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Experimental Study on the Drag Reduction of Surfactant and Microgrooves

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In the drag-reducing surfactant solution, the scale of near-wall vortices could be enlarged, and the drag reduction mechanism of longitudinal microgrooves was related to the scale of near-wall streamwise vortices. The drag reduction mechanisms of surfactant and microgroove might be complementary. In this study, the collaborative drag-reducing performance of surfactant and microgroove was verified by experiment. The collaborative drag-reducing performances of 0.16 - 0.47 mmol/L CTAC/NaSal surfactant solution in two longitudinal microgroove channels at different temperature were investigated. It is found that the drag reduction effect of surfactant solution can be enhanced by microgrooves at 20 °C, and compared with the smooth channel. The maximum drag reduction rate was increased by 5 % for G1 channel and 8 % for G2 channel for 0.22 mmol/L CTAC solution. The critical temperature T_c and critical Reynolds number Re_c of drag-reducing surfactant solution in G1 channel are lower than that in G2 channel, but they are almost the same for G2 channel and smooth channel. The drag-reducing size of microgroove could be enlarged in the drag-reducing surfactant solutions. The collaborative drag-reducing mechanism between surfactant and microgroove might be that the scale of near-wall vortices was enlarged in surfactant solutions, resulting in that microgrooves could restrict more near-wall streamwise vortices and maintain the drag reduction performance in higher Reynolds number.

1. Introduction

For the turbulent flow in the pipe or channel, most of the energy loss is caused by skin friction. Reducing the skin friction drag has become the focus of the current research. Drag can be reduced either by adding small amounts of additives, such as surfactants (Li et al., 2006) or polymers (Al-Wahaibi et al., 2013) which could change the fluid composition and affect the flow resistance or by using passive devices, such as superhydrophobic coating (Moaven et al., 2013) or microgrooves (Quintavalla et al., 2013) which could directly affect the flow without changing the fluid.

For additives, Mysels (1949) found that turbulent friction drag can be reduced by adding drag-reducing additives. As the drag-reducing additives, polymers could reduce the friction drag by up to 80 %. However, polymer solutions showed the mechanical degradation effect strongly, causing their shorter drag-reducing lifetime, which limits the application of polymer solutions in a long-term circular pipeline. Surfactant could also reduce the frictional drag by up to 60 - 80 %, which was less affected by the mechanical degradation effect than the polymers (Bewersdorff and Ohlendorf, 1988). Surfactants are widely used as efficient drag-reducing additives in recent years.

The drag reduction mechanism of surfactant solution is still imperfect after years of research, but some physical insights have emerged. Wei et al. (2009) found that in the drag-reducing surfactant solutions, the formation of the turbulent vortex was inhibited and the scale of vortex became larger by particle image velocimetry (PIV) technique, indicating a turbulent environment with a relatively larger vortex near the wall. To obtain accurate drag predictions of surfactant solution on the superhydrophobic surfaces, Landel et al. (2019) proposed a theory for steady, pressure-driven, laminar, two-dimensional flow in a periodic SHS channel with soluble surfactant. Recently, Gu et al. (2020) investigated the collaborative drag reduction effect of polymers and surfactants. They

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claimed that the mixture showed the higher shear resistance and a good drag reduction effect at higher Reynolds numbers, meaning that the drag reduction performance of surfactant might change when it is combined with other drag reduction methods.

Among passive drag-reducing devices, the longitudinal microgrooves have been extensively investigated. Walsh et al. (1984) found first that when the height of the groove equaled to its spacing, the triangular groove could obtain the optimal drag reduction effect. They considered the grooves as “fences” which could isolate the low-speed streaks near the wall, causing the inhibition of the momentum transfer. Choi (1990) reported that grooves could inhibit the spanwise motions of near-wall streamwise vortex-pairs, causing the weaker bursts and lower shear stresses. Chamorro et al. (2013) proposed that the drag-reducing effect of grooves was related significantly to their size and the scale of near-wall vortices. Chang et al. (2019) performed direct numerical simulations of turbulent flow on a lubricated micro-grooved surface to investigate the effects of this surface on the slip characteristics at the interface and the friction drag. They obtained the maximum drag reduction of 13 % for a rectangular microgroove whose spanwise width and depth in wall units were 12 and 14.4.

By analyzing the existing drag-reducing mechanism of surfactants and microgrooves, it is found that the drag-reducing mechanism of the microgroove is related to the scale of near-wall streamwise vortices. Drag-reducing surfactant solutions can form a broader vortex environment near the wall. It can be speculated that the drag reduction mechanisms between the surfactant solution and microgroove might be complementary. However, there is little information available on their coupling effect. Huang et al. (2016) carried out some investigations on the collaborative drag-reducing performance of surfactant solution and microgroove and verified the complementary characteristic between their drag-reducing mechanisms by experiment. Recently, they also used direct numerical simulation method to verify the collaborative drag-reducing performance of surfactant solution and microgroove (Huang et al., 2018). The collaborative drag-reducing mechanism between the surfactant solution and microgroove still needs to be improved. The purpose of this study is to investigate the coupling drag reduction effect of surfactants and grooves by experiment.

2. Experimental

2.1 Test Facility

The experiments are performed on a closed-loop shown schematically in Figure 1. The system mainly consists of a storage tank, a heater, a stainless steel centrifugal pump, a two-dimensional (2D) channel and other necessary elements. The fluid temperatures are controlled by a 6 kW heater with the accuracy of ± 0.1 K. Two parallel electromagnetic flowmeters are used to measure the low (0.7 - 3 m^3/h) and high (> 3 m^3/h) flow rates. The measuring accuracies of two electromagnetic flowmeters are 0.001 m^3/h for low flow rate and 0.01 m^3/h for high flow rate. The flow rates are adjusted by the stainless steel centrifugal pump. A differential pressure transmitter is used to measure the pressure drop of the test channel by two pressure taps with a distance of 1.1 m.

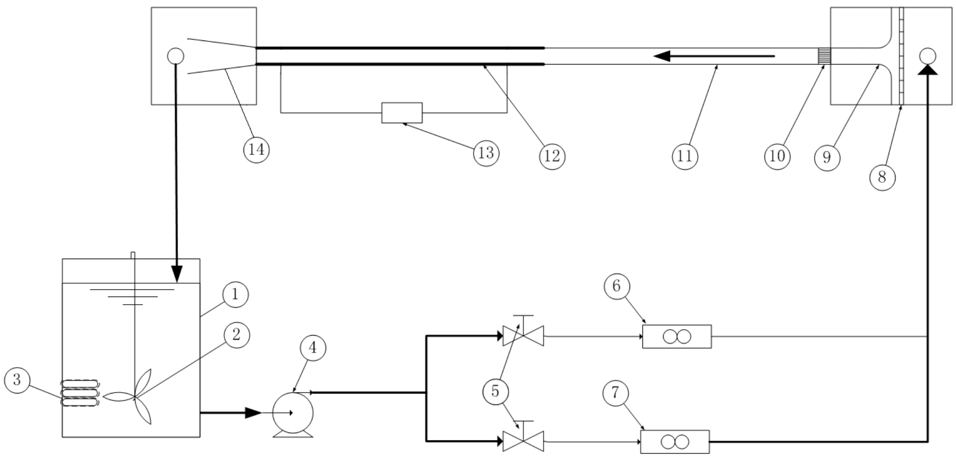


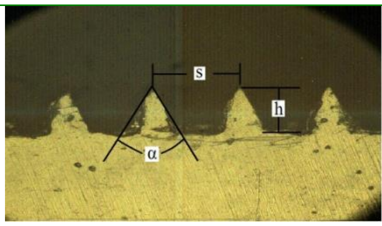
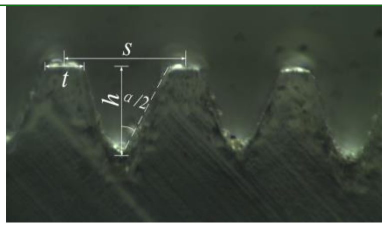
Figure 1: Schematic of experimental system. (1) Storage tank; (2) stirrer; (3) heater; (4) stainless steel centrifugal pump; (5) valve; (6), (7) electromagnetic flowmeter; (8) filter; (9) contraction; (10) honeycomb; (11) 2D channel; (12) test section; (13) differential pressure transmitter; (14) diffuser

The pump circulated the system. The 2D channel of 10 mm height, 125 mm width and 3 m length consisted of a fully developed section and a test section. Each section was 1.5 m. The 2D channel with more than 7 aspect ratio could insure a two-dimensional flow in the centre of the spanwise distance. The fully developed section was long enough to ensure that the fluid in the test section was fully developed turbulence. The test section could be replaced with the smooth channel or the grooved channel.

2.2 Microgrooves

In this study, two longitudinal microgroove channels were investigated, as shown in Table 1. s and h represented the spacing and the depth of grooves. α was the angle of groove tips. t was the width of the grooved tip.

Table 1: Detailed parameter of microgrooves used in the experiment

Case	G1	G2
Grooved shape		
Included angle (α/°)	53	54
Height (h/mm)	0.4	0.2
Spacing (s/mm)	0.7	0.3
Width of grooved tip (t/mm)	0	0.1

2.3 Surfactant

In this study, the cationic surfactant was cetyl trimethyl ammonium chloride (CTAC) with the chemical formula of $C_{16}H_{33}N(CH_3)_3Cl$. The counter-ion salt NaSal with the chemical formula of $C_7H_5NaO_3$ was used with the same weight concentration as that of CTAC. The solvent was tap water, and the surfactant solution is represented by CTAC concentration. Several mass concentrations (0.16, 0.22, 0.31, 0.47 mmol/L) of CTAC solution were tested at different temperatures and Reynolds numbers in the experiment.

2.4 Data Processing

The Fanning friction factor Cf was calculated as follows:

$$C_f = \frac{\Delta PHW}{\rho U_b^2 (H+W)L} \tag{1}$$

Where ΔP is the pressure drop over a specific streamwise distance L of two pressure taps. H and W represent the height and width of the 2D channel; ρ is the density of solvent, and U_b is the bulk mean velocity.
The drag reduction rates were defined as:

$$DR_i\% = \frac{C_{f0} - C_{fi}}{C_{f0}} \times 100\% \tag{2}$$

where C_{f0} is the Fanning friction factor of water in the smooth channel, and subscript i can be replaced by s, g and gs, which represent the conditions of surfactant solution in the smooth channel, groove in water, and surfactant solution in the grooved channel.
The Reynolds number was determined as follows:

$$\mathrm{Re} = \frac{U_b * H}{\nu} \tag{3}$$

where ν is the kinetic viscosity of solvent.

3. Results and discussion

3.1 Drag reduction performance

Figure 2a - 2e show the comparison of drag reduction rate at different temperatures for 0.22 mmol/L CTAC surfactant solution. As shown in Figure 1, “W” means water, and “S” indicates a smooth channel. It can be seen that there is almost no drag reduction effect for G1 channel in water, and it shows the maximum drag reduction rate of 8 % for G2 channel in water. It can also be seen from Figure 2 that compared with surfactant solution in the smooth channel, the maximum drag reduction rates of surfactant solution in the G1 and G2 channel are higher, meaning that the drag reduction effect of surfactant solution can be enhanced by the microgroove. Compared with the smooth channel, the maximum drag reduction rate was increased by 5 % for G1 channel

and 8 % for G2 channel for 0.22 mmol/L CTAC solution at 20 °C. The enhancement effect on the drag reduction rate of surfactant solution in the microgroove channels reflects the collaborative effect between the surfactant solution and microgroove. These phenomena also imply that the drag-reducing size of microgroove can be enlarged in the surfactant solution due to a larger scale of near-wall turbulent vortices in the surfactant solutions. The collaborative drag-reducing mechanism between surfactant and microgroove might be that the scale of near-wall vortices was enlarged in surfactant solutions, resulting in that microgrooves could restrict more near-wall streamwise vortices and maintain the drag reduction performance in higher Reynolds number.
For the other CTAC concentrations, similar phenomena can also be discovered and do not show here again.

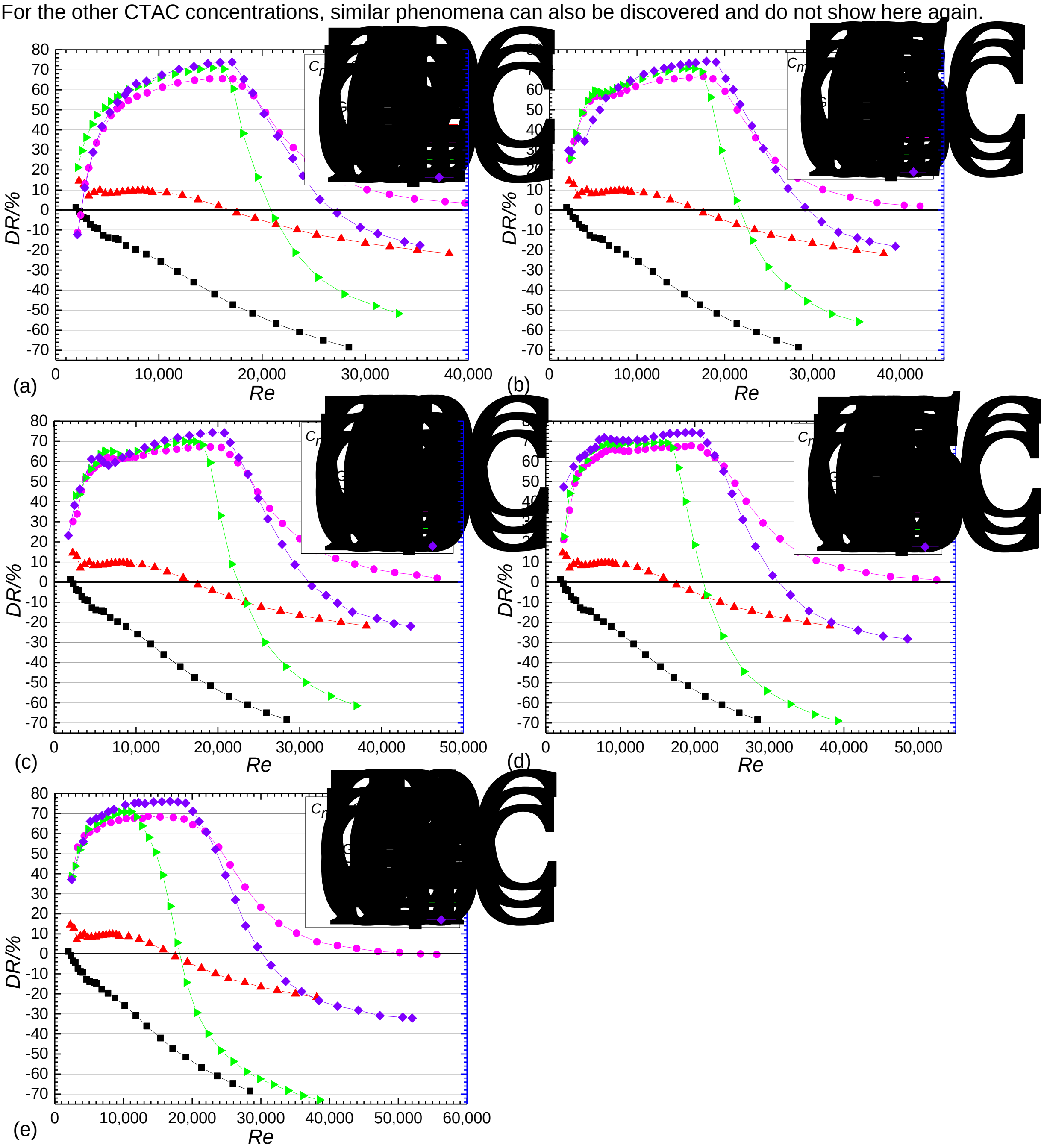


Figure 2: Comparison of drag reduction rate at different temperatures: (a) 20 °C; (b) 25 °C ; (c) 30 °C; (d) 35 °C; (e) 40 °C

3.2 Critical Reynolds number and critical temperature

Figure 3a and Figure 3b show the critical Reynolds number versus temperature at different CTAC concentrations for different channels, and Table 2 presents the essential temperatures at different CTAC concentrations. It can be seen that the critical temperature T_c and critical Reynolds number Re_c of drag-reducing surfactant solution in G1 channel are lower than that in G2 channel, but they are almost the same for G2 channel and smooth channel. The reason may be that the G1 groove is larger than G2 groove, and more near-wall vortices can intrude into the valley of microgroove for G1 groove, causing higher shear stress near the grooved tips. The higher shear stress can more easily destroy the shear-induced structures (SIS) of a surfactant solution which can cause the drag reduction, resulting in the lower critical temperature T_c and critical Reynolds number Re_c of drag-reducing surfactant solution in G1 channel.

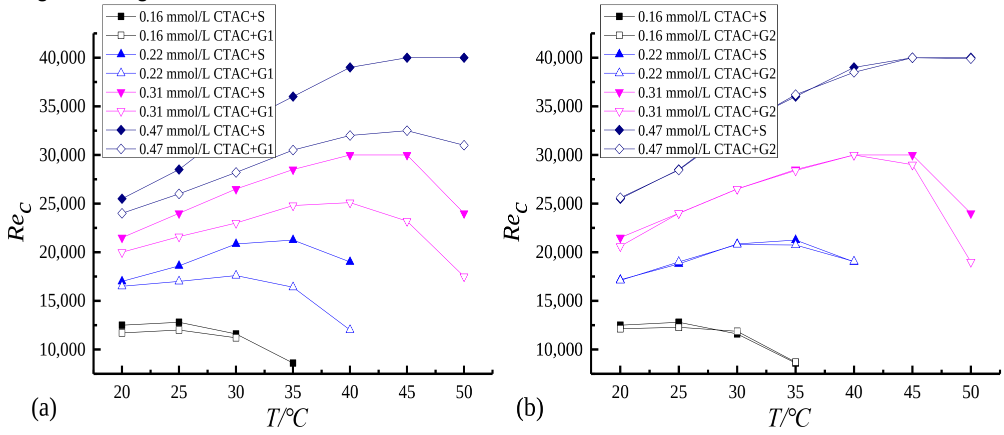


Figure 3: Critical Reynolds number versus temperature at different CTAC concentrations: (a) comparison of G1 and smooth channels; (b) comparison of G2 and smooth channels

Table 2: The critical temperatures at different CTAC concentrations

C_m mmol/L	0.16 mmol/L	0.22 mmol/L	0.31 mmol/L	0.47 mmol/L
Smooth channel	25 °C	35 °C	45 °C	≥ 50 °C
G1 channel	25 °C	30 °C	40 °C	45 °C
G2 channel	25 °C	35 °C	40 ~ 45 °C	≥ 50 °C

4. Conclusions

The drag reduction performance of 0.16 - 0.47 mmol/L CTAC/NaSal surfactant solution in two grooved channels was investigated by experiment in the present study. The conclusions can be summarized as follows:

1). The drag reduction effect of surfactant solution can be enhanced by microgrooves at 20 °C, and compared with the smooth channel, the maximum drag reduction rate was increased by 5 % for G1 channel and 8 % for G2 channel for 0.22 mmol/L CTAC solution. The drag-reducing size of microgroove could be enlarged in the drag-reducing surfactant solutions, which would expand the application field of surfactants and microgrooves.

2). The critical temperature T_c and critical Reynolds number Re_c of drag-reducing surfactant solution in G1 channel are lower than that in G2 channel, but they are almost the same for G2 channel and smooth channel.

3). The collaborative drag-reducing mechanism between surfactant and microgroove might be that the scale of near-wall vortices was enlarged in surfactant solutions, resulting in that microgrooves could restrict more near-wall streamwise vortices and maintain the drag reduction performance in higher Reynolds number. However, the collaborative drag-reducing mechanism was still imperfect and required more extensive and in-depth research. The influence of the wall wettability of microgrooves on the drag reduction performance of the surfactant could be regarded as one of the more meaningful research in the future.

Acknowledgments

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