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International Journal of Heat and Mass Transfer 46 (2003) 5161–5173

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Enhancing heat transfer ability of drag reducing surfactant solutions with static mixers and honeycombs

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Received 22 August 2002; received in revised form 19 April 2003

Abstract

Solutions containing drag reducing additives also show reduced heat transfer which limits their use in district heating and cooling recirculation systems where heat exchange is critical. In this study, static mixers A and B and honeycombs were installed at the entrance to a heat exchanger to break the solution microstructure temporarily and thereby enhancing their heat transfer ability when passing through the heat exchanger. The effectiveness of the destructive devices in enhancing the heat transfer ability of drag reducing cationic and mixed zwitterionic/anionic surfactant solutions was investigated together with the microstructure recovery time and pressure drop penalty paid for the heat transfer enhancement.

1. Introduction

Drag reduction is a turbulent flow phenomenon in which small amounts of drag reducing additives (10–3000 ppm) can greatly reduce the friction factors of a turbulent flow [1]. Polymers and surfactants are the two mostly common used drag reducing additives. Polymer drag reducing additives have been used extensively in crude oil pipelines of companies such as Shell, Conoco, etc. to increase the throughput and to save pumping energy [2]. However, due to the permanent degradation of polymer drag reducing additives after passing through high shear stress sections of pipelines such as pumps, valves, etc., they are not effective in recirculation systems. Accordingly, surfactant drag reducing additives have been studied intensively recently because of their ability to repair themselves rapidly after mechanical degradation making them very promising additives for use in district heating and cooling (DHC) recirculation systems [1].

However, in addition to reduced friction factors, surfactant drag reducing additives also reduce the heat transfer to/from the solution [3–6]. Aguilar et al. [5] 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. Thus, for successful use of surfactant drag reducing additives in DHC systems to save pumping energy, methods to enhance the heat transfer ability of drag reducing surfactant solutions in heat exchangers must be developed.

At least five different methods have been proposed to enhance the heat transfer of drag reducing surfactant solutions till now. Most of them rely on temporarily destroying or altering the surfactant microstructure by mechanical means before flow through heat exchangers so that the solution is "water-like" in its behavior and provides high turbulent heat transfer coefficients. After leaving the heat exchanger, the surfactant microstructure recovers and the solution again exhibits drag reduction behavior. With appropriate balance of heat exchanger length, surfactant microstructure recovery times and control of the surfactant solution flow rate, the drag reduction and heat transfer reduction of the

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doi:10.1016/S0017-9310(03)00221-7

Nomenclature

$D_i = 0.0103$ (m)	inner diameter of test tube
f	Fanning friction factor
h_i (W/m$^2\cdot$°K)	heat transfer coefficient of test fluid inside the inner tube
%HTR	percent heat transfer reduction compared to water at the same Reynolds number
k (W/m$\cdot$°K)	heat conductivity of test fluid
L_b (m)	distance between surfactant solution microstructure recovery location to pressure measurement point, P2
$Nu = \frac{hD}{k}$	Nusselt Number
$PD_n = \dfrac{\Delta P_{n-9}}{\frac{\rho_{\text{fluid}} u_{\text{fluid}}^2}{2}}$	pressure coefficient
%DR	percent drag reduction
Q (m^3/s)	volumetric flow rate of test fluids (measured by magnetic flow meter)
$Re = \frac{\rho D u}{\mu}$	Reynolds number
t_{rec} (s)	microstructure recovery time
u (m/s)	flow velocity of test fluid

Greek symbols

μ (Pa·s)	viscosity of test fluid
ρ (kg/m^3)	density of test fluid

Subscripts and superscripts

i	inside of tube
n	pressure taps in Fig. 1

surfactant solution can be recovered soon after the surfactant solution passes through the heat exchanger as the temporarily destroyed surfactant microstructures can "self-repair" in seconds [1].

One method is to position a pump just before the heat exchanger. The high shear in the pump temporarily destroys the surfactant microstructure giving enhanced heat transfer in the heat exchanger. The surfactant solutions pass through the heat exchanger with a heat transfer coefficient close to a Newtonian fluid. This is the most convenient method but may not be possible for existing district heating or cooling systems or for many newly designed systems.

A second heat transfer enhancement method is to use a fluted tube as the inner tube of a heat exchanger as described by Qi et al. [7]. The spiral wall of the fluted tube generates a swirling motion which also exerts a shear stress on the test fluid. The high shear stress in the fluted tube and the swirling motion both contribute to increasing the heat transfer ability of the solution. Compared with other methods, the pressure drop penalty of this method is quite reasonable. This method is most applicable for heat exchangers in new district heating and cooling systems, however. Similar to fluted tube, investigators in UMSICHT institute in Germany studied the heat transfer enhancement of surfactant solutions by inserting spring coils inside the inner tube of the heat exchanger. This would also be applicable in existing DHC systems. However, no promising results were obtained till now from this method [8].

The third method is to increase the flow velocities of the fluids by installing small diameter tubes or orifice obstructions [8] at the entrance of the heat exchanger. Kishimoto et al. [9] placed a smaller diameter tube at the entrance of a heat exchanger to increase the flow velocity and, therefore the shear stress, on the drag reducing surfactant solution in order to partially destroy the surfactant microstructure and enhance its heat transfer ability. A medium pressure drop penalty was observed associated with medium heat transfer enhancement effects for drag reducing surfactant solutions at high Reynolds number.

A fourth method to enhance the heat transfer ability of drag reducing surfactant solutions is by using ultrasonic energy to temporarily destroy the surfactant microstructure at the entrance to a heat exchanger. The possibility of using ultrasonic energy to destroy the surfactant microstructure has been confirmed by Blais et al. [10] and Yamaguchi et al. [11] who measured the recovery time of surfactant solution microstructures. Studies of ultrasonic destruction are underway at Ohio State.

A fifth method is to insert destructive devices such as static mixers, honeycombs and meshes at the entrance to the heat exchanger. Similar to having a pump at the entrance of the heat exchanger, these destructive devices can exert large shear and extensional stresses on the surfactant solutions which may destroy their microstructures. They have the advantage of being easy to install in existing systems. Pressure drop penalties caused by the destructive devices may be large, however. Li et al. [12] studied the effectiveness of three types of wire mesh plugs in enhancing the heat transfer ability of drag reducing surfactant solutions. They found that the effectiveness of the heat transfer enhancement caused by the mesh plugs depended largely on the Reynolds number and concentration of surfactant.

The third, fourth and fifth methods may be convenient for enhancing the heat transfer of drag reducing surfactant solutions in existing district heating and cooling systems.

In this paper, the effectiveness of different destructive devices, static mixers A and B, and honeycomb in enhancing the heat transfer ability of drag reducing cationic surfactant solutions Ethoquad T13-50/NaSal (5 mM/8.75 mM) and mixed zwitterionic/anionic surfactant solution SPE98330 (1500 ppm) with Trilon A (500 ppm) and formaldehyde (150 ppm) are reported along with pressure drop penalties paid for the heat transfer enhancement and recovery times of surfactant solution microstructures after passing through the destructive devices.

2. Experimental

2.1. Surfactant solutions, test loop and destructive devices

5 mM (2300 ppm) cationic surfactant solution tris (2-hydroxyethyl) tallow ammonium acetate (Ethoquad T13-50 donated by Akzo Nobel) with 8.75 mM (1400 ppm) sodium salicylate (NaSal) and 1500 ppm mixed zwitterionic/anionic surfactant solution (SPE98330 donated by Akzo Nobel) composed of *N*-hexadecylbetaine (27%), sodium dodecylbenzenesulphonate (6.7%), 2-propanol (33%) and water (33.3%) were tested. In 1500 ppm SPE98330 solution, sodium nitrilotriacetate (Trilon A, 500 ppm) and formaldecyde (150 ppm) were added as stabilizing chelator and biocide respectively. Both of the surfactant solutions were prepared with deionized water and stirred for more than 6 hours and stored more than 12 hours before testing.

The experimental setup of the test loop is shown in Fig. 1 and more details about the setup can be found in [7]. The tube-in-tube heat exchanger in the test loop (Fig. 1) is 0.91 m long with an undisturbed region of 663 diameters of ID tube before the entrance to the heat exchanger. In this heat exchanger, steam passes through the annulus to heat the test fluid inside the heat exchanger. Destructive devices are inserted just before the inlet of the tube-in-tube heat exchanger to temporarily destroy the super-ordered microstructures of drag reducing surfactant solutions. A flow filter made by Pall Trinity Micro Corporation (Cortland, NY) was installed to remove solid particles in the system more than 600 diameters before the entrance to the tube-in-tube heat exchanger. At 80 diameters downstream of the tube-in-tube heat exchanger, eight pressure taps with an average interval of 80 diameters were installed to measure the pressure distribution of the test fluid. Comparison of pressure distribution of the test fluid with/without destructive devices at known mean flow velocities allowed estimation of the recovery times of surfactant solution microstructures after degradation by the destructive devices.

Destructive devices tested at the entrance to the tube-in-tube heat exchanger were metal static mixer (mixer A), plastic static mixer (mixer B) and honeycomb. All these destructive devices are inexpensive with no moving parts and thus, low maintenance. Compared with mesh screens, the clogging problems are much less severe.

The honeycomb destructive device tested has a length of 30 cm (3×4 inch) with side length of 1.6 mm (1/16 inch) and area of 6.55 mm^2 per hexagon cell. The equivalent diameter per hexagon cell is around 2.9 mm which is more than 25% of the tube diameter (~10.3 mm). The mixer A tested has 15 helical elements with the length of each helical element about 1.9 cm (0.75 inch). Only four and five helical elements of the mixer B were tested with the length of each helical element about half of those of the mixer A, about 1 cm (0.4 inch). Both static mixers have a diameter of about 1 cm. Characteristics of the destructive devices are listed in Table 1. Fig. 2 shows pictures of mixer B and honeycomb destructive devices.

2.2. Tests performed

Drag reduction tests and heat transfer tests in the tube-in-tube heat exchanger with/without destructive devices were performed to check the drag reduction and the heat transfer reduction behavior of the cationic and mixed zwitterionic/anionic DR solutions.

2.2.1. Drag reduction tests

In drag reduction tests, the test fluids were kept at a constant temperature throughout the loop by the OMEGA temperature controller near tank 1 and cooling water in the fluted tube-in-tube heat exchanger. The objectives of these tests were to obtain baseline information (friction factor vs. Reynolds number) for water and for the drag reducing surfactant solutions used for the heat transfer tests. Flow rates, temperatures and pressure drops of the test fluids between all pressure tap locations #P2 and #P9 were measured. Tests were run at 5 °C temperature intervals from 45 to 70 °C (or to a temperature lower than 70 °C when the surfactant solution lost its drag reduction ability).

2.2.2. Heat transfer tests

Heat transfer experiments were run at 5 °C temperature (inlet temperature of heat exchanger) intervals between 45 and 65 °C (or 60 °C) depending on the upper temperature drag reducing limit of the solution. The temperatures were controlled by adjusting the heating and cooling rates. At a set temperature, the flow rate of the test fluid was adjusted to a target Reynolds number. To determine the heat transfer coefficients of the test fluids in the tube-in-tube heat exchanger, inlet (T2) and outlet (T3) temperatures of the test fluids, inlet temperature (T10) and pressure of steam (P), outlet temperature (T13) of the condensed water together with flow rates of the test fluid (Q) and the steam were measured. Drag reduction tests were performed simultaneously starting at P2, 80 diameters downstream of the tube-in-tube heat exchanger outlet, to check recovery from

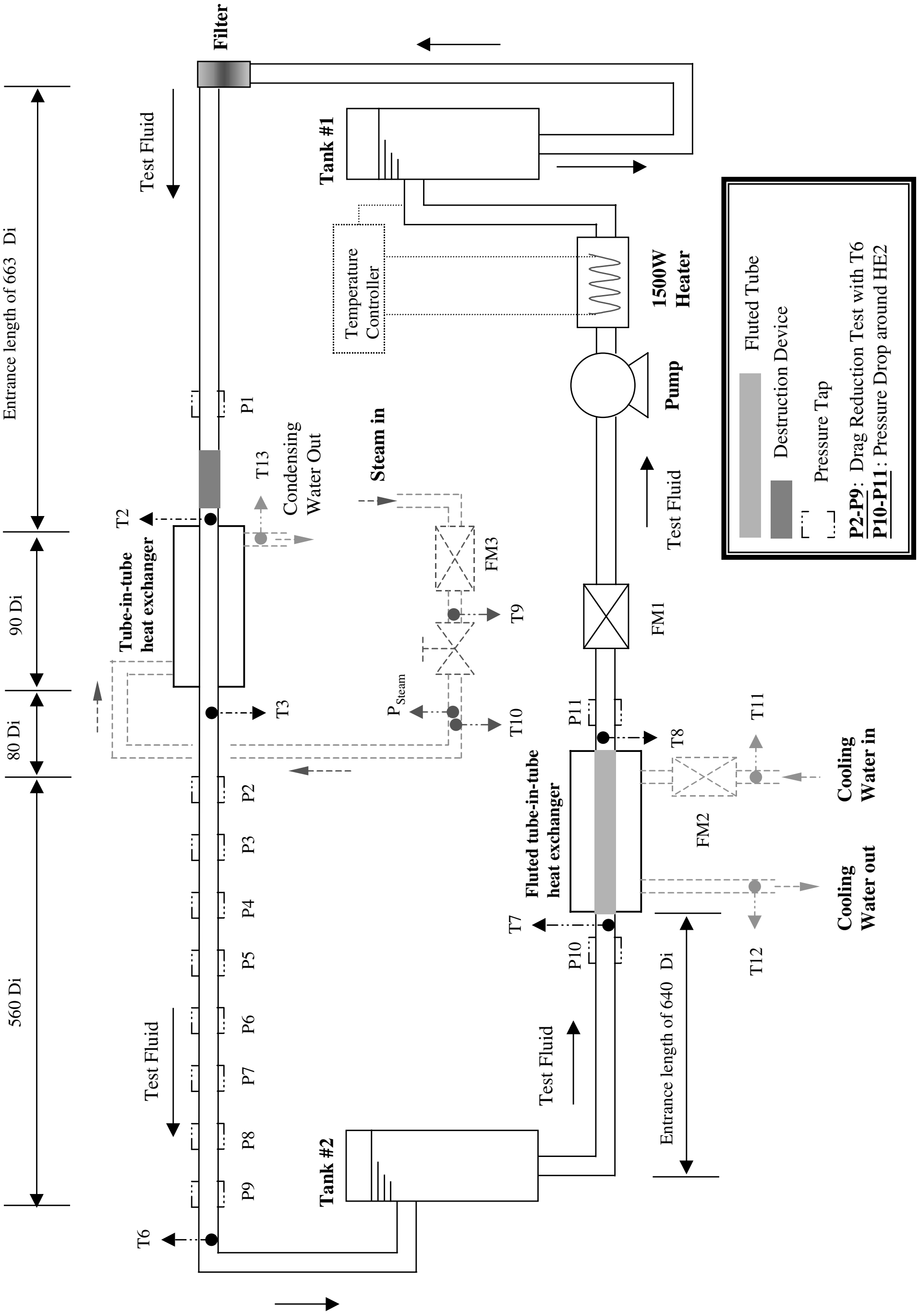


Fig. 1. Schematic view of heat transfer apparatus.

degradation of the test fluids. Pressure drops of the test fluids over the destructive devices and heat exchanger were also measured by measuring pressure drops between P1 and P2 in Fig. 1 which were compared with pressure drops without destructive devices to determine the pressure drop penalty of installing each destructive device.

The objectives of the heat transfer tests were to check the heat transfer enhancement effects of different destructive devices on the drag reducing surfactant solu-

Table 1
Properties of destructive devices

	Metal static mixer (mixer A)	Plastic static mixer (mixer B)	Honeycomb
Size	Helical element; length = 0.75″	Helical element; length = 0.4″	Side of hexagon = 1/16″, length = 4″
# of elements tested	15	4–5	3
Blockage ratio	∼0.05	∼0.05	∼0.01
Mixing method	Divide/merge	Divide/merge	Cut by sharp edge
Turbulence agitation	Production of large scale eddies	Production of large scale eddies	Suppression of large scale eddies

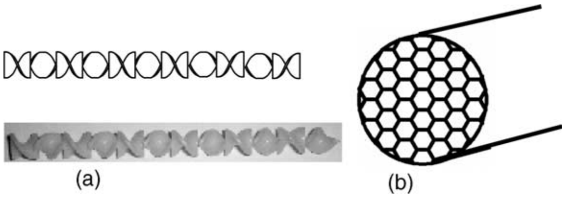


Fig. 2. Destructive devices used (the metal static mixer A has the same shape as the plastic static mixer B with a different length of each helical element) (a) 12 elements of mixer B; (b) honeycomb.

tions and the pressure drop penalties paid for the enhancements. Heat transfer coefficients for tap water were measured first to provide baseline information. Heat transfer tests for the surfactant solutions without destructive devices were also conducted to determine the percent heat transfer enhancement of the destructive devices.

2.2.3. Surfactant solution microstructure recovery time measurements

A series of tests was run to determine the effects of the destructive devices on the drag reducing ability of the surfactants 177 diameters downstream of the destructive devices (80 diameters from the heat exchanger exit) and to estimate the recovery times of the destroyed surfactant solution microstructures. Experiments were run at $Re_{\max}$, $7/8Re_{\max}$, $3/4Re_{\max}$ and $1/2Re_{\max}$ respectively and pressure drops of the test fluids between P2 and P9, P3 and P9, etc., were measured together with temperatures (T6 and T8) and flow rates (Q) of the test fluids and compared with test results for the same surfactant solutions without any destructive device.

3. Data reduction

For convenient comparison of the results between water and surfactant solutions, the thermal-physical properties of water were used in data reduction. The physical and transport properties of water and of the solutions were based on the bulk temperature of the test fluid (T6 in Fig. 1) for drag reduction tests and film temperature for heat transfer tests.

3.1. Friction factors and heat transfer coefficients of test fluids in tube-in-tube heat exchanger

Percent drag reduction was obtained by comparing experimental friction factors of each surfactant solution with calculated solvent (water) friction factors using the von Karman equation:

$$\%\mathrm{DR} = \frac{f_{\mathrm{water}} - f_{\mathrm{surfactant}}}{f_{\mathrm{water}}} \times 100 \tag{1}$$

and

$$f_{\mathrm{water}}^{-\frac{1}{2}} = 4.0\log(Ref_{\mathrm{water}}^{\frac{1}{2}}) - 0.4 \tag{2}$$

Other equations and the data reduction process used to get the friction factors of test fluids are described in detail in [7].

Similar to the definition of %DR, the percent heat transfer reduction of the drag reducing surfactant solution is defined as:

$$\%\mathrm{HTR} = \frac{Nu_{\mathrm{i,water}} - Nu_{\mathrm{i,surfactant}}}{Nu_{\mathrm{i,water}}} \times 100 \tag{3}$$

where

$$Nu_i \text{ (Nusselt number)} = \frac{h_{\mathrm{i}}D_{\mathrm{i}}}{k} \tag{4}$$

$Nu_{\mathrm{i,water}}$ is the Nusselt number of water inside the heat exchanger, $Nu_{\mathrm{i,surfactant}}$ is the Nusselt number of surfactant solution inside the heat exchanger at the same Reynolds number as for water.

The calculation of the heat transfer coefficient of the surfactant solution inside the tube-in-tube heat exchanger used a modified Wilson plot method, the same as used in the fluted tube-in-tube heat exchanger [7]. The detailed data reduction process to determine $h_{\mathrm{i,water}}$ and $h_{\mathrm{i,surfactant}}$ including estimation of the film temperature can be found on the website http://www.che.eng.ohio-state.edu/~qiy/HT.

3.2. Surfactant solution microstructure recovery time

The recovery times of the destroyed micelle microstructures and the effects of the destructive devices on the drag reducing ability of the surfactants were estimated quantitatively. By using measured temperatures, T8 and T6, to get the test fluid density, ρ_{T8} and ρ_{T6} respectively, the flow velocity of test fluid between P2 and P9 can be calculated as

$$u = \frac{Q\rho_{\mathrm{T8}}}{\rho_{\mathrm{T6}}\frac{\pi}{4}D_{\mathrm{i}}^2} \tag{5}$$

where D_{i} is the inner diameter of the test tube. The pressure coefficient between position, Pn, ($n = 2$–9) and P9 can then be obtained:

$$PD_n = \frac{\Delta P_{n-9}}{\frac{\rho_{\mathrm{fluid}} u_{\mathrm{fluid}}^2}{2}} \tag{6}$$

With destructive devices installed at the entrance of the tube-in-tube heat exchanger and if the super-ordered microstructure is not recovered before P9, the pressure coefficient $PD_{n,DD}$ of the surfactant solution with a device will be larger than that of $PD_{n,NDD}$ without destructive devices at the same Reynolds number at all locations between P2 and P9 and t_{rec} is $>(177 + 560)D_{\mathrm{i}}/u$ ($177D_{\mathrm{i}}$ is the distance from the destructive device to pressure measurement point P2 and $560D_{\mathrm{i}}$ is the distance between the pressure measurement points P2 and P9). If the microstructure of the surfactant solution recovered somewhere between P2 and P9, there is a location, b, where $PD_{n,\mathrm{DD}} = PD_{n,\mathrm{NDD}}$ at the same Reynolds number. If L_b is the distance between location b and pressure measurement point P2, The recovery time of a surfactant solution microstructure after passing a destructive device can therefore be estimated as:

$$t_{\mathrm{rec}} = \frac{L_b + 177D_{\mathrm{i}}}{u} \tag{7}$$

4. Results and discussion

Baseline experiments for water without a destructive device were run first to characterize the tube-in-tube heat exchanger. The energy unbalance with water flowing through the heat exchanger heated with saturated steam was less than 15%, which is higher than the 5% value in the fluted tube-in-tube heat exchanger experiments which used cooling water [7]. This high energy unbalance value is probably caused by the uncertainty in measuring the steam flow rate in the outer shell. It is, however, acceptable uncertainty for a steam heated system.

Friction factor tests for water were first conducted as baseline experiments and also for checking the reliability of the friction factor measurements. The average deviation of less than 5% from Von-Karman equation predictions (see [7]) indicates that the friction factor measurements were reliable and for drag reduction tests of surfactant solutions, the same procedure was used.

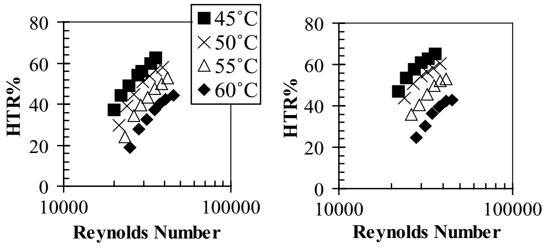
A maximum drag reduction of 70% was observed for the fresh cationic DR solution in the temperature range of 45–65 °C and Reynolds numbers range of 10,000–50,000. No degradation was observed 18 days after the Ethoquad T13-50 solution was prepared as indicated by the drag reduction tests.

For the fresh mixed zwitterionic/anionic DR solution, a maximum drag reduction of 80% was observed in the temperature range of 45–70 °C and Reynolds numbers range of 10,000–50,000. However, drag reduction test results for this solution after it experienced 60 hours of mechanical shear over a seven-day period indicated that the solution was partly degraded. The solution lost its drag reduction capacity completely at 70 °C and significant loss of drag reduction capacity was also observed at lower temperatures (except at 60 °C) at high Reynolds numbers. For this reason, the drag reduction ability of the solution was closely monitored during the heat transfer tests. Detailed analysis of the drag reduction test results of both solutions can be found in [7].

4.1. Ethoquad T13-50 (5 mM) with NaSal (8.75 mM) (Cationic DR Solution)

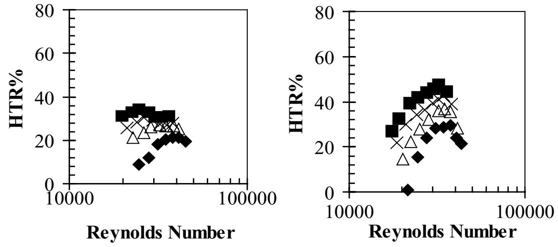
4.1.1. Drag reduction tests accompanying heat transfer tests

Fig. 3 shows heat transfer reduction of the cationic DR solution with different destructive devices (honeycomb, 15 elements of mixer A, 4 elements of mixer B and 5 elements of mixer B) installed at the entrance of the heat exchanger. The test fluid inlet temperature ranged from 45 to 60 °C and Reynolds numbers ranged from 10,000 to 50,000. To check for surfactant solution degradation during the heat transfer experiments, drag reduction tests were performed simultaneously between pressure measurement points P2 (80 diameters downstream of the heat exchanger exit) and P9. These drag reduction test results are important for correlating the effectiveness of the devices in enhancing heat transfer with drag reduction recovery. If drag reduction after 80 diameters is at the level of the undisturbed surfactant solution, either the microstructure of the surfactant has been restored or no breakup of microstructure occurred. However, if drag reduction was lost, there are three possible reasons. (1) The surfactant solution microstructure has not yet reformed after experiencing severe shear by the destructive device. (2) The surfactant solution may have been heated above the upper temperature limit for effective drag reduction at the exit temperature of the heat exchanger. (3) The surfactant solution was permanently degraded by bugs in the system before entering the heat exchanger. For (1), little or no drag reduction of surfactant solution will be observed between P2 and P9 compared with fresh surfactant solutions. Comparison of test fluid outlet temperatures with upper temperature limits for drag reduction should indicate whether (2) applies. For (3), subsequent drag



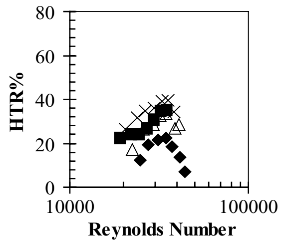
(a) Without any Destructive Device

(b) Honeycomb



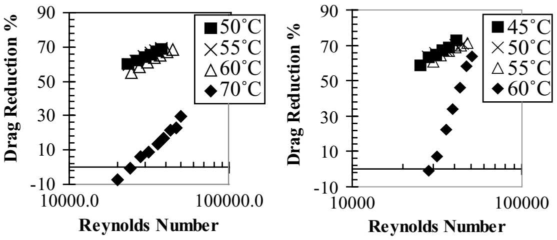
(c) 15 elements of mixer A

(d) 4 elements of mixer B



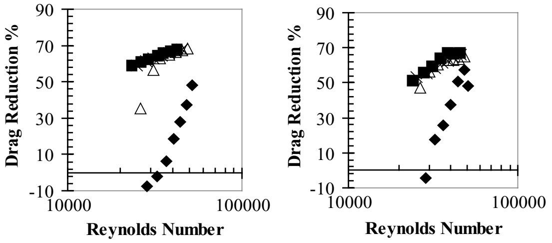
(e) 5 elements of mixer B

Fig. 3. Heat transfer reduction (HTR) of Ethoquad T13-50/NaSal (5 mM/8.75 mM) in the steam heated exchanger with different destructive devices vs. Reynolds number. Note: Temperatures shown are the inlet temperatures of the test fluids, the outlet temperatures of test fluids are about 6–9 °C higher than the inlet temperatures.



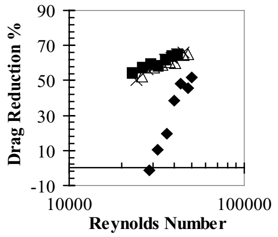
(a) Without Any Destructive Devices

(b) Honeycomb



(c) 15 elements of mixer A

(d) 4 elements of mixer B



(e) 5 elements of mixer B

Fig. 4. Drag reduction test results of Ethoquad T13-50/NaSal (5 mM/8.75 mM) during heat transfer tests with different destructive devices. Note: Temperatures shown in figures (b)–(e) are the inlet temperatures of the test fluids. The outlet temperatures of test fluids are about 10 °C higher than the inlet temperatures.

reduction measurements on the test solution without any destructive device could show whether permanent drag reduction had occurred.

Fig. 4 presents corresponding drag reduction test results obtained between 80 and 640 diameters downstream of the heat exchanger exit (P2–P9). The temperatures listed in these figures are test fluid inlet temperatures to the heat exchanger. The drag reduction measurements were obtained at the exit temperature of the heat exchanger which is about 10 °C higher than the inlet temperature. For example, with inlet temperature of 60 °C for test fluids, the drag reduction measurements were conducted at an exit temperature near 70 °C. As mentioned, the upper temperature limit of drag reduction for the fresh cationic DR solution is 65 °C. Large drag reduction percentages were observed at all inlet temperatures below 55 °C as shown in Fig. 4. This indicates that Ethoquad T13-50 solution was not permanently degraded in the heat transfer tests with any destructive device as its drag reduction effectiveness beyond 80 diameters downstream of the heat exchanger exit was almost the same as that of the fresh solution without any destructive device. The low drag reduction values at 60 °C inlet temperature (≅70 °C outlet temperature) are due to approaching the upper temperature limit for drag reduction.

4.1.2. Heat transfer reduction (HTR) with different destructive devices

The heat transfer reduction data of the cationic DR solution without any destructive device shown in Fig. 3a indicate that the maximum heat transfer reduction of the cationic DR solution reaches 65% in the tube-in-tube heat exchanger with steam heating at high Reynolds numbers and at an inlet temperature of 45 °C. In the tested Reynolds number range of 20,000–50,000 and inlet temperature range of 45–60 °C, HTR increases with

Reynolds number and decreases with increasing temperature which is consistent with the drag reduction results shown in Fig. 4.

Fig. 3b shows that the honeycomb destructive device has little or no effect on enhancing heat transfer ability of the cationic DR solution. Heat transfer experiments with three elements of mixer B were also conducted and results similar to those for honeycomb were obtained. As can be seen, the 15 element mixer A (Fig. 3c) and 4 (Fig. 3d) and 5 (Fig. 3e) element mixer B gave significant reductions in HTR of the solution. With the 15 element mixer A as the destructive device, the maximum heat transfer reduction percentage of the cationic DR solution drops to around 35% and at high Reynolds numbers, heat transfer reduction percent decreases with increasing Reynolds number because of higher shear stresses at high Reynolds number resulting in more damage to the micelles. With increasing length of mixer B, the heat transfer reduction of the cationic DR surfactant solution decreases as shown in Fig. 3d and e. However, even with five elements of mixer B, the maximum heat transfer reduction percentages of the cationic DR solution are still around 40% which is not as low as with 15 elements of mixer A. That is, 15 elements mixer A are more effective in enhancing the heat transfer ability of the cationic DR solution than five elements of mixer B.

According to Li et al. [12], the production of turbulence in a flow is necessary to enhance the heat transfer ability of the surfactant solutions. When solutions passed through the destructive devices, they experienced high shear stress which can break up the rodlike or threadlike micelles so that they behave more like a Newtonian fluid with enhanced heat transfer ability. In addition to that, the smaller flow area (with certain blockage ratio) and shape of the destructive devices such as dividing/merging with static mixers could also promote turbulence production and, therefore, better heat transferability.

From the experimental results shown in Fig. 3, the shear stress the surfactant solutions experienced when passing through the honeycomb may be not large enough to break the micelles. With its cells aligned in the flow direction (Fig. 2), instead of promoting turbulence, the honeycomb destructive device may actually reduce the turbulence level of the flow passing through it due to the reduction of velocity fluctuations in the radial direction with turbulent eddy sizes of the same order as the cell diameters. That is, the honeycomb may straighten the flow and make it more laminarized. In addition, because of its large cell size with equivalent diameter per hexagon cell of around 2.9 mm, the increased shear stress caused by the reduced passage area may not be large enough to break the micelles. These explain the small heat transfer enhancement effect of the honeycomb observed on the cationic DR solution (Fig. 3).

The helical static mixer consists of left- and right-twisting helical elements placed at an angle of 90° to each other. Each element twists through an angle of 180°. When surfactant solution passes through the static mixer, the fluid is either divided, rotated, channeled or diverted through each element of the mixer which promotes turbulence and vortex production both in the flow and radial directions. The shear effects of static mixers on surfactant solutions depend strongly on the fluid velocity and shape of the helical elements. With the same static mixer, the greater the fluid velocity, the higher the shear stresses.

As mentioned in the experimental section, the length of each helical element in the mixer A is about twice that of the mixer B. With the same total static mixer length, the mixer B should be more effective in promoting turbulence with higher shear stresses than the mixer A because of the higher frequency of dividing and merging of the flow. In our experiments, however, only four to five elements (total length = 4 or 5 cm) of mixer B were tested while 15 elements (total length ≈ 28 cm) in the mixer A were tested. Therefore, it is not surprising that the heat transfer enhancement effects (Fig. 3) of the 15 elements of mixer A were greater than the four or five elements of mixer B. However, as can be seen from Fig. 3, the differences between the heat transfer enhancement effects of the 5 element of mixer B and the 15 elements of mixer A were small.

4.1.3. Pressure drop across destructive device and tube-in-tube heat exchanger

Pressure drops over the destructive devices (honeycomb, 15 elements of mixer A, four elements of mixer B) and the tube-in-tube heat exchanger plus 80 tube diameters beyond the heat exchanger exit to pressure measurement point P2 (i.e., P1–P2 in Fig. 1) for the cationic DR solution with an inlet temperature of 45 °C are presented in Fig. 5. For comparison, pressure drops of the same solution with no destructive device are also shown together with pressure drops of water without any destructive device.

At any Reynolds number, pressure drop of the cationic DR solution across the device increases in the order of honeycomb, 15 elements of mixer A, four elements of mixer B and five elements of mixer B. Similar results were obtained for pressure drops measured at other inlet temperatures. At the same Reynolds number, the pressure drop of the cationic DR solution with honeycomb is about the same as that of water without any destructive device. Pressure drops for the five element of mixer B for Reynolds numbers from 10,000 to 50,000 could not be obtained due to the limitation of our pressure transducer. For the same reason, we were unable to measure the pressure drops of four elements mixer B above a Reynolds number of 24,000 and the 15

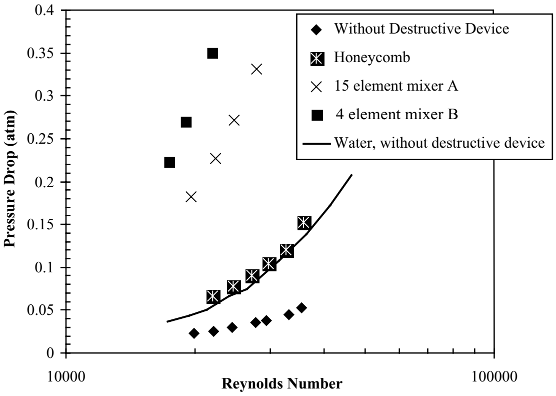


Fig. 5. Pressure drop of Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution over destructive devices and heat exchanger ($T = 45$ °C). Note: Pressure drops with destructive devices of five elements of mixer B were beyond the limit of our pressure transducer.

elements mixer A above a Reynolds number of 30,000. From Fig. 5, it can be seen that at Reynolds number of less than 30,000, the pressure drop of the cationic DR solution with 15 elements of mixer A is nearly four times that of water without a destructive device while the pressure drop of the solution with four elements of mixer B is nearly six times that of water without a destructive device at Reynolds numbers less than 24,000.

Using the honeycomb destructive device with its cells aligned in the flow direction, the pressure drop of the cationic DR solution is low. But this device causes little heat transfer enhancement of the cationic DR solution so it is not useful. From Figs. 3 and 5, it can be seen that although the heat transfer enhancement effects of the 15 element of mixer A are greater than those of the four and five element of mixer B, the pressure drops for the latter are much larger at all the Reynolds numbers tested.

Figs. 3 and 5 show that enhanced heat transfer of the cationic DR solution is always associated with a pressure drop penalty. For the 15 element mixer A, which is the most effective destructive device tested, the pressure drop of the cationic DR solution is nearly four times that of water without any destructive device at Reynolds numbers below 30,000. Gasljevic and Matthys [13] obtained similar results. They reported that a pressure drop of more than 1 bar was needed to break up the microstructure of Ethoquad T13-50/NaSal (5 mM/12.5 mM), a solution which is more stable than our 5 mM/8.75 mM solution because of the higher counterion concentration. Change of helical element geometry (shape and unit length of each element) of the static mixer is needed to obtain better heat transfer enhancement with smaller pressure drop penalty.

4.1.4. Estimation of surfactant solution microstructure recovery time

In order to check the recovery time of the temporarily destroyed microstructure of the cationic DR solution, pressure distribution tests downstream of the heat exchanger were performed with four elements of mixer B at 50 °C. The pressure coefficient distribution (Eq. (6)) results are presented in Fig. 6. The first pressure drop measurement point (P2) is located 177 diameters downstream of the destructive device. Comparisons of the pressure distribution with four elements of mixer B and without any destructive device at four Reynolds numbers were made to determine the time needed for the solution to regain its drag reduction ability, i.e., recovery time for the microstructures in the surfactant solution. $Re_{\max}$ in Fig. 6 means the maximum Reynolds number that could be reached in our system ($\approx$50,000).

As can be seen, the pressure coefficients of the surfactant solution are almost the same with and without the destructive device at $Re_{\max}$, 7/8 $Re_{\max}$, 3/4 $Re_{\max}$ and 1/2 $Re_{\max}$ at all measuring points downstream from the tube-in-tube heat exchanger exit. At $Re_{\max}$, it takes about 1 s for surfactant solution to flow the 177 diameters from the destructive device to P2. This indicates either the micelle structure of the cationic DR solution is too strong to be completely broken up by the shear stress caused by four elements of plastic static mixer or the microstructure of the solution is restored quickly (less than 1 s) after break-up. As can be seen from Fig. 3d, the maximum heat transfer reduction of the cationic DR solution at 50 °C with this destructive device was almost 40% suggesting that the microstructure was not completely broken up. The pressure drop measured over

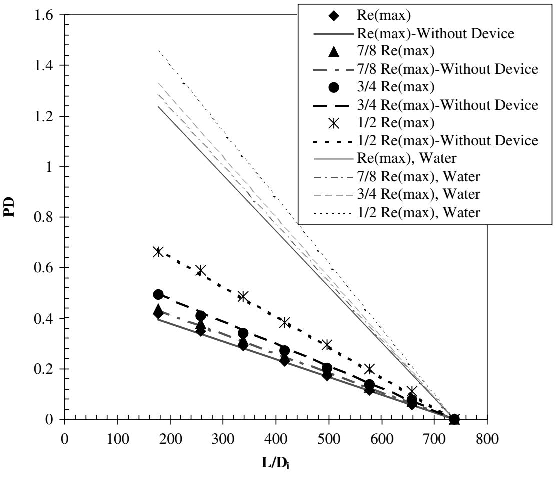


Fig. 6. Pressure coefficient distribution of Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution downstream of destructive device—four elements of mixer B ($T = 50$ °C) ($Re_{\max} = 42{,}000$).

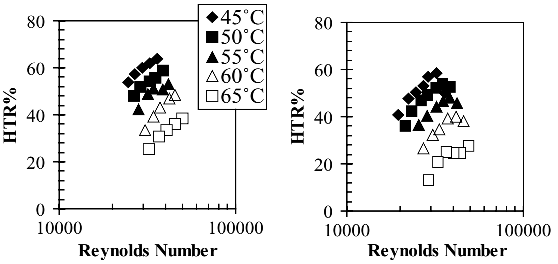
four elements of mixer B and the tube-in-tube heat exchanger is greater than 0.37 atm at $Re = 30{,}000$ (Fig. 5).

4.2. SPE98330/HCHO/Trilon A (1500 ppm/150 ppm/500 ppm) (Mixed Zwitterionic/Anionic DR Solution)

4.2.1. Drag reduction tests accompanying heat transfer tests

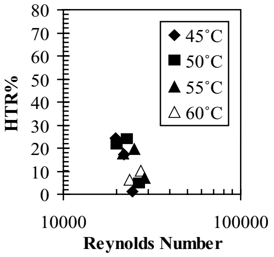
Heat transfer reduction results for the mixed zwitterionic/anionic DR solution without any destructive device and with destructive devices honeycomb and 15 elements of mixer A are given in Fig. 7. As mentioned earlier, the mixed zwitterionic/anionic surfactant solution degraded somewhat after circulating in the experimental system. In order to monitor the degradation of the surfactant solution, the drag reduction ability of the solution was measured 80 diameters downstream of the heat exchanger exit (between P2 and P9) simultaneously with the heat transfer tests. Results are shown in Fig. 8 together with the age of the test fluid. Drag reduction measurements were at the outlet temperature of the tube-in-tube heat exchanger, which is about 10 °C higher than the inlet temperature.

Qi et al. [7] showed that after two days (8 h circulation), the SPE98330 solution lost some of its drag reduction ability compared with fresh solution at the highest temperature 72–73 °C. As mentioned in Section 4.1.1, there are three possible reasons for the loss of surfactant solution drag reduction ability during the heat transfer tests: (1) the upper temperature limit for drag reduction was exceeded; (2) the super-ordered microstructure of the SPE98330 surfactant solution was temporarily destroyed by the destructive device and can not recover in the time of flow to the drag reduction measurement region; (3) permanent degradation of the solution. If the latter is the main reason for the loss in drag reduction ability, little can be learned about the effect of the destructive devices.



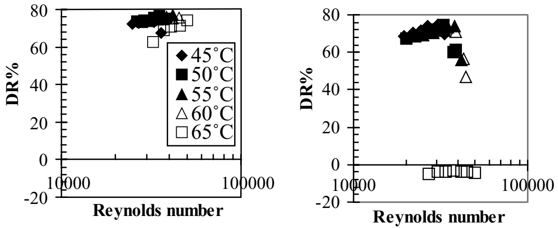
(a) Without any destructive device (age of solution : 2 days)

(b) Honeycomb (age of solution: 4 days)



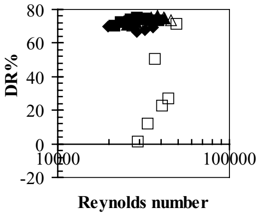
(c)15 elements of mixer A (age of solution: 3 days)

Fig. 7. Heat transfer reduction (HTR) of SPE98330/HCHO/Trilon A (1500 ppm/150 ppm/500 ppm) solution with different destructive devices installed at the heat exchanger entrance.



(a) Without any destructive device (age of solution : 2 days)

(b) 15 elements of mixer A (age of solution: 3 days)



(c) Honeycomb (age of solution: 4 days)

Fig. 8. Drag reduction test results of SPE98330 (1500 ppm) surfactant solution accompanying heat transfer tests in the heat exchanger with destructive devices installed at the entrance vs. Reynolds number. Note: Temperatures shown are the inlet temperatures of the test fluids. The outlet temperatures of the fluids are about 6–9 °C higher than the inlet temperatures. Drag reduction tests were conducted at the outlet temperatures.

With the 15 element mixer A, at inlet temperatures of 50, 55 and 60 °C, the drag reduction ability of the solution was partially lost at Reynolds numbers above 35,000. At a test fluid inlet temperature of 65 °C, the SPE98330 surfactant solution lost its drag reduction ability completely (Fig. 8b) as the outlet temperature of the solution was 75 °C or higher. The observed drag reduction loss of the SPE98330 solution with mixer A at 65 °C (Fig. 8b) is probably due to a combination of exceeding the upper temperature limit for drag reduction and unrecovered super-ordered microstructure at high Reynolds numbers. On the day after the experiments with the 15 element mixer A, heat transfer experiments with the mild shearing honeycomb were performed and drag reduction was found to be only partly lost at 65 °C inlet temperature (Fig. 8c, four days, $T_{\mathrm{out}} =\sim 74$ °C) and not at all at 45, 50, 55 and 60 °C inlet temperatures in the whole Reynolds number range. Therefore, the surfactant solution tested with the 15 element mixer A was not permanently degraded on the third day.

4.2.2. *Heat transfer reduction (HTR) with different destructive devices*

At high Reynolds number with no destructive device (Fig. 7a) or with the honeycomb (Fig. 7b), heat transfer reduction as high as 65% was obtained for the mixed zwitterionic/anionic DR solution, which is about the same as that for the cationic DR solution. The heat transfer reduction increased with Reynolds number and decreased as temperature increased.

The honeycomb destructive device had very little effect on enhancing the heat transfer ability of this solution. This is similar to the results with the cationic DR solution (Fig. 3b). The 15 elements of mixer A reduced the heat transfer reduction of the SPE98330 solution below 30% at all inlet temperatures (45–60 °C) in the Reynolds number range of 10,000–30,000 (Fig. 7c). The explanation for the different heat transfer enhancement effects of the honeycomb and the 15 element mixer A is given in Section 4.1.2.

4.2.3. *Pressure drop across destructive device and tube-in-tube heat exchanger*

The pressure drops of mixed zwitterionic/anionic DR solution flowing through the destructive devices and the heat exchanger at an inlet temperature of 45 °C are shown in Fig. 9. For comparison, pressure drops of the solution and water without destructive devices at different Reynolds numbers were also measured. At the same Reynolds number, the pressure drop of the surfactant solution over the 15 element mixer A is much higher than that of the honeycomb. Similar results were obtained at other temperatures. For the 15 element mixer A, pressure drops could not be measured at high Reynolds numbers because of the limitations of our pressure transducer. But the trend of pressure drop increase with Reynolds number can be clearly seen in Fig. 9.

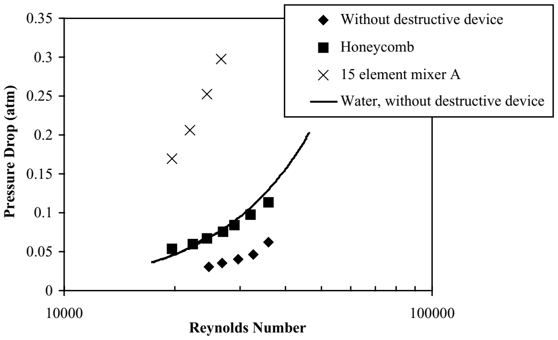


Fig. 9. Pressure drop of SPE98330/HCHO/Trilon A (1500 ppm/150 ppm/500 ppm) solution over destructive devices and heat exchanger ($T = 45$ °C).

The ratio of the pressure drop of the mixed zwitterionic/anionic DR solution over the 15 element mixer A to that of water without destructive device is nearly 4 at the tested Reynolds number range at 45 °C, which is similar to that of the cationic DR solution shown in Fig. 5. The pressure drop of the solution with honeycomb is very close to that of water without any destructive device below Reynolds number of 30,000 and above 30,000, it is even lower than that of water without any destructive device.

From the heat transfer enhancement effects (Fig. 7) and pressure drop penalty of the solution shown in Fig. 9, the mixer A may also be a useful device for enhancing the heat transfer ability of the mixed zwitterionic/anionic DR solution as it may be for the cationic DR solution.

4.2.4. *Estimation of surfactant solution microstructure recovery time*

Pressure distribution tests downstream of the destructive devices located at the entrance to the heat exchanger were performed for the mixed zwitterionic/anionic DR solution. Results with the 15 element mixer A are shown in Fig. 10. As can be seen from Fig. 7, this

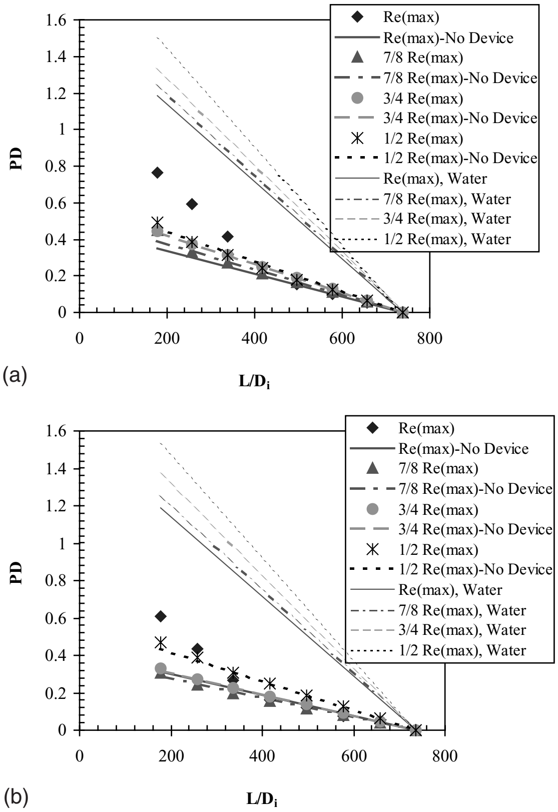


Fig. 10. Pressure coefficient distribution of SPE98330/HCHO/Trilon A (1500 ppm/150 ppm/500 ppm) solution downstream of the 15 element mixer A ($Re_{\max} = 42{,}000$) (age of solution: 1 day, no degradation observed). (a) $T = 55$ °C; (b) $T = 60$ °C.

device works well in enhancing the heat transfer ability of the surfactant solution by promoting turbulence and producing high shear stresses which destroy the microstructures of the surfactant solutions. By comparing pressure distributions of mixed zwitterionic/anionic DR solution with and without a destructive device, recovery time for the destroyed surfactant solution microstructures can be estimated. Experiments were performed at four Reynolds numbers, that is $Re_{\max}$ ($Re_{\max} = 42,000$), $7/8Re_{\max}$, $3/4Re_{\max}$, $1/2Re_{\max}$ and two temperatures, 55 and 60 °C. The pressure measurements start at 177 diameters downstream of the destructive device (P2).

At 55 °C and $Re_{\max}$, the pressure coefficient for the mixed zwitterionic/anionic DR solution with the metal static mixer is much higher than that without a destructive device up to $L/D_i \approx 480$ as shown in Fig. 10. That is, the microstructure of the surfactant solution is not fully recovered until about $L/D_i \approx 480$. From this length and the flow velocity of the fluid, the recovery time of the surfactant solution microstructure after breakup is estimated to be around 2.5 s for $T = 55$ °C and for $Re_{\max}$ at $T = 60$ °C, recovery is at $L/D_i \approx 420$ or about 2.0 s. Not surprisingly, the recovery time of the surfactant solution microstructures decreases with increasing temperature.

There is little difference between the pressure coefficients downstream of the heat exchanger with or without destructive devices at $7/8Re_{\max}$, $3/4Re_{\max}$ and $1/2Re_{\max}$. This may be because the shear stresses created by the 15 element mixer A at these lower Reynolds numbers are not great enough to break up the microstructure of the mixed zwitterionic/anionic DR solution or that the partially broken microstructure is restored before the region where the pressure drop measurements were made (1–1.8 s).

5. Conclusions

1. Among the destructive devices tested, it was found that 15 elements of mixer A is the best device to enhance the heat transfer ability of the cationic DR solution with a modest pressure drop penalty (about four times that of water without any destructive devices). It is also very effective in enhancing the heat transfer ability of the mixed zwitterionic/anionic DR solution with about the same pressure drop penalty.

2. Although the pressure drop penalty of the honeycomb device is very low in both the cationic DR solution (Fig. 5) and the mixed zwitterionic/anionic DR solution (Fig. 9), it is not very effective in enhancing the heat transfer ability of the solutions (Figs. 3b and 7b).

3. The shape of the destructive device plays an important role on its effects in enhancing the heat transfer ability of the surfactant solutions with reasonable pressure drop penalty. In the case of static mixers with the cationic DR solution, with the same helical element morphology (shape and length of each element), the heat transfer enhancement of the solution increases with the number of elements used in the static mixer (Fig. 3d and e) but is accompanied by a significant increase in pressure drop penalty (Fig. 5). By adjusting both the number of elements and the unit length of each helical element in the static mixer, a static mixer with maximum heat transfer enhancement and minimum pressure drop penalty can be developed.

4. Use of lower surfactant concentration and/or a lower counterion/cationic surfactant molar ratio may facilitate microstructure break-up and better heat transfer enhancement of the surfactant solutions.

5. Pressure distribution tests from 177 diameters downstream of the heat exchanger exit indicate that the microstructure of the cationic DR solution recovers very quickly after its breakup with the destructive device of four elements of plastic static mixer at $Re_{\max}$, $7/8Re_{\max}$, $3/4Re_{\max}$ and 1/2 $Re_{\max}$ (Fig. 6) with full drag reduction recovery observed in less than 1 second. It can be inferred that for destructive devices such as honeycomb or three elements of mixer B which had less effect on the microstructure of the surfactant solution, the solution recovers much more quickly or is not degraded completely which explains the smaller heat transfer enhancement of these destructive devices.

6. Recovery time of surfactant solution microstructure decreases with increasing temperature. Recovery time of 2.5 s was measured for the mixed zwitterionic/anionic DR solution with the 15 element mixer A at $T = 55$ °C and 2.0 s at $T = 60$ °C at $Re_{\max}$.

Acknowledgements

Y. Qi appreciates the support of The Ohio State University Fellowship and a Presidential Fellowship. The research was supported in part under grant 12,074E, Program in Science and Technology Cooperation, Office of Science Advisor, US Agency for International Development.

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