transfer reduction in a lower temperature range. This information will be useful for future designs incorporating this technology.

1. Experimental

1.1 Materials

The drag-reducing additive used for the air conditioning system of a skyscraper in Tokyo was a commercial product, LSP-01M (LSP Cooperative Union, Shunan), which contains the following:

- Cationic surfactant: oleylbishydroxyethyl -methylammonium chloride, $C_{18}H_{35}N(C_2H_4OH)_2CH_3Cl$, Commercial name: Ethoquad O/12 produced by Lion Akzo Co.
- Counter ion: sodium salicylate (NaSal) HOC_6H_4COONa
- Corrosion inhibitor for iron and zinc: sodium molybdate, Na_2MoO_4
- Corrosion inhibitor for copper:

Commercial name: Chiolite, produced by Chiyoda Chemical Co.

The weight ratio of the surfactant and NaSal is 1.67, which was determined previously (Saeki *et al.*, 2013) as the suitable concentration by taking into account both the drag-reducing effect and the heat transfer characteristics. The drag-reducing additive used for the laboratory experiment was also a mixture of Ethoquad O/12 and NaSal.

1.2 Air conditioning system of Tokyo skyscraper

Our group used the drag-reducing technology for the practical air conditioning system of a 23-story skyscraper in Tokyo with a 3-story basement and a total floor space of 88,000 m^2. The water capacity of the system was 140 m^3. The air conditioning system consisted of the following three systems:

1) Lower-level system:
   Primary loop with 14 heat pumps
   Secondary loop to fan coil units and air handling units
2) Middle-level system:
   Primary loop with 6 heat pumps
   Secondary loop to fan coil units and air handling units
3) Upper-level system:
   Primary loop with 15 heat pumps to fan coil units and air handling units

Plate-type heat exchangers were installed to transfer the heat from the primary loops to the secondary loops. Since the detailed plumbing constitution is not formally open, the drag-reducing effect was evaluated by comparing the flow rates obtained before and after the addition of LSP-01M. The experiment was conducted during the cooling operation in the summer of 2012, and the flow rate was measured using an ultrasonic flowmeter (Model Portaflow X, Fuji Electric Co.).

1.3 Laboratory heat transfer experiment

The experimental apparatus used for the drag reduction and heat transfer measurements is a recirculation system, shown in **Figure 1**. Drag-reducing agents were added to a tank and solutions were prepared. The temperature of the solutions was controlled by a heater with a temperature control device. The flow rate was controlled by an inverter system installed to a main pump and was measured by an electromagnetic flow meter (Model FD-83,

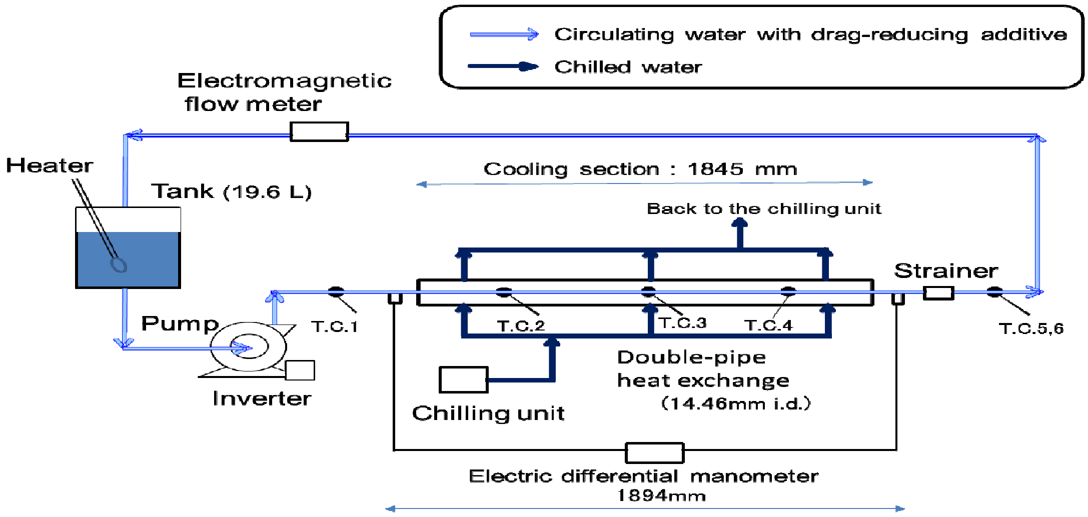

Fig. 1 Experimental apparatus

Keyence Co.). The cooling section was a double-pipe heat exchanger which consisted of an inner copper tube and an outer polyvinyl chloride (PVC) pipe. The copper tube was a practical heat exchanger tube (inside dia. 14.5 mm, outside dia. 17.1 mm). The length of the heat exchanger was 1845 mm. Enough chilled water (4°C) was supplied to the outer pipe to obtain a constant wall temperature condition during the cooling section. The wall temperatures outside the copper pipe were measured at three points (thermocouples [T.C.] 2, 3, and 4) by T-type thermocouples buried in the pipe (depth = 0.5 mm), and the average wall temperature, T_{wall}, was calculated. The inlet temperature, T_{in}, was measured just before the section (T.C. 1). Two T-type thermocouples (T.C. 5 and 6) were fixed at different positions inside the pipe just after a strainer, and the outlet temperature of the heat exchanger, T_{out}, was obtained by averaging these values. All of the thermocouples were connected to a data logger (Model ZR-RX40, Omuron Co.). The uncertainty in any thermocouple reading was less than ±0.05°C. All of the data were obtained over 5 min and averaged. The temperature difference between the inlet and outlet of the heat transfer test section was set at more than 0.5°C throughout the experiments. The pressure drop was measured with an electric differential manometer (Model MT-210, Yokogawa Electric Co.) between taps installed in a 1894-mm-long copper pipe.

Friction factors were determined as follows using Eq. (1).

$$f = \frac{1}{4}\Delta P \frac{D}{L} \frac{1}{\rho u^2/2} \tag{1}$$

For a convenient comparison of the drag reduction results between water and test solutions, I defined a drag reduction rate, *DR*%, as follows in Eq. (2).

$$DR\% = \frac{f_{\mathrm{w}} - f_{\mathrm{s}}}{f_{\mathrm{w}}} \times 100 \tag{2}$$

Reynolds numbers were calculated with the property of water (Ohlendorf, 1986) at the average temperature of the inlet and outlet of the test section. The amount of heat flow was calculated using Eq. (3).

$$Q = GC_{\mathrm{p}}(T_{\mathrm{out}} - T_{\mathrm{in}}) \tag{3}$$

The heat transfer coefficient was calculated using Eq. (4).

$$h = \frac{\mathrm{Q}}{A\Delta T_{\mathrm{lm}}} \tag{4}$$

Where, ΔT_{lm} is a log mean temperature difference defined as Eq. (5).

$$\Delta T_{lm} = \frac{(T_{\mathrm{in}} - T_{\mathrm{wall}}) - (T_{\mathrm{out}} - T_{\mathrm{wall}})}{Ln[(T_{\mathrm{in}} - T_{\mathrm{wall}}) / (T_{\mathrm{out}} - T_{\mathrm{wall}})]} \tag{5}$$

Here, for a convenient comparison of the heat transfer results between water and test solutions, I defined the heat transfer reduction rate, *HTR*%, as follows with Eq. (6).

$$HTR\% = \frac{h_{\mathrm{w}} - h_{\mathrm{s}}}{h_{\mathrm{w}}} \times 100 \tag{6}$$

2. Results and Discussion

2.1 Drag-reducing effect for the skyscraper's air conditioning system

Before the addition of the drag-reducing additive, the average flow rate of the lower primary loop was 508 m^3/h, the frequency setting of the inverter was 46 Hz, and the current of the loop main pump was 46A. LSP-01M was injected from a branch arm of the pump discharged pipe at the concentration 3000 mg/L (the concentration of Ethoquad

O/12 was 300 mg/L). As the drag reduction occurred, the flow rate rose to 575 m^3/h, which is equivalent to a flow rate increase of 13.1%. The flow rate was then adjusted to the former value (508 m^3/h) by reducing the frequency of the inverter to 34 Hz. Consequently, 31.0% energy saving was achieved for the lower primary loop, assuming that the voltage and power factor are constant.

Table 1 shows the overall results of the energy-saving rate for the air conditioning system. The energy-saving rate depends on the loops, which might be caused by the difference in plumbing constitution, the pumping power, the operation rate of the air conditioners, and so on. As a result, the addition of LSP-01M brought about a more than 15% reduction in energy consumption of the pumps in this project.

Table 1 Energy-saving rate evaluated for each loop of the skyscraper

Level	Loop	Energy-saving rate [%]
Upper	Primary	21.0
Middle	Primary	N/A
	Secondary	36.9
Lower	Primary	31.0
	Secondary	15.0

2.2 Heat transfer characteristics of drag-reducing surfactant solutions in a lower temperature range

As a preliminary work, drag-reduction measurements were carried out on Ethoquad O/12 (200 mg/L) with NaSal solutions at different weight ratios at 12.5°C. **Figure 2** shows the friction factors, *f*, and the Reynolds numbers, *Re*, for the solutions. The friction factor decreased with the Reynolds number and reached minimum values at *Re*=20737. At this point, the drag reduction percent was around 60% and the average velocity was 1.73 m/s. When the Reynolds number was further increased, the drag reduction was lost rather abruptly. The minimum friction factor values were almost the same for the weight ratios 1.67 to 5.0. Also, taking into account the cost of the additive, the weight ratio 1.67 is suitable to obtain a sufficient drag-reducing effect in a lower temperature range, which is the same value as that obtained for a higher temperature range (Saeki *et al.*, 2013). In the practical applications of the drag-reducing effect, the adsorption of the surfactant to a pipe wall occurs frequently, which leads to excess counter ion conditions. Even the ratio of NaSal increases from the suitable value; however, no serious problem may occur with the drag-reducing effect.

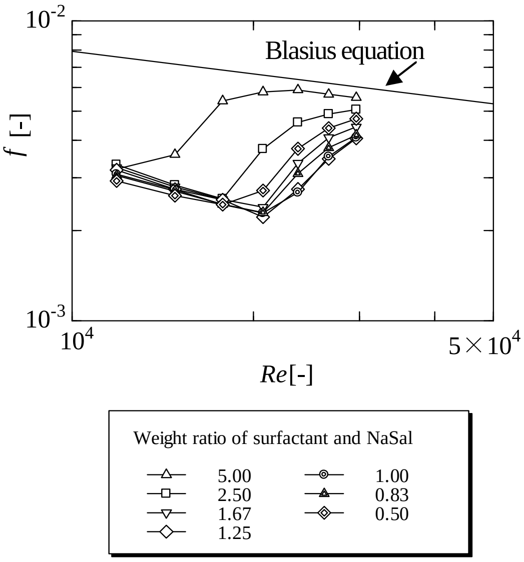

Fig. 2 Drag reduction results for Ethoquad O/12 and NaSal systems at different weight ratios at 12.5°C

Figure 3 shows the drag reduction results for Ethoquad O/12 and NaSal systems at different surfactant concentrations. A typical trend of the drag reduction can be seen for 200 mg/L, i.e. the drag reduction increased with the Reynolds number and reached the maximum point. When the Reynolds number was further increased, the drag reduction was lost rather abruptly. Since this phenomenon might be caused by the breakup of the surfactant micelle structures due to high shear, the maximum point was shifted to a lower Reynolds number for the lower concentration. In contrast, the 500 mg/L solution maintained a high level of drag reduction over a higher Reynolds number range.

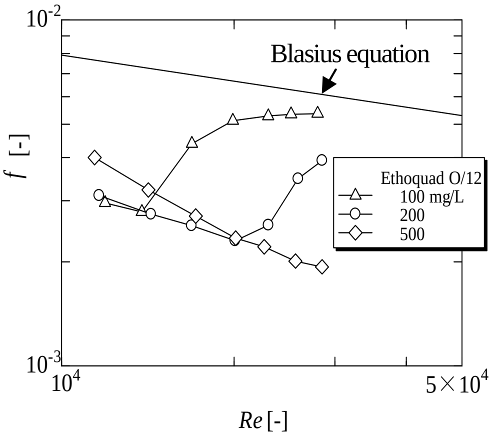

Fig. 3 Drag reduction results for Ethoquad O/12 and NaSal systems at different concentrations at 12.5 °C

Figure 4 gives the corresponding heat transfer test results for the solutions. The figure presents the relation between the $Nu/Pr^{0.4}$ values and the Reynolds numbers. All of the solutions with the drag-reducing additive showed significant heat transfer reduction. The 100 and 200 mg/L Ethoquad O/12 solutions reached the Newtonian line (cf. the Dittus–Boelter equation) in a higher Reynolds number region; however, the 500 mg/L solution maintained a high level of heat transfer reduction.

Figure 5 shows the *DR%* for the Ethoquad O/12 solutions in which the horizontal axis was chosen as the average velocity. In this experimental range, the maximum drag reduction reached a peak of around 65%. The average velocity that showed the maximum *DR%* decreased with the decrease of the surfactant concentration. Micelle aggregates of the drag-reducing surfactant are expected to suffer mechanical degradation inside heat exchangers, in which the average velocity inside the equipment is usually designed to be in the range of 2.0 m/s to 2.5 m/s for practical air conditioning systems.

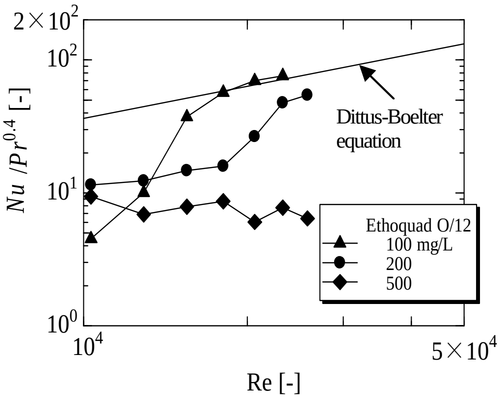

Fig. 4 Heat transfer results for Ethoquad O/12 and NaSal systems at different concentrations at 12.5 °C

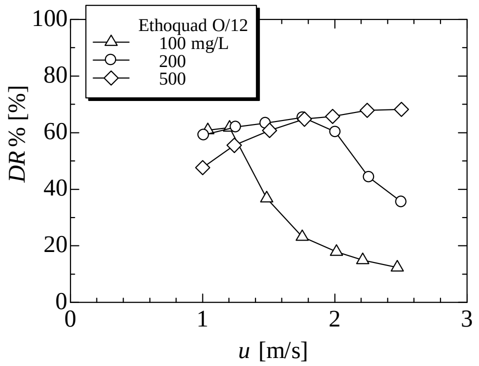

Fig. 5 Drag reduction as a function of average velocity for Ethoquad O/12 and NaSal systems at different concentrations at 12.5°C

Figure 6 shows the *HTR%* for the solutions versus the average velocity. The maximum drag reduction reached a peak of 75% to 90%. The 100 and 200 mg/L Ethoquad O/12 solutions showed considerably small *HTR%* values at the average velocity > 2 m/s, which confirms that no serious problem of heat transfer occurred inside exchangers.

Since the absolute values of *DR%* do not accord with those of *HTR%*, the analogy between the momentum and heat transfer is invalid for the drag-reducing flow. However, a tendency which shows a sudden fall at higher Reynolds numbers (higher average velocity) is similar to the *DR%* with *HTR%* for the same additive concentration. One of the reasons for this inconsistency of the analogy law may be related to the complex rheology of the drag-reducing solution.

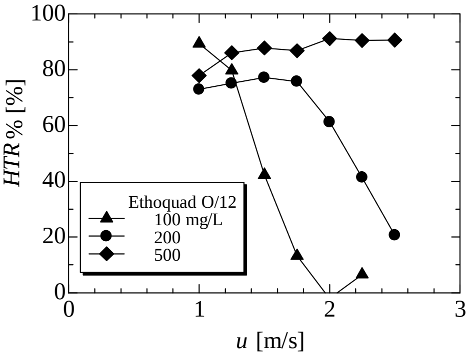

Fig. 6 Heat transfer results as a function of average velocity for Ethoquad O/12 and NaSal systems at different concentrations at 12.5°C

Finally, as a practical aspect of the drag-reducing application, maintaining the concentration of the surfactant is quite important to prevent the heat transfer reduction, as well as to obtain sufficient energy saving by the drag reduction.

Conclusions

A drag-reducing technique was adopted for the air conditioning system of a 23-story skyscraper in Tokyo, the pumps of which showed a more than 15% reduction of energy consumption. Based on the drag reduction results and the heat transfer characteristics of a surfactant, Ethoquad O/12, the analogy between the momentum and heat transfer for the drag-reducing flow might be invalid for the drag-reducing flow; however, the trend of *DR%* with Reynolds number is almost the same as that obtained with *HTR%*. Maintaining the concentration of the surfactant is quite important to prevent the heat transfer reduction as well as to obtain sufficient energy saving by the drag reduction.

Acknowledgements

I thank Mr. T. Matsumura and Mr. Y. Terada of the LSP Cooperative for the valuable information and discussion on the skyscraper project , and student colleagues S. Kobayashi and S. Shigemura for their assistance with the experiments.

Nomenclature

A = cross-sectional area inside a tube [m^2]
C_p = specific heat [J·kg^{-1}·K^{-1}]
D = tube diameter [m]
DR% = drag reduction percent defined by Eq. (2) [%]
f = friction factor [-]
G = flow rate [kg·s^{-1}]
h = heat transfer coefficient [J·m^{-2}·s^{-1}·K^{-1}]
HTR% = heat transfer reduction percent defined by Eq. (8) [%]
L = length of the test section [m]
Nu = Nusselt number [-]
Pr = Prandtl number [-]
Q = volumetric flow rate [m^3·s^{-1}]
Re = Reynolds number [-]
T = temperature [°C]
u = average velocity [m/s]
ΔP = pressure difference [Pa]
ΔT = temperature difference [°C]
ρ = density [kg/m^3]
<Subscript>
s = surfactant
w = water

Literature Cited

Aguilar G., K. Gasljevic, and E. F. Matthys; "Asymptotes of Maximum Friction and Heat Transfer Reductions for Drag-reducing Surfactant Solutions," *Int. J. Heat Mass Transfer*, **44**, 2835-2843 (2001)

AIST (The National Institute of Advanced Industrial Science and Technology); AIST Press, Tsukuba, Japan, "Energy Saving by Rinse Ingredient!" (2008) (in Japanese)

Inaba, H., K. Ozaki, N. Haruki and H. Asano; "Flow Resistance and Heat Transfer Characteristics of Water Solution Flow with Surfactant in Circular Tubes," *Trans. Jap Soc. Mech. Enginrs*, B, **61**, 3304-3310(1995)

Inaba, H. and N. Haruki; "Flow Resistance and Heat Transfer Characteristics of Cold Water Pipe Flow with Surfactant for Cold Heat Energy Transport," *Trans. Jap Soc. Mech. Enginrs*, B, **63**, 1336-1343(1997) (in Japanese)

Nobuchika, K., T. Nakata, K. Sato, F. Yamagishi, S. Tomiyama, H. Inaba, A. Horibe and N. Haruki; "Drag Reduction and Heat Transfer Enhancement of Water Flow in a Pipe Using New Surfactants for Environmentally Acceptable Drag Reducing Additives," Proc. of Symp. on Energy Engineering in the 21st Century, Hong-Kong, P. Cheng, ed., Wallingford, U. K., 695-700 (2000)

Ohlendorf, D., W. Interthal, and H. Hoffmann: "Surfactant Systems for Drag Reduction: Physico-Chemical Properties and Rheological Behaviour," *Rheol. Acta*, **25**, 468-486 (1986)

Qi, Y., Y. Kawaguchi, Z. Lin, M. Ewing, R. N. Christensen and J. L. Zakin; "Enhanced Heat Transfer of Drag Reducing Surfactant Solutions with Fluted Tube-in-tube Heat Exchanger," *Int. J. Heat Mass Transfer*, **44**, 1495-1505 (2001)

Qi, Y., Y. Kawaguchi, R. N. Christensen and J. L. Zakin; "Enhancing Heat Transfer Ability of Drag Reducing Surfactant Solutions with Static Mixers and Honeycombs," *Int. J. Heat Mass Transfer*, **46**, 5161-5173 (2003)

Saeki, T., K. Tokuhara, T. Matsumura, and S. Yamamoto; "Application of Surfactant Drag Reduction for Practical Air Conditioning Systems" (in Japanase), *Trans. Jap Soc. Mech. Enginrs*, B, **68**, 1482-1488 (2002)

Saeki, T., Y. Yoshida, N. Tanaka, S. Kobayashi, and S. Shigemura; "Drag Reduction and Heat Transfer Reduction of Cationic Surfactant Solutions During the Heating Operation of an Air Conditioning System," *Kagaku Kogaku Ronbunshu*, **39**, 1-8 (2013)

Steiff, A., K. Klopper and P. Weinspach; "Influence of Drag Reducing Additives in Heat Exchangers," Proc. of 11th IHTC, 317-322, Kyongju, Korea (1998)

Usui, H., "Heating Process and Apparatus by the Thermal Energy Transportation from a Short Distance Heat Source," Japanese Patent No.3453583 (1992)

Usui, H. and T. Saeki; "Drag Reduction and Heat Transfer Reduction by Cationic Surfactants," *J. Chem. Eng. Japan*, **26**, 103-106 (1993)

Tokuhara, K. and H. Usui, "Flow Accelerants for Fluids and Thermal Energy Transportation Method Using Them," Japanese Patent No.3671450 (1995)