Research Article

Combined Effects of Temperature and Reynolds Number on Heat Transfer Characteristics of a Cationic Surfactant Solution

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The heat transfer characteristics of a dilute cationic surfactant solution, CTAC/NaSal aqueous solution, were experimentally investigated in a fully developed two-dimensional water channel flow at different temperatures ranging from 15 °C to 60 °C and at different mass concentrations, namely, 75, 100, and 200 ppm. The magnitudes of the maximum achievable heat transfer reduction (HTR) at the above three different surfactant concentrations are all about 90%. The cationic surfactant solution showed a great heat transfer reduction phenomenon, which was greatly affected by concentration, temperature, and Reynolds number. It was supposed that temperature and shear stress are two kinds of energy applied on the surfactant microstructure, which can be helpful to the surfactant network formation or dissociation depending on their values.

1. Introduction

Since the drag reduction phenomenon is discovered by Toms in 1948 [1], polymers and surfactants as two drag-reducing additives were studied by many researchers [2–4]. Polymer drag-reducing additives have been used extensively in crude oil pipelines of companies such as Shell and Conoco to increase the throughput and to save pumping energy [2]. However, due to the permanent decrease of drag reduction performance of polymer after passing through high shear stress sections of pipelines, they are not effective in closed circuit systems such as district heating and cooling (DHC) recirculation system. In contrast to polymers, the mechanical degradation of surfactants is only temporary [3].

In addition to the drag reduction effect, another noticeable effect of surfactant drag-reducing additives is the heat transfer reduction that occurs between a solid boundary and the flowing fluid [4–6]. Wei et al. [6] showed that heat transfer reduction is always a little larger than drag reduction. This reduced heat transfer behavior of drag-reducing surfactant solutions is an obstacle to their application in DHC systems since heat exchange in heating or cooling is essential.

Some research focused on the effect of the Reynolds number [7] and the concentration [8] on the drag reduction and heat transfer induction of the surfactant solutions. But there are few details, systematic investigations, and deep analyses of the concentration, the Reynolds number, and the temperature effects on the heat transfer reduction of the surfactant solution. In this paper, the combined effects of concentration, Reynolds, and temperature on the heat transfer behavior of CTAC/NaSal surfactant solution were experimentally investigated and analyzed from the viewpoint of thermal energy and shear stress energy in detail.

2. Experimental Apparatus and Procedure

2.1. Test Facility. The water channel test facility for heat transfer experiments was a closed loop shown schematically in Figure 1. The system consisted of a reservoir tank (0.45 m³), a stainless steel centrifugal pump, a settling chamber equipped with a nozzle, a two-dimensional channel, a diffuser, an electromagnetic flowmeter with a resolution of ±0.01 m³/min, the stainless steel tube, and some necessary components to connect the equipments. In order to get different fluid temperatures, a control system with a 4.4 kW heater was installed in the reservoir tank. The temperature of the fluid was controlled to ±0.1 K around the prescribed value.
The surfactant aqueous solution was circulated by the pump and supplied to the settling chamber. The chamber was equipped with a perforated pipe, stainless steel mesh, and 1/17 contraction nozzle. At the entrance of the test section, a 45 mm long honeycomb with $8 \times 8 \text{ mm}^2$ rectangular openings was used to remove large eddies.

The two-dimensional channel was 10 mm high, 125 mm wide, and 3 meters long (inside measurement), which was connected straightly by two sections of 1.5 meters each. The channel walls were of 20 mm thickness and made of transparent acrylic resin except for the heating wall. The heating wall consisted of a 2-mm thick stainless steel plate and five independent strips of electric heaters each of which was made by gluing a Nichrome heating wire (3 mm thick, 10 m long, 200°C resistance temperature, and 1000 W peak power) on the outer surface of the base plate by using an electrically insulating but highly conductive adhesive (Dow Corning Silicone, Dow Corning Co., Ltd., America). The five heaters having the same spanwise width as the channel width were 280 mm long along the flow direction, and thus all the five heaters were 280 mm long along the flow direction. Each heater was independently heated by an AC power supply. The voltage and electric resistance were measured to calculate the local wall heating power $Q$. On the midline of the channel span, five T-type thermocouples were embedded into the outer surface of the stainless steel 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 five parts of the stainless steel 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 $T_0$. The local bulk temperatures $T_f$ corresponding to the other parts of the heating plate were estimated from the heat balance between the heating power and temperature increment of the flow. A data acquisition unit, PXI 6221 (National Instruments Co., America) having a high A/D resolution of $\pm 20,000$, was connected to a personal computer that automatically converted the thermocouples’ output voltages into temperatures. Temperatures were monitored to ensure that data in the steady state was being acquired. All the temperature readings were obtained and averaged over about ten minutes.

2.2. Sample Material. In the experiments, the tested cationic surfactant was cetyl trimethyl ammonium chloride (CTAC) (Shandong Fusite Chemical Co., Ltd., China, 70% purity), with a molecular weight of 320.0 g/mol, which is less affected by calcium and sodium naturally existing in tap water. Sodium salicylate (NaSal) (Yixing City Shenguang Medicine Chemicals Co., Ltd., China, 99% purity), with molecular weight of 160.1 g/mol, was used as the counterion to stabilize the solution structure. The surfactant solution was prepared by adding the same mass concentrations of surfactant and counterion to the desired tap water for the heat transfer measurements. The surfactant solution is marked by the concentration of CTAC, and solutions of three mass concentrations (75, 100, and 200 ppm) were made for the heat transfer reduction (HTR) measurements.

2.3. Heat Transfer Reduction. The local Nusselt number was determined as

$$\text{Nu}_x = \frac{h_x H}{\lambda_s} = \frac{H}{L W} \frac{Q_x}{W (T_w - T_f)}. \quad (1)$$

In this paper, we used the averaged Nusselt number which was determined as

$$\overline{\text{Nu}} = \frac{\overline{Q} H}{L W \lambda_s} = \frac{\frac{1}{5} \sum_{x=1}^{5} \text{Nu}_x}{5}, \quad (2)$$

where $Q_x$ is heating power, $H$ the channel height, $W$ the channel width, $L$ the total length of the heaters along the flow direction, $\lambda_s$ the thermal conductivity of the surfactant solution, $T_w$ the local wall temperature, and $T_f$ the local bulk fluid temperature. Here, the thermal conductivity of solvent was used instead of that of surfactant solution. One reason is that the surfactant concentrations involved in the experiments were so low that the thermal physical parameters were almost the same as those of solvent; another reason is that the comparison of the experimental results between pure solvent and surfactant solution becomes convenient. According to Ohlendorf et al. [9], the shear-reduced structure (SIS) made up of rod-like micelles exists as long as the solution is sheared and disappears at once after the shear is stopped. It is generally believed that SIS is essential for drag reduction and heat transfer reduction through suppressing the turbulence in the turbulent flow at high Reynolds number [10, 11]. For a given test facility, the local heat transfer coefficient $h_x$ mainly depends on the heat convection; however the thermal conductivity $\lambda_s$ is just decided by physical property and temperature of drag-reducing fluids. So using the thermal conductivity of water instead of that of surfactant solution can be convenient to understand the turbulence suppression degree of the surfactant additives. Furthermore, in the most application-oriented studies, such a treatment is convenient for comparing the heat transfer results of the solvent with the surfactant solution under the same situations of flow and heat flux [10]. The viscosity and thermal conductivity values

Figure 1: Schematic diagram of two-dimensional water channel.
used in various nondimensional numbers are obtained at the temperature corresponding to specific experimental condition. For example, for the 15 °C experimental condition of the bulk fluid, the viscosity and thermal conductivity are at 15 °C.

The heat transfer reduction of the drag-reducing flow from that of solvent flow was defined as HTR:

\[ \%\text{HTR} = \frac{\text{Nu}_s - \text{Nu}_f}{\text{Nu}_s} \times 100, \]

where \( \text{Nu}_s \) is the Nusselt number of solvent.

In order to test the reliability of the experimental system, the test result of the tap water solvent was compared with the Gnielinski’s formula [12] under the same experimental condition. The Gnielinski’s formula is expressed as

\[ \text{Nu}_D = 0.012 \left( \text{Re}_D^{0.87} - 280 \right) \text{Pr}_f^{0.4} \left[ 1 + \left( \frac{D}{L} \right)^{2/3} \right] \text{ct}, \]

where \( \text{ct} = (\text{Pr}_f/\text{Pr}_w)^{0.11}, \ \text{Pr}_f/\text{Pr}_w = 0.05-20, \) the hydraulic diameter, \( L \) the total length of the heaters along the flow direction, \( \text{Re}_D \) Reynolds number based on the hydraulic diameter \( D \), \( \text{Pr} \) Prandtl number, the suffix \( f \) represents bulk temperature, and suffix \( w \) represents wall temperature.

### 3. Results and Discussion

Figure 3 shows the variation of averaged Nusselt numbers of 75, 100, and 200 ppm CTAC/NaSal surfactant solution flow with Reynolds number in the 2D channel at several different temperatures ranging from 15 °C to 60 °C. For comparison, the Gnielinski’s equation for the heat transfer of Newtonian turbulent flow in the hydraulic fully developed and thermally developing region is also shown by a solid line in the same figure.

Figures 2(a)–2(c) show similar variation trends of Nusselt numbers with Reynolds number. The measured Nusselt numbers of water flow appear very well with the curve of Gnielinski’s equation, validating the reliability of the experimental system. In a certain Reynolds number region, the Nusselt number of the surfactant solution is smaller than that of water, showing a great heat transfer reduction (HTR) phenomenon. It is also shown that the Nusselt numbers are very small in the lower Reynolds number region with a value about 2 and increase slowly before a certain Reynolds number, above which the Nusselt numbers increase rapidly up to higher values about 100 but still a little lower than the curve of Gnielinski’s equation. It is suggested that the heat transfer performance is improved with increasing Reynolds number, and the improved level is high in the higher Reynolds number region. The Reynolds number above which the Nusselt number begins to increase rapidly, in other words, the HTR begins to decrease rapidly is so-called the critical Reynolds number (Re_c). Heat transfer performances are different at different temperatures, indicating an obvious effect of temperature. For the same concentration, the critical Reynolds number increases as the temperature increases, and thus the heat transfer reduction range is enlarged. However, the critical Reynolds number starts to decrease with temperature when the temperature exceeds critical value depending on the corresponding concentration. The temperature above which the HTR begins to increase rapidly is defined as the critical temperature (T_c).

The relationship between the critical Reynolds number and temperature is shown in Figure 3 at different concentrations. We can see that at lower temperatures, the critical Reynolds number just shows little difference among the three different concentrations. As the temperature is increased, low-concentration solution will reach the maximum critical Reynolds number (corresponding to the critical temperature) very quickly, and then the critical Reynolds number at this concentration decreases rapidly with further increasing temperature. The increase in concentration increases the critical Reynolds number and also the critical temperature. For example, the critical temperatures for 75, 100, and 200 ppm surfactant solutions are 40, 45, and 50 °C, respectively, and the critical Reynolds numbers corresponding to the critical temperatures increase from 13400 for 75 ppm to 18000 for 100 ppm, and then to 30900 for 200 ppm. This phenomenon has also been noticed by other researchers [6, 10, 13].

Figures 4(a)–4(c) show heat transfer reduction (HTR) measured at different temperatures, Reynolds numbers, and surfactant mass concentrations in a two-dimensional channel. It can be seen in Figure 4(a) that the HTR is higher in lower Reynolds number region, exceeding 90% and does not decrease until critical Reynolds numbers above which the HTR decreases very quickly to a very small value. At lower temperatures, the Reynolds number can reach the critical value easily and the heat transfer performance increases with further increasing Reynolds number above the critical value. The range of low heat transfer performance is enlarged as the temperature is increased up to the critical temperature above which the heat transfer performance is improved sharply. This phenomenon is so called temperature effect, as mentioned above.

Also, we can see in Figure 4(a) that for all temperatures not exceeding the critical value, the maximum HTRs are all about 92%. The same phenomenon can be seen in Figures 4(b) and 4(c). Comparing Figures 4(a), 4(b), and 4(c), we can find that at the same temperature below the critical temperature of the solution, the higher concentration solution has the wider range of low heat transfer performance: for instance, for 75 ppm surfactant solution at the temperature of 40 °C, the Reynolds number range of low heat transfer is from 3000 to 15100; however, the Reynolds number ranged from 3000 to 21200 for solution at the concentration of 100 ppm and the temperature of 40 °C and the Reynolds number ranged from 5000 to 31500 for 200 ppm surfactant solution at 40 °C. Thus it can be seen that the heat transfer characteristic was greatly affected by the surfactant concentration. In a small range of Reynolds number, the HTR increases to, and keeps in the maximum value before and then decreases with further increasing Reynolds number above the critical value. The range of low heat transfer performance is enlarged as the temperature increases before a critical temperature above which the expansion
of low heat transfer performance has a setback with further increasing temperature.

Since the heat transfer reduction behavior is closely related to the micellar network in the surfactant solution, these phenomena may be explained by the effects of Reynolds number (shear stress) and temperature (thermal/Brownian motion) on the micellar network. We consider that the main energy applied to the solution consists of two parts, the thermal energy ($H$) and shear energy ($S$). For cationic surfactants, under the right conditions of surfactant/counterion chemical structures, ratios, concentrations, and temperatures, they form rod-like micelles [14]. The length of rod-like micelles is about dozens of times diameter of the micelles which is about several nanometers, and the length of rod-like micelles increases with increasing surfactant concentration [9]. Under a proper shear stress, the rod-like micelles form a network structure called shear-induced structure (SIS) [15] and align themselves along the flow direction to suppress turbulent flow near the wall [9], which is often stated to be responsible for the occurrence of heat transfer reduction [10, 16, 17]. Both the shear action and temperature can affect the formation and destruction of the shear-reduced structure (SIS). For dilute surfactant solutions, at a certain shear rate, the viscosity remains relatively constant for

![Figure 2: Averaged Nusselt numbers at 75, 100, and 200 ppm.](image)
a period of induction time before beginning to increase due to the free rotation of the spherical micelles, then the shear thickening was observed by acquiring sufficient energy which is the combination of the shear rate and the flow duration [18, 19]. What is more, the induction time energy which is the combination of the shear rate and the shear thickening was observed by acquiring sufficient energy through the collision to overcome the mutual exclusion to aggregate, forming the supermolecular shear-reduced structure (SIS) which need more shear energy corresponding to bigger critical Reynolds number to be destroyed. When the temperature increases to a certain level, the SISs transform to spherical micelles, which has been proved by Lu et al. [11] using transmission electron microscopes (TMEs). This is the reason that when the temperature increases to a critical value, the critical Reynolds number decreases.

Through comparing Figures 3 and 3, we can find that the Nusselt number increases slowly and the HTR keeps in a considerable value before the critical Reynolds number, which can be explained by the theory that turbulent flow is suppressed to a state which is in between the laminar and turbulent flow states. Because the levels of suppression are almost the same for a given surfactant concentration with different temperatures below the corresponding values, the HTR is almost invariant before critical Reynolds number for different temperatures, as shown in Figure 3. With further increasing temperature above the critical value, some of the SISs fracture and transform to spherical micelles, which reduces the proportion of superorder rod-like micelle structures and enhances the turbulence intensity of the flow, so the heat transfer performance can be improved in lower Reynolds number range.

From Figure 3, we can see that the critical Reynolds number increases with increasing temperature which is below the corresponding critical temperature for a given concentration surfactant solution. Considering the fact that the Brownian motion is enhanced with increasing temperature, we may conjecture that the shear-induced structure (SIS) is easily formed in the surfactant solution and the strength of these big structures are increased. Therefore, a larger Reynolds number is needed to improve the heat transfer performance; in other words, a larger shear stress is needed to disassociate the micellar networks. However, when the temperature exceeds the critical value, the corresponding critical Reynolds number decreases with further increasing temperature above the critical value. The reason for this phenomenon is that the SISs transform to spherical micelles because of the larger thermal energy added to the solution. At the same time, we can see in Figure 3 that the critical temperature and critical Reynolds number increase as the concentration increases. It is suggested that the rod-like micelles are longer and stronger with increasing concentration and need more thermal energy to disrupt SISs to spherical micelles and more shear stress energy to destroy the net structure SISs adhered to the wall.

The heat transfer reduction of CTAC/NaSal solutions with the same proportion in terms of mass ratios has also been studied by Zhou et al. [22] and Zhang et al. [23] in the 50 × 500 mm and 20 × 250 mm two-dimensional channel, respectively. They found that the maximum HTRs for fully developed thermal boundary layer were 55% and 68%; however the HTR is 92% in the present experiment conducted in 10 × 125 mm two-dimensional channel. It suggests that the HTR increases with the decreases of the size of two-dimensional channel, according to the finding that DR increases with the decrease of the pipe diameters [24]. According to Zhou et al. [22], the reduction of heat transfer rate of surfactant solutions increases as the concentration is increased and then keeps a maximum value without further increasing with the concentration. This critical concentration is about 80 ppm; this agrees with the present experimental findings that all the maximum HTRs are about 92% for 75, 100, and 200 ppm surfactant reducing solution.

The same concentration, temperature, and Reynolds number can work together to impact on the heat transfer performance of the surfactant solution both positively and negatively: under the condition of the critical temperature ($T_c$) and the critical Reynolds number ($Re_c$), the two major energies constitute the critical energy of the solution for a given concentration of solution. Therefore, in practical engineering fields, the goal of energy savings can be achieved by controlling the temperature and Reynolds number of the flow. When the solution temperature is lower, the best heat transfer performance can be got by increasing Reynolds number to a value exceeding the critical Reynolds number.
Otherwise when the solution temperature is close to the critical temperature, in order to get the better heat transfer effect, the solution can be heated to a temperature just a little higher than the critical temperature. Of course, the study in this paper is just a qualitative analysis of the interesting heat transfer reduction phenomena; the relationship between the shear and thermal energy and their contribution to the heat transfer reduction remain to be further studied.

Such experimental data obtained in this experiment as temperatures in Figure 3 and Reynolds numbers in Figures 3 and 3 do not reach the same value on the right side of the abscissas; it is because the variation trend can be reflected by the obtained data and it is not necessary to get more data.

4. Conclusions

Turbulent heat transfer characteristics of CTAC/NaSal surfactant drag-reducing flow with concentrations of 75, 100, and 200 ppm in a two-dimensional channel at various
Reynolds numbers and temperatures were experimentally investigated. The main conclusions drawn from this study are as follows.

1. There exists a critical temperature in each different concentration solution, below which the critical Re, the efficient range of drag reduction, the drag-reducing characteristics of the solution increase with increasing temperature.

2. For a surfactant solution with a given concentration, there exist two factors of temperature and Reynolds number affecting the heat transfer characteristic greatly. In order to get the quantitative analysis of influence exerted by these two factors, we defined critical Reynolds number ($Re_c$) and critical temperature ($T_c$) which increase with increasing concentration.

3. For $Re < Re_c$, the HTR increases to a considerable maximum value about 92% quickly due to the shear-induced structure SIS formed at a suitable Reynolds number (shear stress) range. The micellar network can be destroyed by the higher shear stress corresponding to the critical Reynolds number, and the destruction is intensified with further increasing Reynolds number. Therefore, the heat transfer performance increases remarkably as the Reynolds number increases on the condition that Reynolds number exceeds the critical value at a given concentration and a given temperature.

4. The temperature affects the heat transfer performance because of the thermal motion of surfactant micelles. For $T < T_c$, the Brownian motion of micelles gets intense with increasing temperature and the formation of SIS becomes more and more easy, resulting in wider and wider range of low heat transfer performance. When the temperature reaches the critical value, the heat transfer coefficient comes to the minimum value and then starts to increase with further increasing temperature. The reason is that when the temperature exceeds the critical one, the Brownian motion is so intense that the shear-induced network structure SISs transform to spherical micelles.

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References


