International Journal of Heat and Mass Transfer 52 (2009) 3547–3554

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Drag-reducing and heat transfer characteristics of a novel zwitterionic surfactant solution

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ARTICLE INFO

Article history:
Received 26 May 2008
Received in revised form 27 February 2009
Accepted 2 March 2009
Available online 15 April 2009

Keywords:
Novel zwitterionic surfactant
Drag-reduction
Heat transfer enhancement
Elongational stress

ABSTRACT

Experiments were conducted to study the drag-reduction and heat transfer performances of a newly synthesized zwitterionic surfactant solution (oleyl trimethylaminimide) in a two-dimensional channel. For testing the drag-reduction at subzero temperatures, a 20% ethylene glycol aqueous solution (EG/W) was used as solvent. The surfactant concentration ranged from 50 to 1000 ppm and the temperature was −5 and 25 °C, respectively. It was found that the novel zwitterionic surfactant solution showed both drag and heat transfer reduction characteristics, which were affected by concentration and temperature. The maximum drag-reduction was 83% at 25 °C for 200 ppm surfactant solution. The effects of addition of $NaNO_2$ to the surfactant solution were also investigated. For enhancing heat transfer of the surfactant drag-reducing flow, a destructive device, named Block, was designed and used in the experiments. The Block device has two contracting–expanding flow passages on both sides respectively with the central part blocked. It was found that the Block device can enhance the heat transfer performance of the novel zwitterionic surfactant solution to some extent while having a very small pressure drop penalty compared with other researcher's destructive devices due to the dominant action of elongational stress.

1. Introduction

Surfactant drag-reduction is a well-known phenomenon. The friction drag can be greatly reduced by adding a small amount of surfactant into turbulent flows. In the Reynolds number region of industrial interest, the amount of turbulent friction drag-reduction (DR) sometimes approaches 80% [1–3]. Surfactants are widely accepted as the most practical drag-reducing additives in district heating and cooling systems (DHC) for reducing pumping power or increasing flow rate because they are rather stable and show no permanent mechanical degradation compared with polymers [4,5].

In a district cooling system, working fluid is chilled at a central station and then is fed to a primary system which circulates the chilled fluid to cool fluid in one or more secondary systems often several kilometers away. The secondary system circulates the cooled fluid to remove heat from buildings in a district. For the district cooling system, in addition to adding surfactant drag-reducing additives (DRAs) into the circulating fluid in the primary system to save pumping energy, adding ethylene glycol to the water allows the working fluid to be chilled to subzero temperatures thus increasing the temperature difference between the circulating fluid leaving and returning to the chiller in the primary system, thus reducing the mass flow rate giving further savings in pumping energy. In conventional district cooling systems, water is used as the working fluid and is usually cooled to about 5 °C at the outlet of the central station, whereas a subzero temperature of −5 °C can be obtained by using a 20 wt% ethylene glycol based water solution (EG/W solution) as the working fluid in the primary system. The return temperature to the central station is about 15 °C for both cases. Thus the temperature difference can be increased from 10 °C when using water to 20 °C by using 20 wt% EG/W solutions, allowing the mass flow rate of the circulating fluid to be reduced by a factor of two. Therefore, it is of great importance to study the drag-reduction and heat transfer behaviours of surfactant solution in EG/W solvent at subzero temperatures.

There are only three studies of surfactant drag-reduction in the presence of co-solvent. To increase the heating capacity of heated pipe bundles in subsea oil production systems from the Gullfaks

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doi:10.1016/j.ijheatmasstransfer.2009.03.008

Nomenclature

C_m	surfactant concentration, (ppm)
c_p	specific heat, (kJ/kg K)
f	Fanning friction factor, $\tau_w/(0.5\rho U_b^2)$
h	heat transfer coefficient, $q_w/(T_w$-$T_b)$, (W/m^2 K)
H	channel height, (m)
L	distance between the two pressure taps for ΔP measurements, Fig. 2, (m)
L_1	distance between the two pressure taps for ΔP_1 measurements, Fig. 2, (m)
Nu	local Nusselt number, $h/(H\lambda)$
Pr	Prandtl number, $\mu c_p/\lambda$
q_w	local wall heat flux, (W/m^2)
Re	Reynolds number, $\rho U_b H/\mu$
Rec	critical Reynolds number
T_b	local fluid temperature, (°C)
T_{in}	inlet fluid temperature, (°C)
T_r	Trouton ratio
T_w	wall temperature, (°C)
U	local time-mean streamwise velocity, (m/s)
U_b	bulk velocity, (m/s)
x	streamwise direction
y	wall normal direction
Greek symbols	
ΔP	pressure drop in the heating section, Fig. 2, (Pa)
ΔP_1	pressure drop over destructive device, Fig. 2, (Pa)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	elongational stress (Pa)
τ	shear stress (Pa)
τ_w	wall shear stress, $\Delta PH/2L$, (Pa)

South field in the North Sea, a zwitterionic surfactant was added to the heating medium of 17% EG/W, which resulted in over 50% flow rate increase [6]. Hellsten and Oskarsson [7] also showed the DR ability of zwitterionic/anionic surfactant mixtures in 5–35% EG/W from 30 to 80 °C. Zhang et al. [8] further investigated the effect of EG on surfactant drag-reduction. They tested the drag-reduction performance of Ethoquad O12 in 20% EG/W from 0 to 50 °C, and found that the addition of EG as a co-solvent reduced DR effectiveness, but the negative effect diminished at lower temperature. The heat transfer performance of surfactant in EG/W was not reported. As is well known, heat transfer reduction always appears in the surfactant drag-reducing flow with water as the solvent. Li et al. [1–3] made detailed heat transfer measurements. They found that the heat transfer coefficient decreased drastically and the heat transfer reduction (HTR) was somewhat larger than that of the drag-reduction. This is a serious drawback in district cooling systems because the circulating fluid removes heat and heat transfer characteristics in heat exchangers are of great importance. It is generally believed that the surfactant DR and HTR are caused by the formation of micellar network structures in the surfactant solution. Heat transfer enhancement of drag-reducing surfactant solutions may be obtained by temporarily destroying the surfactant micellar networks with destructive devices, such as wire meshes [2], static mixers [9] and fluted tubes [10]. These destructive devices actually enhanced the heat transfer of the surfactant solution greatly, but the pressure drop also increased greatly due to the large shear stresses generated by the destructive devices.

In the present study, a drag-reducing channel flow of a newly developed zwitterionic surfactant solution in EG/W solvent at both subzero and room temperatures was experimentally studied for understanding its drag-reduction and heat transfer characteristics. For heat transfer enhancement while avoiding the large pressure drop penalty problem, a new type of destructive device having contracting–expanding flow passages was designed and tested in the drag-reducing channel flow.

2. Experimental apparatus and procedure

2.1. Test facility

The water channel test facility for turbulent drag and heat transfer experiments was a closed loop shown schematically in Fig. 1. The system consisted of a reservoir tank (2.0 m^3), a pump, a chiller, a settling chamber equipped with a nozzle, a two-dimensional channel, a diffuser and an electro-magnetic flowmeter with a resolution of 0.01 m^3/min. The chiller was connected to the reservoir tank with cooling pipes and has a capacity of 11 kW to cool down the surfactant solution in the reservoir tank to -10 °C. In order to maintain a constant fluid temperature at low temperatures, a 15 kW heater was installed in the reservoir tank to provide a heat balance with the chiller. At high temperatures, a cooling coil immersed in the reservoir tank was used instead of the chiller to maintain a heat balance with the heater. The temperature of the fluid was controlled to within ±0.1 K around a prescribed value. A 9-mm thick insulation layer, made of Armaflex F-020 (product of Armacell LLC) having a thermal conductivity of 0.04 W/m K, was attached on the outside surfaces of the tank, the channel and connecting pipes between the tank and the channel.

The surfactant solution was circulated by the pump and supplied to the settling chamber. The chamber was equipped with a perforated pipe, stainless steel mesh and 1/12.5 contraction nozzle. At the entrance of the test section, a 150-mm long honeycomb having 10×10 mm^2 rectangular openings was used to remove large eddies.

The two-dimensional channel was 40 mm high, 500 mm wide and 10 m long (inside measurement), which was connected straightly by five sections of 2 m each. The last section served as a heat transfer section with a single-sided heating surface. The 20 mm thick channel walls made of transparent acryl resin except for the heating wall. The schematic of the heating section is shown in Fig. 2. The heating wall consisted of a 3-mm thick copper plate and ten independent strips of electric heaters each of which was made by embedding a Nichrome wire into a patch of silicon rubber. The ten heaters having the same spanwise width as the channel width were sequentially glued on the outer surface of the copper plate by an electrically insulating but highly thermal conductive adhesive (Shin-Etsu Silicone, Shin-Etsu Chemical Co., Ltd., Japan), and thus the heating plate was divided into 10 parts along the flow direction. Each heater was independently heated by an A.C. power supply. The voltage and current were measured to calculate the local wall heat flux q_w. Ten T-type thermocouples were embedded into the outer surface of the copper plate with the positions corresponding to the centers of the heater patches for local wall temperature measurements. An independent heater-sensor circuit was designed for each heater to control the local wall temperature T_w. In the experiments, the local wall temperatures of all ten parts of the copper plate were set to the same value, making the heating plate serve as an isothermal heater. One thermocouple was set at the entrance of the heating section corresponding to the first part of the heating plate to measure the inlet bulk temperature. The

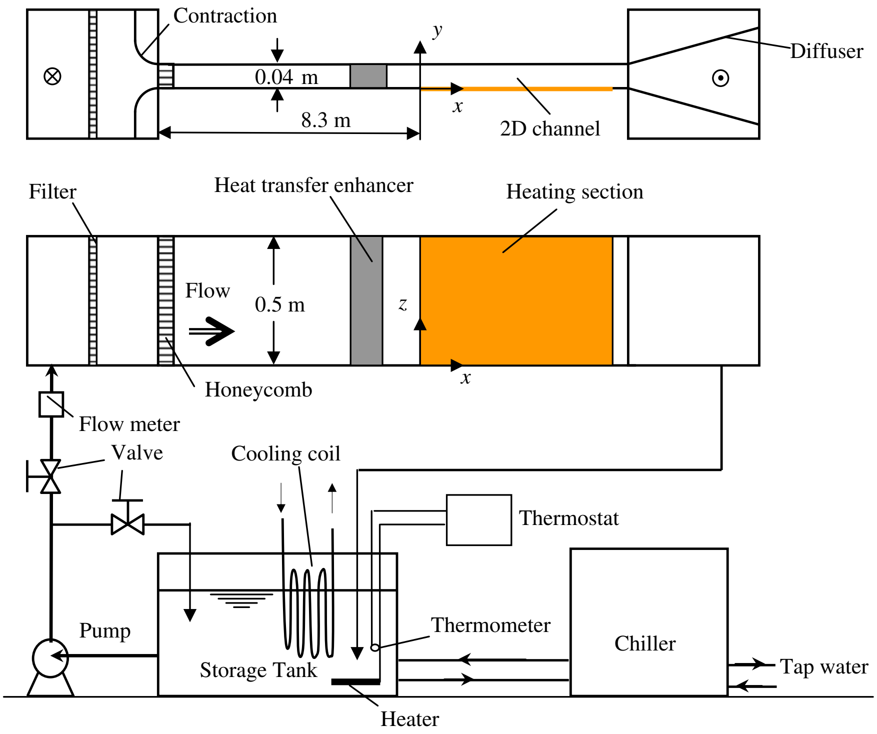


Fig. 1. Experimental facility.

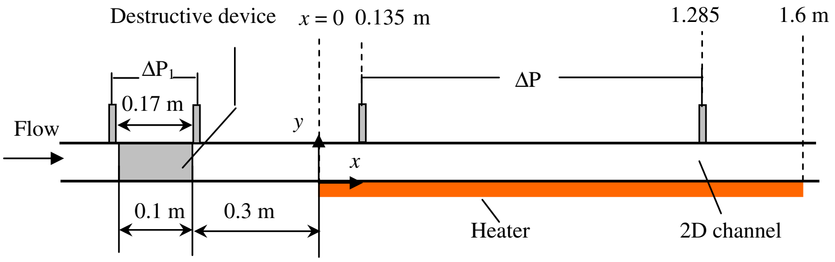


Fig. 2. Heating section.

local bulk temperatures corresponding to the other parts of the heating plate were estimated from the heat balance between the electric power and temperature increment of the flow. A data acquisition unit, IMDA 100-01E (Yokogawa Electric Co., Japan) having a high A/D resolution of ±20,000 was connected to a personal computer that automatically converted the thermocouples' output voltages into temperatures. When all temperatures were monitored to reach a steady state, temperature readings started and lasted for several minutes. The average values of the temperatures were used as experimental data. The local heat transfer coefficient was calculated based on the local wall temperature, T_w, local bulk temperature, T_b, and local heat flux, q_w, at the heating plate surface.

The local pressure drop ΔP_1 across the destructive device was measured by static pressure taps with a pressure transducer resolution of 0.1 Pa. The pressure drop ΔP over a distance of 1.15 m in the heating section was also measured to calculate the friction factor, f, downstream from the destructive devices.

2.2. Destructive device

A destructive device can destroy the surfactant micellar network structures and thus promote the heat transfer of the drag-reducing flow. Most of the previous studies employed destructive devices to generate large shear stresses for destroying the micellar networks, resulting in a large pressure drop penalty since the wall shear stress is directly proportional to the pressure drop. Elongational stress can also destroy the micellar structure but has a smaller effect on the pressure drop. Therefore, in this study, a new destructive device, Block, was designed to utilize the elongation

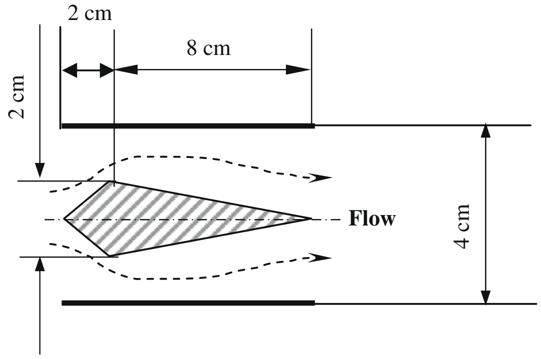


Fig. 3. Block destructive device.

stress effect on enhancing heat transfer of surfactant drag-reducing flow, as shown in Fig. 3. The Block destructive device has a length of 10 cm and a width of 4 cm, and has two contracting–expanding flow passages on both sides respectively with the central part blocked. The contracting–expanding ratio of the flow passage is 0.5. The surfactant flow passing through the Block device will experience an acceleration first and then a deceleration, which causes the flow to experience higher shear and elongation rates for the destruction of surfactant micellar networks.

2.3. Surfactant solutions

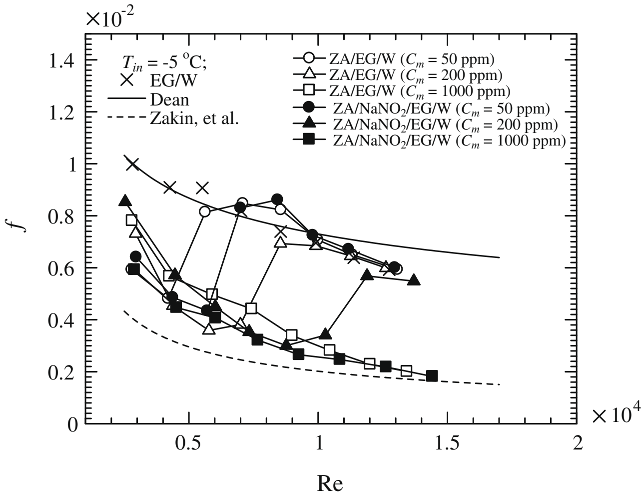
The surfactant tested was a newly developed zwitterionic surfactant (oleyl trimethylaminimide), designated ZA here, which was synthesized by Ohio State University. About 20 wt% EG/water solution was used as the solvent. Three different mass concentrations of 50, 200, and 1000 ppm of ZA were tested. ZA is a newly synthesized surfactant. There are no data in the literature for its CMC (Critical Micelle Concentration). However, literature data for zwitterionics of different structures but containing C18 alkyl groups show CMC values below 0.01 millimoles (33.8 ppm), well below the concentrations studied in this paper. To test the effect of salt, experiments were also conducted with $NaNO_2$ added to the surfactant solution. The mass ratio of $NaNO_2$ to ZA was 1:5. $NaNO_2$ is used for corrosion protection in real applications. For convenient comparison of the drag-reduction and heat transfer of surfactant solution with the results obtained by the solvent, the physical properties of the solvent were used for computing the Reynolds number, the Nusselt number and the Prandtl number of both the 20 wt% EG/water flow and the surfactant solution flow. The physical properties of EG/water solution can be found in Ref. [11]. The temperature of the surfactant solution was set to −5 °C in the experiments. Experiments were also conducted at 25 °C for investigating the temperature effect.

2.4. Uncertainty analyses

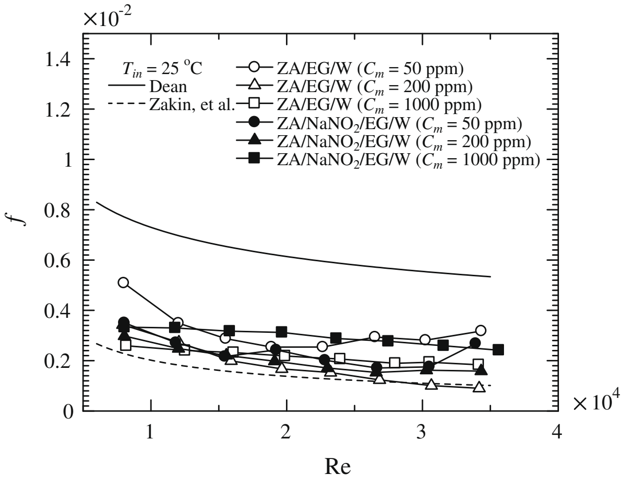
Uncertainties of the calculated results were estimated by using the root-sum-square method of Kine and McClintock [12]. By calibration of the measuring instruments, the uncertainties of measured values for temperature, pressure drop, flow rate, voltage and resistance of the electric heater were determined to be ±0.1 °C, ±1.0 Pa, $\pm 7.5 \times 10^{-3}$ m^3/min, ±1.4 V, and ±0.01 Ω, respectively. The distance of the pressure taps, the length of the heating plate, channel height, and spanwise width have uncertainties of ±0.7 mm, ±0.7 mm, ±0.1 mm, and ±0.14 mm, respectively. For convenience, the uncertainties of the experimental results that were calculated from measured values were expressed as percentages compared to the values of the results. The pressure drop measured for the Block destructive device has uncertainty of less than ±0.5%. The bulk velocity and Reynolds number both have uncertainties of ±1.5%. Because of the small values of pressure drops of drag-reducing flows, the wall shear stress, τ_w, and friction factor, f, have uncertainties of ±3.5% and ±4.7%, respectively. The uncertainties of the heat transfer coefficients are affected significantly by uncertainties of temperature and the heat flux. With the heat loss taken into account, the uncertainties of heat transfer coefficients are estimated to be less than ±6% for drag-reducing flow. The uncertainties of Nusselt numbers are essentially almost equal to the uncertainties of heat transfer coefficient.

3. Results and discussion

Fig. 4(a) and (b) show the friction factors of ZA surfactant solution flow in a smooth channel for three different surfactant concentrations with and without the addition of $NaNO_2$ at T_{in} = −5 and 25 °C, respectively. For comparison, the friction factors given by Dean's equation [13] for two-dimensional Newtonian turbulent flow and the minimum friction factor for surfactant drag-reducing flow given by the Zakin et al. equation [14] are also shown in Fig. 4(a) and (b). All surfactant solutions show obvious drag-reduction (DR) which is defined as the percentage reduction of the friction factor of drag-reducing flow below that of solvent flow (Newtonian fluid). At T_{in} = −5 °C and C_m < 1000 ppm, there exists a critical Reynolds number, Rec, above which the DR vanishes. Rec increases with increasing surfactant concentration. It was pointed out by Ohlendorf et al. [15] that the length and thus strength of rod-like micelles increase with increasing surfactant concentration. The critical Reynolds number is actually a threshold at which the network of rod-like micelles starts to disintegrate. Therefore, it is expected that the disassociation of the surfactant micellar network with high concentrations must occur at a high threshold of Reynolds number. No critical Reynolds number is found for C_m = 1000 ppm and 200 ppm at T_{in} = 25 °C due to the limited pump ability for generating a relative large flow rate (shear stress) in the present study. At T_{in} = −5 °C, the addition of $NaNO_2$ widens the Reynolds number range for effective DR by increasing Rec, whereas at T_{in} = 25 °C, it reduces the drag-reduction effectiveness for concentrations of 200 and 1000 ppm.



(a) T_{in} = -5 °C



(b) T_{in} = 25 °C

Fig. 4. Friction factors versus Reynolds number in a two-dimensional smooth channel.

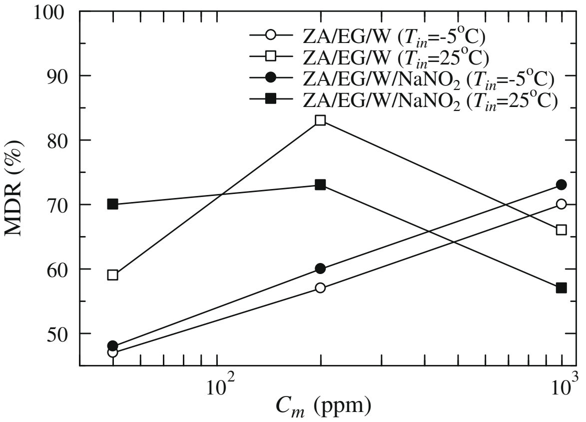
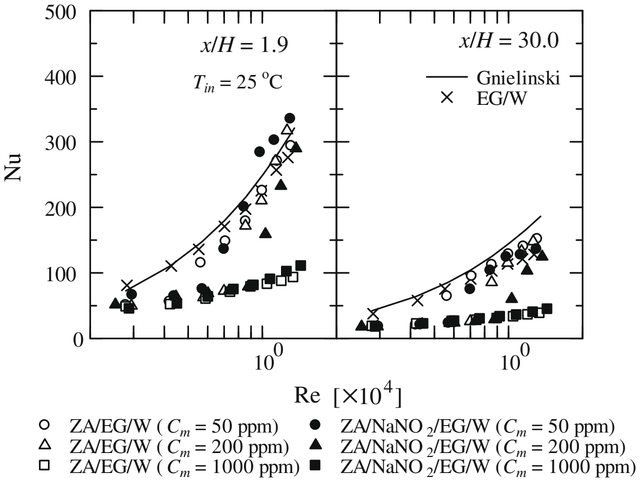


Fig. 5. Maximum drag-reduction versus C_m for ZA/EG/W with and without NaNO$_2$.

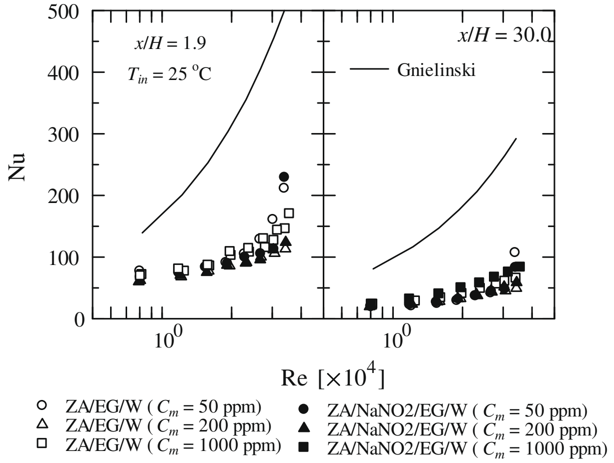
Fig. 5 shows the maximum drag-reduction (MDR) versus the surfactant concentration, C_m, for ZA/EG/W with and without NaNO$_2$. For the lower concentrations of 50 and 200 ppm, the maximum drag-reduction (DR) at 25 °C (59% at 50 ppm and 83% at 200 ppm) was larger than that at −5 °C (47% at 50 ppm and 57% at 200 ppm); while for 1000 ppm, the maximum DR at 25 °C (66%) is a little smaller than that at −5 °C (70%). Addition of NaNO$_2$ (the mass ratio of NaNO$_2$ to ZA was 1:5) slightly increased the maximum DR at −5 °C, but the maximum DR was decreased by 10% at 25 °C for the concentrations of 200 and 1000 ppm.

From the results shown in Figs. 4 and 5, we can see that the addition of NaNO$_2$ has two different effects on the drag-reduction performance of ZA surfactant solution. It can enhance the drag-reduction performance at low temperatures and low concentrations, whereas it has a negative effect on the drag-reduction performance at high temperatures and high concentrations.

Fig. 6(a) and (b) show the local Nusselt numbers of ZA surfactant solution flow in a smooth channel for three different surfactant concentrations with and without NaNO$_2$ at T_{in} = −5 and 25 °C, respectively. For comparison, the results for EG/W flow and Gnielinski's equation [16] for the heat transfer of Newtonian turbulent flow in the hydraulic fully developed and thermally developing region are also shown. All surfactant solutions at 25 °C show obvious heat transfer reduction (HTR) which is defined as the percentage reduction of Nusselt number of drag-reducing flow relative to solvent flow. The characteristics of the heat transfer reduction are similar to those of the drag-reduction shown in Fig. 4. We can see that there is a large decrease of Nusselt numbers of the surfactant flow compared to that of the EG/W flow at low Reynolds numbers (the maximum HTR is about 70%). At T_{in} = −5 °C, for Reynolds numbers larger than Rec, the Nusselt numbers of the surfactant flow increase up to the same values of EG/W flow, due to the complete destruction of the surfactant micellar network structures caused by large shear stresses. However, at 1000 ppm, no critical Reynolds number was found and HTR is large. Generally, the local Nusselt numbers are largest at the station near the entrance of the heating section and decrease with increasing distance away from the entrance. The micellar networks in ZA surfactant solution were weak at low temperatures and low concentrations and were destroyed giving small or no HTR.



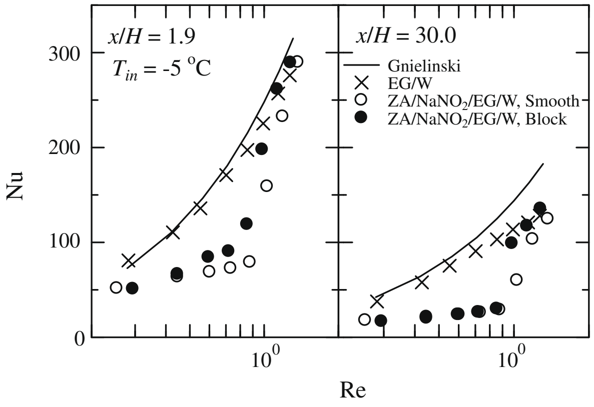
(a) T_{in} = -5 °C



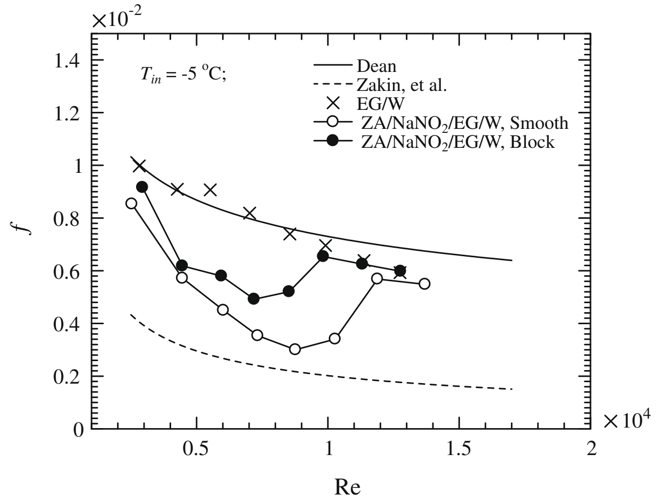
(b) T_{in} = 25 °C

Fig. 6. Local Nusselt number versus Reynolds in a two-dimensional smooth channel.

Effective surfactant DR in EG/W solvent at subzero temperatures is desirable for the new approach to energy savings in district cooling systems mentioned in the Introduction section. However, the HTR problem must be solved before real applications are possible. We have developed a destructive device for heat transfer enhancement at minimum pressure loss (see Fig. 3). Fig. 7 shows the heat transfer and drag-reduction results for the 200-ppm ZA/NaNO$_2$/EG/W with the Block destructive device designed in the present study at T_{in} = −5 °C. Fig. 7(a) shows the local Nusselt number versus Reynolds number at two different stations downstream from the Block destructive device. For comparison, the results for a smooth channel without the Block destructive device for EG/W and surfactant solutions are also shown. The heat transfer performance with the destructive device shows some improvement compared to that for the smooth channel. Li et al. [2] found that when the Reynolds number was close to the critical Reynolds number, their mesh plug could promote the heat transfer coefficient of drag-reducing flow effectively. At Re = 10,000, the average heat transfer reduction decreases from 44% for the smooth channel to 18% for the Block destructive device. Fig. 7(b) shows the friction factors of surfactant solutions versus Reynolds number, which were measured downstream from the entrance of the heating section. For comparison, Dean's line for Newtonian turbulent flow [13] and Zakin et al. asymptote for maximum drag-reduction of surfactant solutions [14] are also shown. We can see that the DR for the case with the destructive device is smaller than that for the smooth case. This indicates that the micellar structures are partially destroyed by the destructive device. The decrease of DR caused by the destructive device corresponds to the heat transfer enhancement shown in Fig. 7(a). At Re = 10,000, the drag-reduction de-



(a) Local Nusselt Number



(b) Friction factors

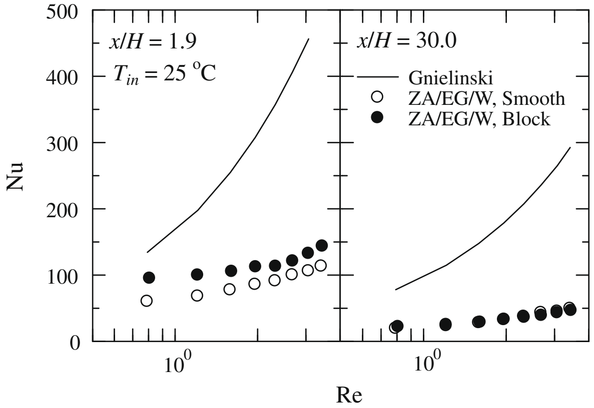
Fig. 7. Effect of Block destructive device on heat transfer and drag-reductions of 200-ppm ZA/NaNO$_2$/EG/W solution at $T_{in} = -5$ °C.

creases from 51% for the smooth channel to 6% for the Block destructive device. The heat transfer reduction is larger than the drag-reduction. The heat transfer and drag-reduction results for the 200-ppm ZA/EG/W with the Block destructive device at $T_{in} = -5$ °C are almost the same, so they are not reported here.

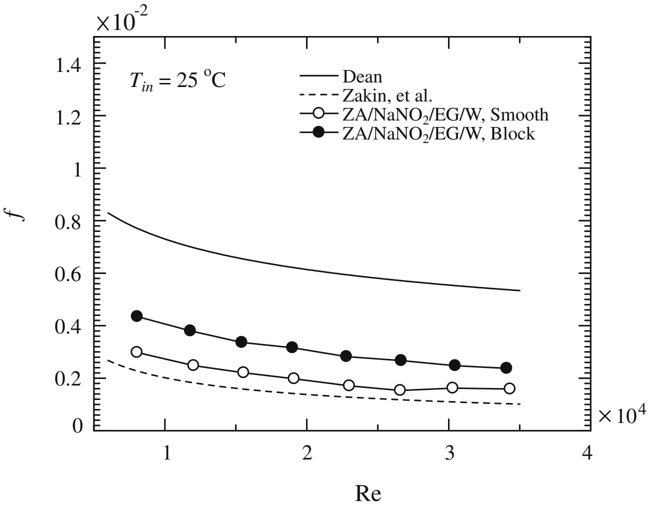
After the fluid flows through the destruction area, flow re-develops and one may wonder if the heat transfer is enhanced even in the case without surfactants. The analysis is as follows. The elongational flow generated in the Block destructive device can break the surfactant network microstructure, making the surfactant lose drag-reduction ability and thus increasing heat transfer. From the comparison of friction factors in Fig. 7(b), we can see that the surfactant flow with and without the Block destructive device at a Reynolds number of about 13,000 shows the same friction factor as that of the solvent EG/W, indicating that the surfactant solution has lost its drag-reduction ability completely without the destructive device. For this kind of surfactant flow without drag-reduction, the elongation flow in the Block destructive device has no effect on heat transfer enhancement. If flow re-development after the destruction device can enhance heat transfer greatly, the Nusselt number for the surfactant solution with the block at Re of 13,000 should be much larger than that without the block. However, from the left figure in Fig. 7(a), we can see that the Nusselt numbers at the Reynolds number of about 13,000 are almost the same for the solvent EG/W and the surfactant solution with and without the Block destructive device. This indicates that the flow re-development after the device has a negligible effect on heat transfer enhancement. However, the heat transfer of the surfactant drag-reducing flow can be enhanced by the destructive device when the flow loses drag-reduction ability.

Fig. 8 shows the heat transfer and drag-reduction results for the 200-ppm ZA/EG/W with the Block destructive device at $T_{in} = 25$ °C. Fig. 8(a) shows the local Nusselt number versus Reynolds number at two different stations downstream from the Block destructive device. The Block destructive device has a minor enhancing effect on the heat transfer of the surfactant drag-reducing flow only at a very short distance from the entrance. Since no critical Reynolds number is detected in the investigated Re range, the large heat transfer enhancement near Rec shown in Fig. 7(a) is not observed here. Fig. 8(b) shows the friction factors of surfactant solutions versus Reynolds number. We can see that the DR for the case with the destructive device is smaller than that for the smooth case although the mean heat transfer enhancement is not obvious.

Fig. 9 shows the dimensionless pressure drop of surfactant solutions over the destructive device. The pressure drops for all surfactant drag-reducing flows and EG/W flows are almost the same, and are much lower (10–80 times lower) than those for the destructive devices of Mixers A and B tested in a 5-mM Ethoquad T13/NaSal surfactant drag-reducing flow [9] and for the destructive device



(a) Local Nusselt Number



(b) friction factors

Fig. 8. Effect of Block destructive device on heat transfer and drag-reductions of 200-ppm ZA/EG/W solution at $T_{in} = 25$ °C.

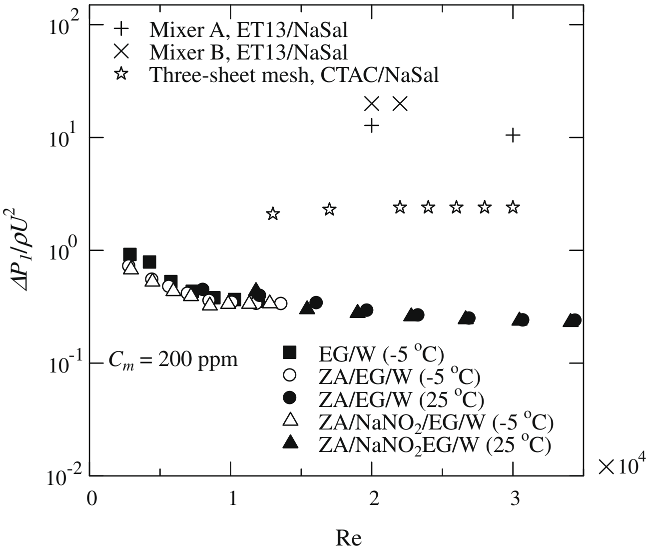


Fig. 9. Local pressure drop across the Block destructive device.

of mesh with three sheets tested in a 30-ppm CTAC/NaSal surfactant drag-reducing flow [2].

For overall evaluation of heat transfer enhancement and pressure loss by destructive device, we propose a heat transfer enhancement coefficient C_{HTE}, which is defined as

$$C_{HTE} = \frac{(\mathrm{Nu}'_m - \mathrm{Nu}_m)/\mathrm{Nu}_m}{\Delta P_1/\rho U_b^2} \tag{1}$$

where Nu_m is the mean Nusselt number of drag-reducing flow in a smooth channel, and Nu'_m is the mean Nusselt number of drag-reducing flow with destructive device. Eq. (1) represents the heat transfer enhancement of drag-reducing flow caused by destructive device relative to a smooth channel per unit pressure loss. Table 1 lists the maximum values of C_{HTE} for the destructive devices of the Block in the present study and the mesh in Ref. [2]. The maximum C_{HTE} values were obtained from measurements at different Reynolds numbers. For investigating the surfactant effect, the value of C_{HTE} for the Block device in a preliminary experiment is also shown for a 40-ppm CTAC (Cetyltrimethyl Ammonium Chloride) solution with water as the solvent and the same concentration of NaSal (Sodium salicylate) as the counterion. We can see that the values of C_{HTE} are different for the same Block destructive device with different surfactant solutions. This is probably due to different time characteristics for the micellar networks for different surfactant solutions. Therefore, we can not compare the C_{HTE} values for different surfactant solution directly. For the same surfactant solution of CTAC/NaSal/W with the same temperature at a similar concentration, we can see that the Block device achieves much larger values of C_{HTE}, about seven times the C_{HTE} value of the mesh device. The CTAC surfactant solution with the higher concentration of 40 ppm has a stronger micellar network than the 30 ppm and is therefore more resistant to break down by the destructive devices.

Table 1
Maximum C_{HTE} values for Block and mesh destructive devices.

Destructive devices	Block	Block	Mesh [2]
Surfactant solution	ZA/NaNO$_2$/EG/W	CTAC/NaSal/W	CTAC/NaSal/W
Surfactant concentration (ppm)	200	40	30
Temperature (°C)	−5	30	30
Re	10,000	50,000	30,000
C_{HTE}	1.8	5.5	0.8

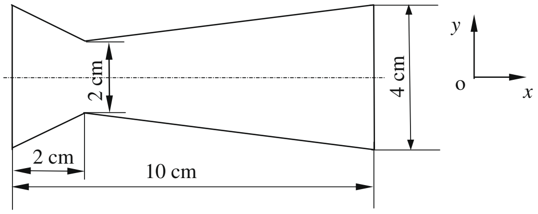


Fig. 10. Geometry of the contracting–expanding channel.

Li et al. found that the mesh device has a very limited effect in enhancing the heat transfer for a 40-ppm CTAC surfactant solution compared with that for a 30-ppm one [2]. Therefore, the Block destructive device can give a larger heat transfer enhancement under the same condition of pressure drop penalty compared with the mesh destructive device.

The improvement in enhancing heat transfer is attributed to the elongation stress. Here, a simplified model is used to analyze the elongational stress contribution to the destruction of micellar networks in a model contracting–expanding channel, the geometry of which is shown in Fig. 10. Considering the energy contributed by turbulence in a drag-reducing flow probably only amounts to 20% of the total energy [17], for simplifying the calculation, we omitted the contribution from turbulence and evaluated the shear and extension stresses on the micellar networks in surfactant drag-reducing flow by

$$\tau = \mu \frac{\partial u}{\partial y}, \tag{2}$$

$$\sigma = Tr \times \mu \frac{\partial u}{\partial x}, \tag{3}$$

where Tr is the Trouton ratio depending on the thermo-physical properties of the solution.

The velocity distribution in the y direction at different x direction positions is obtained by inter- and extrapolations from experimental data.Power consumptions defined in terms of the shear stress P_τ and extensional stress P_σ will be

$$P_\tau = \int_V \frac{\partial(\tau \cdot u)}{\partial y} dV, \tag{4}$$

$$P_\sigma = \int_V \frac{\partial(\sigma \cdot u)}{\partial x} dV, \tag{5}$$

where V denotes the volume of the contracting–expanding channel. Hence, the power percentage of the extension stress $r_{p\sigma}$ is

$$r_{p\sigma} = 100 \times \frac{P_\sigma}{P_\tau + P_\sigma}. \tag{6}$$

Power consumption along the channel can be correlated with the pressure drop ΔP by

$$P_s = \Delta P \times S_{av} \times u_{av} = P_\tau + P_\sigma \tag{7}$$

Here S_{av} is the averaging cross-section area normal to the flow.

The typical experimental data of a 50 ppm ZA/EG/W drag-reducing channel flow are used here for numerical computation. From Eqs. (2)–(7), we get $T_r = 60$ and $r_{p\sigma} = 96.3$, indicating that the elongational stress plays a dominant role in destroying the micellar networks in the contracting–expanding channel. Therefore, the idea of using elongational stress to destroy micellar networks is feasible for designing efficient destructive devices to enhance heat transfer of drag-reducing flows. In this study, the Reynolds number must be properly selected to be near the critical Reynolds number for obtaining large heat transfer enhancement, indicating that the elongational stress generated by the Block destructive device is not large enough. Further improvements of the destructive device are to be made by increasing elongational stress, one of which is to increase the contracting–expanding ratio of the flow passage of the destructive device.

4. Conclusions

Two-dimensional drag-reducing channel flow of a novel zwitterionic surfactant solution, ZA, with the concentration ranging from 50–1000 ppm was experimentally studied with and without the addition of $NaNO_2$. A newly designed destructive device, Block, was tested for enhancing heat transfer of drag-reducing surfactant flow. The main conclusions are;

(1) All surfactant flows showed large drag-reduction and heat transfer reduction. For $T_{in} = -5$ °C, the effective DR region expanded with increasing C_m. The ZA surfactant drag-reducing flow showed a higher DR performance at 25 °C than that at −5 °C.
(2) The addition of $NaNO_2$ can enhance the drag-reduction performance at low temperatures and low concentrations, whereas it has a negative effect on the drag-reduction performance at high temperatures and high concentrations.
(3) The Block destructive device can enhance heat transfer of ZA surfactant solutions at −5 °C near the entrance of the heating section or near the critical Reynolds numbers, while having a very small pressure drop penalty compared with the mesh destructive devices, which is attributed to the dominant action of elongational stress.

Acknowledgement

We gratefully acknowledge the financial support from the NSFC Fund (No. 10602043, 50821604, 10872060, 50876114), the key project of State Education Ministry of China (No. 106142) and the program for new century excellent talents in university (NCET-07-0680).

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