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International Journal of Heat and Mass Transfer 44 (2001) 1495–1505

International Journal of HEAT and MASS TRANSFER

www.elsevier.com/locate/ijhmt

Enhanced heat transfer of drag reducing surfactant solutions with fluted tube-in-tube heat exchanger

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Received 26 October 1999; received in revised form 9 June 2000

Abstract

Solutions containing drag reducing additives also show reduced heat transfer which limits their use in hydronic cooling and heating systems where heat exchange is critical. For Reynolds numbers 10,000–50,000 and test fluid inlet temperatures 50–70°C, a fluted inner tube heat exchanger showed increased heat transfer coefficients for both cationic and zwitterionic/anionic drag reducing surfactant solutions. The pressure drop penalty for heat transfer enhancement of the cationic surfactant solution flowing through the fluted tube is high while for the zwitterionic/anionic solution, significant heat transfer improvement was achieved with only a modest pressure drop penalty. © 2001 Elsevier Science Ltd. All rights reserved.

1. Introduction

The flow phenomenon by which small amounts of additives can greatly reduce the turbulent friction factor of a fluid is called drag reduction. It can be used to reduce energy consumption, increase flow rate and decrease the sizes of pumps, pipes and fittings in flow systems such as district heating and cooling systems.

High polymers and surfactants are two types of additives used as drag reducers. In the past thirty years, extensive investigations have been made on polymer solution drag reduction. However, their susceptibility to mechanical degradation makes them unsuitable for circulation systems. Under high stress, surfactant drag reducers also suffer temporary mechanical degradation, but this degradation of their microstructure is temporary because surfactants have the ability to "repair" themselves in times of the order of seconds [1]. Therefore, surfactant drag reducers have the potential to be used in district heating or district cooling circulation systems. In these systems, hot or cold water is circulated to buildings of a district from a central station and pumping energy is a major operating cost. High polymer drag reducing additives are mechanically degraded too quickly to be useful in such systems.

However, the effectiveness of surfactant drag reducers is limited to a certain range of temperatures and Reynolds numbers. Rose et al. [2,3] and Chou et al. [4] pointed out that the upper temperature limit for effective drag reduction by cationic surfactants depends on alkyl chain length while the solubility of the surfactant determines the lower temperature limit. It is a characteristic of surfactant drags reduction that when the Reynolds number increases to a critical value, drag reduction drops to zero. This critical Reynolds number corresponds to a critical wall shear stress at which the surfactant microstructure breaks down. Several researchers [2,3,5,6] reported that critical wall shear stress is independent of tube diameter but it does have a close relationship with the nature, concentration, and temperature of the cationic surfactant and the counterions present. Both the mechanical degradation as well as the high temperature loss of drag reduction are reversible

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PII: S0017-9310(00)00203-9

Nomenclature

$D_i = 0.0103$ (m)	inner diameter of test tube
%DR	percent drag reduction
f	Fanning friction factor
h_i (W/m^2 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 K)	heat conductivity of test fluid
$L_0 = 5.74$ (m)	length of the pressure drop section
$Nu = hD/k$	Nusselt number
ΔP (Pa)	pressure drop of test fluid as it flows through the test section (P2–P9 in Fig. 1)
$Pr_{water} = (\mu_{water} C_{water})/k_{water}$	Prandtl number of water
Q (m^3/s)	volumetric flow rate of test fluids
$Re = \rho DV/\mu$	Reynolds number
V (m/s)	mean flow velocity of test fluid
ρ (kg/m^3)	density of test fluid
Greek symbols	
μ (Pa s)	viscosity of test fluid
τ_w (Pa)	wall shear stress of test fluid
Subscripts and superscripts	
i	inside of tube
o	outside of tube
w	wall

because of the "self-repairability" of the surfactants' microstructures.

Along with the reduction in momentum transport, drag reducing fluids also have been found to reduce heat transfer coefficients particularly in tube-in-tube heat exchangers [2,7,8]. This is a serious drawback in using drag reducing fluids in district heating and cooling circulation systems because in these systems the circulating fluid supplies/removes heat, and heat transfer characteristics in heat exchangers are of great importance. The heat transfer reduction that accompanies drag reduction is probably caused by thickening of the viscous boundary near the wall which increases the thermal resistance between wall and bulk fluid [9] and the reduction in radial turbulence intensities. Thus, if formation of the viscous boundary layer near the wall is disturbed, the heat transfer ability of the drag reducing fluid should be enhanced. In this paper, a fluted tube was used as the inner tube of the heat exchanger to provide continuous disturbances of the viscous boundary near the wall. While fluted tubes enhance the heat transfer from the fluid to the tube wall, there is a penalty caused by use of fluted tubes as the pressure drop of the fluid flowing through the heat exchanger is increased compared with that of a smooth tube. Heat transfer enhancement and the penalty incurred will be discussed later.

Above the critical wall stress, drag reduction is lost and the heat transfer ability of the fluid is restored to Newtonian fluid levels. Ohlendorf et al. [10] pointed out that surfactants possess drag reducing ability because of the presence of rod-like micelles which aggregate and form super-ordered structures under moderate shear. When the critical wall shear stress is reached, the aggregates break down. The spiral wall of the fluted tube generates a swirling motion which also exerts a shear stress on the test fluid. If the shear stress in the fluted tube is greater than the critical shear stress for degradation of the drag reducing surfactant solution, the super-ordered microstructure of the surfactant solution will be destroyed and the heat transfer ability of the solution will increase.

2. Experimental

2.1. Test loop

A schematic of the experimental flow loop is shown in Fig. 1. The total length of the system is about 29 m. The inner diameter of the smooth stainless steel tube is 1.03 cm and the outer diameter is 1.27 cm. In order to reduce heat loss from the system, all tubes were thermally insulated by elastomer foam rubber ($T_{max} = 104$°C) and the steam lines by PVC covered polymeric foam ($T_{max} = 204$°C). Two tanks, each of volume of 16.7 l, were installed at the two ends of the system as reservoirs and fluctuation dampers for the test fluids.

Two heat exchangers were installed in the system. One is a tube-in-tube heat exchanger to heat water or surfactant solution and the other is a fluted tube-in-tube heat exchanger to cool the test fluid. The tube-in-tube heat exchanger is steam heated in the annulus. To control fluid temperature in some of the drag reduction tests, a thermal regulator (OMEGA Temperature Controller, CN76000) was installed near Tank 1. This regulator controlled an electric heater to control temperatures in the drag reduction experiments. To control temperature in the low temperature drag reduction experiments, the fluted tube exchanger with cooling water in the annulus was used to remove heat from the system. During heat transfer tests, the electric

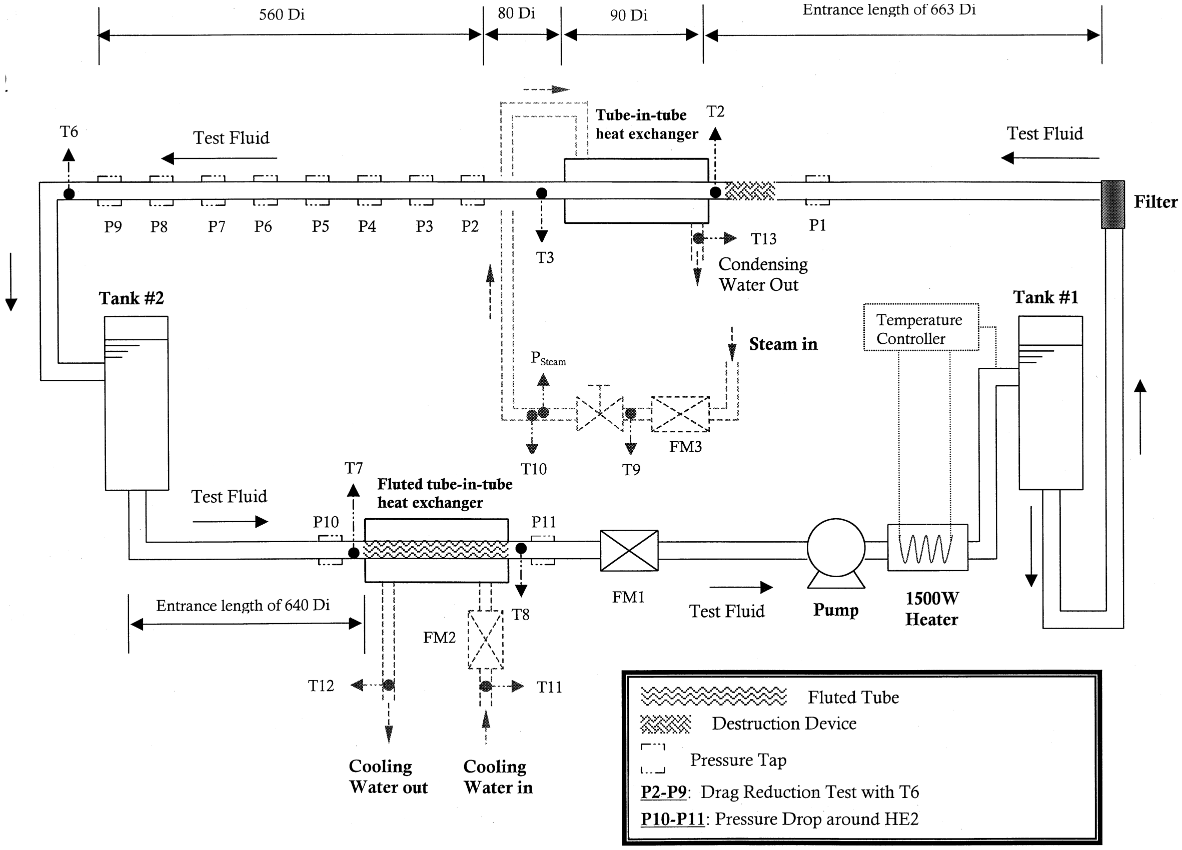


Fig. 1. Schematic of experimental apparatus.

heater controlled by the temperature controller was not used and the desired test fluid temperature was obtained by manually adjusting the heating and cooling rates. 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.

The fluted tube-in-tube heat exchanger is 0.91 m long with four starts (four flutes intersect any cross-section) on the inner tube (see Fig. 2 [11]). The flutes improve the heat transfer to or from the test fluid inside the heat exchanger. Since this heat exchanger was designed to be the cooling portion of the system, cooling water flows through its annulus. There is a smooth tube entrance length of more than 600 diameters before both exchangers to ensure fully developed turbulent fluid flow before water or surfactant solution enters the exchangers.

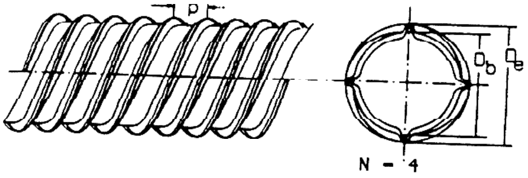


Fig. 2. Spirally fluted tube and definition of geometry [11].

The pumping system consisted of a stainless steel centrifugal pump (Eastern Industries) with bypass and a flow control valve to regulate the flow to the desired flow rate between 0–10.37 l/min. This flow rate was then monitored by a Rosemount Model 8701 magnetic flow meter together with Rosemount Model 8702 magnetic transmitter which sends analog inputs to the data acquisition system. The uncertainty in the measured flow rate is about 0.015 l/min which is 0.4% of the minimum flow rate used in these experiments. An OMEGA–MAG magnetic flow meter (FMG-700) was used to measure the cooling water flow rate to the fluted tube heat exchanger with an uncertainty of 0.08 l/min which is 0.2–1.5% of the flow rates used. These two flow meters were calibrated by the weight-stop watch method and their analog outputs were sent to the data acquisition system and monitored by computer.

A Rosemount differential pressure transducer (0/0.37 atm, 4/20 mA) was used to measure the pressure drops of test fluids over test locations P2 and P9 for drag reduction tests and pressure drops of test fluids in the fluted tube-in-tube heat exchanger. This pressure transducer was calibrated by using a Dead Weight Tester (Ashkroft Gauge Tester, Type 1300) with an uncertainty of 5.73 Pa. This gave a percent error range of 0.015–0.15% over the range of pressure drops measured.

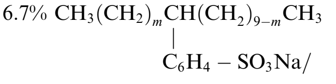
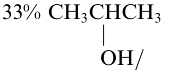
Temperatures of the test fluids were measured with T-Type thermocouples (0.42 cm diameter, 7.6 cm length) which were connected to one of our data acquisition components ISO-Rack 16 Backplane. This backplane incorporates screw terminals for wiring inputs and outputs and cold junction compensation for thermocouples. Compact thermocouple modules 5B47-T-07 (Analog Devices) were installed on the backplane to provide signal conditioning and hundreds of volts isolation from harsh environments with ±0.05% span accuracy and ±0.02% span nonlinearity. All the thermocouples were carefully calibrated using 0.2°F graduation precision thermometers (Miller & Weber) in seven different temperature ranges. These thermometers were calibrated against a NIST master standard accurate to better than 1°F. The absolute temperatures read by the thermocouples were not critical, however, only the temperature differences. The uncertainty in any thermocouple reading is less than ±0.08°C.

The data acquisition system consists of an ISO-Rack 16 Backplane (Computer Board), compact thermocouple signal conditioning modules (5B47-T-07, Analog Devices) for temperature, compact isolated current signal conditioning modules (5B32-01, Analogy Devices) for pressure and flow rates, and CIO-DAS16Jr AD converter board (0.01% ± 1 LSB (Least Significant Bit) accuracy, Computer Board) inside the computer. Like the compact thermocouple modules 5B47-T-07, the 5B32-01 modules provide signal conditioning and noise isolation for the pressure transducer and the flow meters. All conditioned analog signals from these modules were sent to the AD converter CIO-DAS16Jr inside the computer. Data acquisition software (Labtech View) samples data at a frequency of 1 HZ from the CIO-DAS16Jr board. All the temperature, flow rate and pressure drop data were monitored through the computer and determined to be nearly constant before data acquisition began. All the data measured during the experiments were averages obtained over 2–5 min.

2.2. Materials

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 zwitterionic 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 active SPE98330 solution, sodium nitrilotriacetate (Trilon A, 500 ppm) and formaldehyde (150 ppm) were added as stabilizing chelator and bug killer, respectively (see Table 1). The 5 mM Ethoquad T13-50 cationic surfactant was mixed with 8.75 mM counterion sodium salicylate and deionized water for more than 6 h and stored more than 12 h before testing. The concentration of Ethoquad T13-50 and its molar ratio (5 mM/8.75 mM) with NaSal gave good drag reduction in turbulent pipe flow and a recovery time after mechanical degradation of tens of seconds [12,13]. Since the SPE98330 zwitterionic/anionic surfactant solution was found to degrade quickly after the solution was prepared, 150 ppm of the biocide formaldehyde was added in addition to 500 ppm of Trilon A, a chelating agent. These additives were recommended by Akzo Nobel. The SPE98330 solution was well mixed with 500 ppm Trilon A, 150 ppm formaldehyde and deionized water and stored for more than 12 h before testing.

Table 1
List of tested surfactants

Additive	Supplier	Chemical formula of the surfactant
Ethoquad T13-50	Akzo Nobel	$[C_{17.3}H_{34.5}\text{–}N(CH_2CH_2OH)_3]^+CH_2CO_2^-$
SPE98330[a]	Akzo Nobel	27% $CH_3(CH_2)_{15}{}^{-}N^+(CH_3)_2CH_2COO^-$/  6.7% $CH_3(CH_2)_m\underset{\substack{\vert \\ C_6H_4 - SO_3Na}}{CH}(CH_2)_{9-m}CH_3$/  33% $CH_3\underset{\substack{\vert \\ OH}}{CH}CH_3$/ 33.3% Water

[a] 500 ppm Trilon A (sodium nitrilotriacetate), a chelating agent and 150 ppm of formaldehyde, a biocide, were added to SPE98330.

2.3. Tests performed

Drag reduction tests and heat transfer tests in the fluted tube-in-tube heat exchanger were performed to check the drag reduction and the heat transfer reduction behavior of the Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution and the SPE98330 (1500 ppm) solution. Corresponding pressure drops of the solutions over the fluted tube-in-tube heat exchanger were also measured to check the pressure drop penalty paid for the heat transfer enhancement.

During drag reduction tests, the test fluid was 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 to be used for the heat transfer tests. Flow rates, temperatures and pressure drops of the test fluids over test locations #P2 and #P9 were measured. Tests were run at 5°C temperature intervals from 45°C to 70°C (or until the surfactant solution lost its drag reduction ability).

For the heat transfer tests in the fluted tube-in-tube heat exchanger, inlet and outlet temperatures of the test fluids entering the heat exchanger, inlet and outlet temperatures of the cooling water in the annulus of the heat exchanger and flow rates of the test fluids and the cooling water were recorded to obtain heat transfer coefficients of the test fluid. Tap water was run first as the test fluid to get baseline data. Drag reduction tests at positions #P2 to #P9 were run simultaneously with the heat transfer tests to check for any permanent degradation of the drag reducing surfactant solutions. Experiments ranged from inlet temperatures of 50–70°C at intervals of 5°C.

The objective of the tests was to check the heat transfer enhancements caused by the inner fluted tube. Pressure drops of the test fluids over the heat exchanger (#P10 to #P11) were also measured to check the pressure penalties paid for the heat transfer enhancements obtained.

3. Data reduction

For convenient comparison of the results between water and surfactant solutions, the thermal–physical properties of water was 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.

All the data for drag reduction and heat transfer reduction were processed using Microsoft Excel 97. Friction factors and heat transfer coefficients were obtained as follows.

3.1. Friction factors

The Fanning friction factors were determined as

$$f = \frac{\tau_w}{(1/2)\rho V^2} = \frac{\Delta P D_i}{2\rho V^2 L_0} = \frac{\pi^2 D_i^5 \Delta P}{32\rho L_0 Q^2}. \tag{1}$$

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

$$\%\mathrm{DR} = \frac{f_{\mathrm{water}} - f_{\mathrm{surfactant}}}{f_{\mathrm{water}}} \times 100 \tag{2}$$

and

$$f_{\mathrm{water}}^{-(1/2)} = 4.0\log(Re\, f_{\mathrm{water}}^{(1/2)}) - 0.4 \tag{3}$$

in which Reynolds number for pipe flow for a Newtonian fluid is defined as

$$Re = \frac{\rho D_i v}{\mu} = \frac{4\rho Q}{\pi \mu D_i}. \tag{4}$$

3.2. Heat transfer coefficients of test fluids in fluted tube-in-tube heat exchanger

Percent heat transfer reduction of the drag reducing surfactant solution is calculated as

$$\%\mathrm{HTR} = \frac{Nu_{i,\mathrm{water}} - Nu_{i,\mathrm{surfactant}}}{Nu_{i,\mathrm{water}}} \times 100, \tag{5}$$

where

$$Nu_i \text{ (Nusselt number)} = \frac{h_i D_i}{k}, \tag{6}$$

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

To calculate heat transfer coefficients of test fluids inside the heat exchanger, the modified Wilson plot method was used in which suitable functions involving unknown "disposable" constants are selected to express the inside and outside heat transfer coefficients in terms of the relevant parameters. The constants are then determined by summing up the inside, wall and outside heat transfer resistances and "fitting" them to the total heat transfer resistance calculated from total heat flux. In our case, the modified Wilson plots were used differently for water and for drag reducing solutions.

Details of the procedures used for determining $h_{i,\mathrm{water}}$ and $h_{i,\mathrm{surfactant}}$ can be found on the website http://www.er6.eng.ohio-state.edu/~qiy/HT.

4. Results and discussion

4.1. Drag reduction tests

4.1.1. Water

Friction factor tests for water were first conducted as baseline experiments. For these tests, the test fluid's flow rates, temperatures and pressure drops over location #P2 to #P9 were measured. Fig. 3 shows the results of water friction factors at various temperatures and Reynolds numbers. All points lie close to the Von-Karman equation with the average deviation less than 5%. This demonstrates the reliability of the friction factor measurements. Tests for surfactant drag reducing solutions were conducted using the same procedure.

4.1.2. Ethoquad T13-50 (5 mM) with sodium salicylate (8.75 mM)

Fig. 4 presents the results of drag reduction tests with fresh cationic surfactant solution (Ethoquad T13-50 (5 mM) with 8.75 mM sodium salicylate counterion) for Reynolds numbers from 10,000 to 50,000 and temperatures from 45°C to 70°C. A maximum drag reduction of 70% was observed from 45°C to 65°C. This maximum drag reduction value for the fresh solution is lower than that of the same solution 18 days later (Fig. 7).

At the same Reynolds number, drag reduction of the fresh solution decreases with increasing temperature. When temperature reaches 70°C, drag reduction of Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution sharply decreases to about 10–20% (see Fig. 4). Therefore, 65°C can be called the upper temperature limit for drag reduction of fresh Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution. Drag reduction tests accompanying heat transfer experiments showed that the maximum drag reduction increased to about 80% at 50°C, 55°C and 60°C after 18 days with the solution exposed to mechanical shear for 48 h (Figs. 4 and 7) while the upper temperature limit decreased. Similar results were obtained after 35 days (with about 95 h pumping). The solution began to degrade after 45 days with about 120 h of circulation.

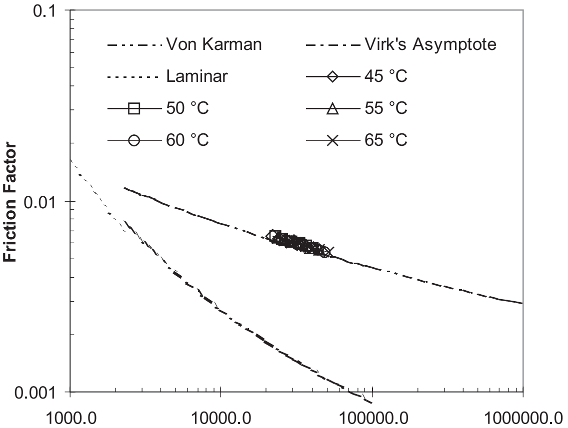


Fig. 3. Friction factor vs. Reynolds number data for water.

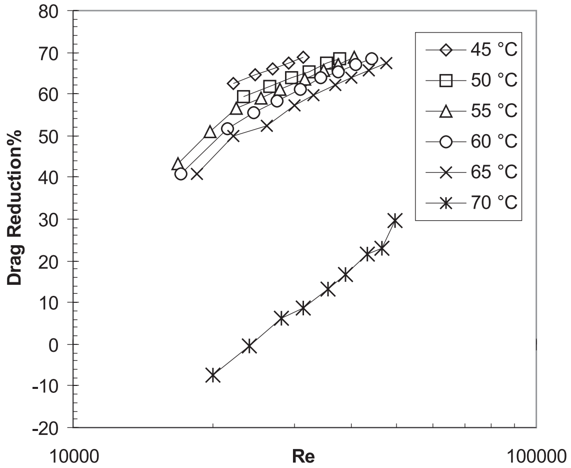


Fig. 4. Drag reduction of fresh Ethoquad T13-50/NaSal (5 mM/8.75 mM) vs. Reynolds number.

Fig. 4 also shows that drag reduction of the Ethoquad T13-50 solution increases with Reynolds number. This is not surprising because as shear increases, more and more rodlike micelles align to form super-ordered structures until the critical wall shear stress is reached. Because of the pressure drop limit of our experimental system, we did not reach the critical wall shear stress for degradation of this surfactant solution.

4.1.3. SPE98330 (1500 ppm) with 500 ppm Trilon A and 150 ppm formaldehyde

Drag reduction test results for the fresh zwitterionic/anionic surfactant solution SPE98330 (1500 ppm) are presented in Fig. 5(a). In the temperature range of 45–70°C, drag reduction as high as 80% was observed at high Reynolds numbers. Drag reduction results at 45°C and 50°C are somewhat lower than those for 55–70°C at low Reynolds number, but above 40,000 there is little difference between the low temperature and the high temperature results. While for the Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution, 65°C is the upper temperature limit for drag reduction, for the SPE98330 (1500 ppm) solution the upper temperature limit could not be determined because 70°C is the highest temperature we could reach in this equipment.

Both the fresh SPE98330 (1500 ppm) solution and Ethoquad T13-50 (5 mM) solution show increases in drag reduction with Reynolds number below their critical Reynolds numbers or critical wall shear stresses (not reached in these experiments with Ethoquad T13-50 or fresh SPE98330). Fig. 5(b) presents the drag reduction

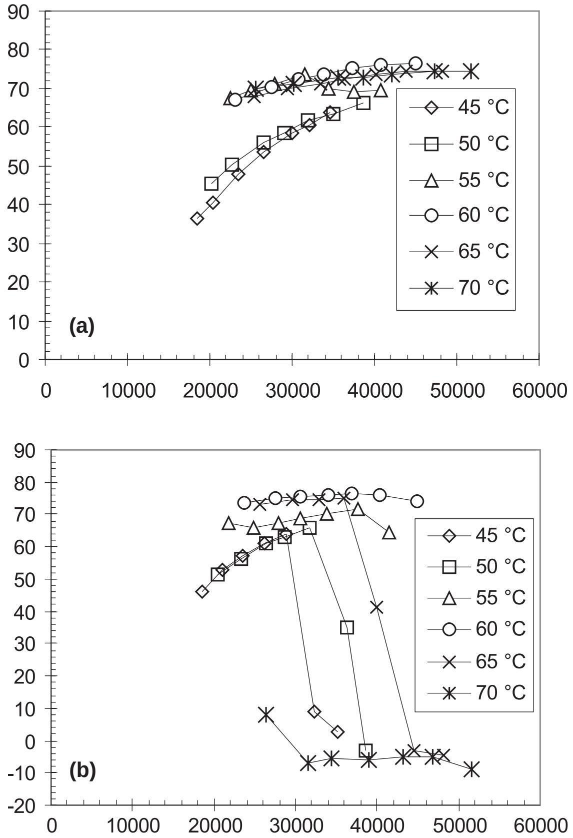


Fig. 5. (a) Drag reduction of fresh SPE98330 (1500 ppm) with Trilon A (500 ppm) and formaldehyde (150 ppm) vs. Reynolds number. (b) Drag reduction of SPE98330 (1500 ppm) with Trilon A (500 ppm) and formaldehyde (150 ppm) after 7 days (60 h of circulation) vs. Reynolds number.

test results for the SPE98330 solution after it experienced 60 h of mechanical shear over a seven day period. The solution lost its drag reduction capacity completely at 70°C. At lower temperatures at high Reynolds numbers, significant loss of drag reduction capacity was also observed except at 60°C. For this reason, the drag reduction ability of the solution was monitored during the heat transfer tests.

4.2. Heat transfer tests in fluted tube-in-tube heat exchanger

The fluted tube-in-tube heat exchanger was the cooling portion of the circulating system with test fluid flowing inside and cooling water outside. The energy balance with water flowing through both sides of this heat exchanger is ±5%. In order to compare the effectiveness of the fluted tube in enhancing the heat transfer ability of drag reducing fluids, heat transfer experiments with water as the test fluid were conducted first. Heat transfer reductions for surfactant solution were calculated from Eq. (5). To monitor the degradation of the surfactant solutions, drag reduction tests of the solutions between test locations #P2 and #P9 were checked for each run. The drag reduction test results (Figs. 7 and 10) will be presented together with the corresponding heat transfer results (Figs. 6 and 9).

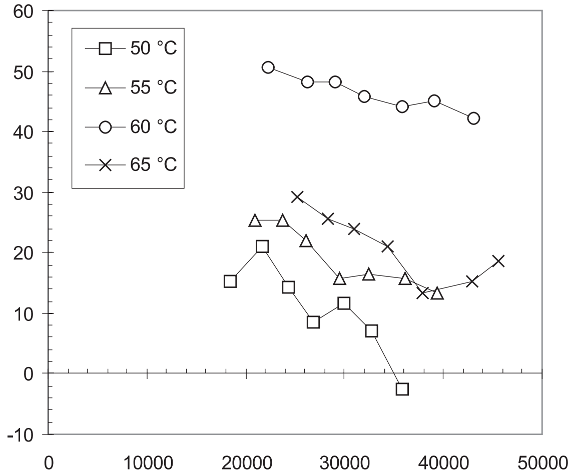


Fig. 6. Heat transfer reduction of Ethoquad T13-50/NaSal (5 mM/8.75 mM) in the fluted tube heat exchanger – 18 days after the solution was prepared.

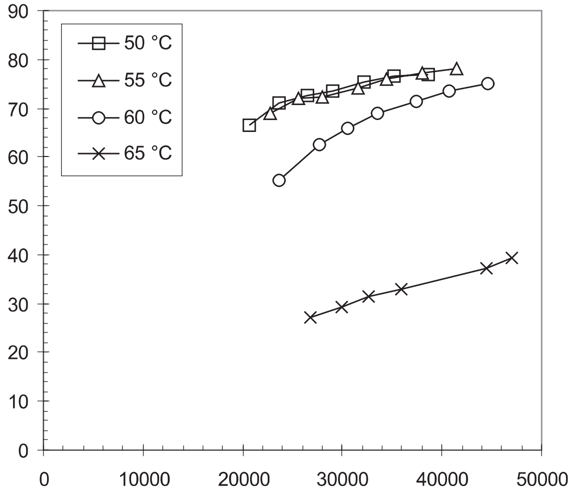


Fig. 7. Drag reduction results of Ethoquad T13-50/NaSal (5 mM/8.75 mM) during heat transfer tests – 18 days after the solution was prepared.

4.2.1. Ethoquad T13-50 (5 mM) with sodium salicylate (8.75 mM)

Heat transfer test results for the cationic surfactant solution Ethoquad T13-50/NaSal (5 mM/8.75 mM) in the fluted tube-in-tube heat exchanger at different inlet temperatures and Reynolds numbers are shown in Fig. 6. Results in Fig. 6 were obtained from experiments 18 days after the solution was prepared. Since the fluted tube-in-tube heat exchanger is a cooling portion of the system, the average temperature of test fluid inside the heat exchanger is 5°C lower than the listed inlet temperature. Fig. 7 presents the corresponding drag reduction test results before the solution entered the heat exchanger. They are similar to the fresh solution (Fig. 4) although the maximum drag reduction is a little larger and the upper temperature limit is lower.

The largest heat transfer reduction in Fig. 6 is about 50% for the fluted tube heat exchanger at low Reynolds number at an inlet temperature of 60°C even though the pressure drop of the solution in the fluted tube was close to that of water entering the fluted tube at 60°C as shown in Fig. 8. Repeated experiments with Ethoquad T13-50 solution confirmed that at this inlet temperature which is just below its upper temperature limit for drag reduction, heat transfer reduction ranged from 50% to 40% as Reynolds number increased. Less than 30% heat transfer reduction was found for Ethoquad T13-50 solution at inlet temperatures of 50–55°C, with the 50°C entering fluid showing only small heat transfer reductions. However, they both showed large pressure drops across the fluted tube. We would have expected the partially degraded solutions to show pressure drops across the fluted tube closer to those for water. We do not have an explanation for this anomalous behavior.

At the inlet temperature of 65°C, which is in the region of the upper temperature limit for drag reduction for the solution (Fig. 7), the heat transfer reduction is less than 30%. As mentioned earlier, for an inlet temperature of 65°C in a cooling heat exchanger, the average test fluid temperature is around 60°C inside the heat exchanger. Thus, the upper temperature limit for heat transfer reduction is around 60°C which is near the upper temperature limit for drag reduction for the Ethoquad T13-50 solution (see Fig. 7). Christenson and Zakin [8] noted that the upper critical temperature for loss of drag reduction for another cationic surfactant solution Kemamine Q-2983C/NaSal (2000 ppm/2000 ppm) was just a little lower than that for the loss of heat transfer reduction.

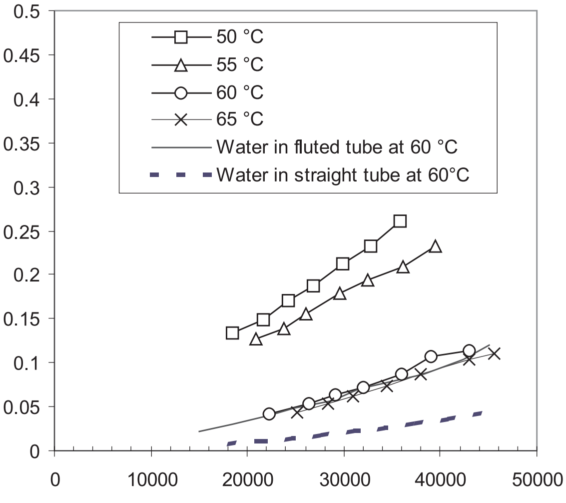


Fig. 8. Pressure drop of Ethoquad T13-50/NaSal (5 mM/8.75 mM) in the fluted tube heat exchanger – 18 days after the solution was prepared.

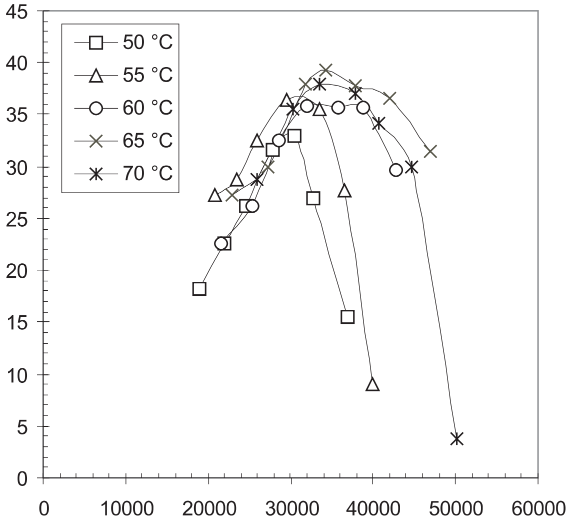


Fig. 9. Heat transfer reduction of SPE98330 (1500 ppm) with Trilon A (500 ppm) and formaldehyde (150 ppm) in the fluted tube heat exchanger – 2 days after the solution was prepared.

Fig. 6 shows that the heat transfer reduction diminishes as Reynolds number increases. It was pointed out by Sellin et al. [9] that the reduction in heat transfer ability of a drag reducing solution is mainly caused by thickening of the viscous boundary layer. The fluted tube adds swirls to the turbulent flow and periodic disruptions to the development of the viscous boundary layer near the tube surface with its changing surface geometry. These disturbances of the main flow and the viscous boundary layers in the fluted tubes enhance the heat transfer of surfactant solutions and the effect should be greater at higher flow rates. In addition, in some cases, the additional stresses in the swirling flow may break down the surfactant microstructure.

As noted above, the maximum heat transfer reduction in the fluted tube heat exchanger is 50% compared with that of water in the fluted tube (Fig. 6). By using Nusselt's equation for water in a smooth tube

$$Nu_{\text{water,smoothtube}} = 0.023Re^{0.8}Pr^{0.4} \tag{7}$$

and Christensen's equation for water in a fluted tube

$$Nu_{\text{water,flutedtube}} = 0.0236Re^{0.886}Pr^{0.4} \quad (8)$$

in the turbulent Reynolds numbers range of our experiments (10,000–50,000), the heat transfer enhancement of water inside a fluted tube compared with water in a straight tube of equivalent diameter is 2.4–2.6. Therefore, even with a maximum heat transfer reduction of 50%, the Nusselt number of Ethoquad T13-50/NaSal (5 mM/8.75 mM) surfactant solution in the fluted tube-in-tube heat exchanger is about 1.2 times that of water in a straight tube of equivalent diameter. This is a very encouraging result. However, we must also consider the pressure drop penalty paid for this enhancement.

Fig. 8 shows the measured pressure drop of Ethoquad T13-50/NaSal (5 mM/8.75 mM) in the fluted tube heat exchanger at different inlet temperatures and Reynolds numbers. The measured pressure drop of water in the fluted tube entering at 60°C and the calculated pressure drop for water at 60°C in a straight tube of equivalent diameter using the Von-Karman equation are also shown in Fig. 8. The pressure drop of the Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution across the fluted tube decreases with increasing temperature with pressure drops close to those of water at 60°C and 65°C. It is surprising that the pressure drop of the 60°C inlet temperature solution, which was apparently undegraded giving heat transfer reduction of 40–50% (Fig. 6), is almost the same as that of 60°C water in the fluted tube (Fig. 8). The pressure drop of the Ethoquad T13-50/NaSal solution at 60°C in the fluted tube is 2.6–3.5 times that of water in a straight tube at 60°C with the same equivalent diameter. However, as can be seen from Fig. 8, the pressure drops of Ethoquad T13-50/NaSal solution at 50°C and 55°C are much larger . Whether this penalty is acceptable or not depends on the size scale of the system. For example, for the Ethoquad T13-50 solution, a maximum pressure drop of 0.26 atm across the 0.91 m long fluted tube heat exchanger was observed at 50°C at the maximum Reynolds number of 36,000. This pressure drop of 0.26 atm is equivalent to the friction loss of energy in 620 diameters for water at 50°C. If the system pipe length is many times longer than 620 diameters, this pressure drop penalty may be relatively small compared with total losses in the system.

While the above results are from one set of experiments, repeat experiments conducted in the same Reynolds number and temperature ranges gave similar results.

Therefore, it can be concluded that the fluted tube significantly enhances the heat transfer ability of the Ethoquad T13-50 surfactant solution tested. There is a penalty paid for this enhancement, however, so that the advantage of using a fluted tube exchanger depends on the details of the circulation system.

4.2.2. SPE98330 (1500 ppm) with Trilon A (500 ppm) and formaldehyde (150 ppm)

Fig. 9 shows the heat transfer reduction of SPE98330 (1500 ppm) in the fluted tube heat exchanger in the experimental inlet temperature range of 50–70°C and Reynolds numbers from 10,000 to 50,000 2 days after the solution was prepared. In this experimental range, the maximum heat transfer reduction reaches a peak of 40%. Fig. 10 gives the corresponding drag reduction test results for the solution which shows that the SPE98330 (1500 ppm) surfactant solution was not degraded at the time of these heat transfer tests.

The data in Fig. 9 suggest that the SPE98330 (1500 ppm) surfactant solution experienced breakdowns in structure at high Reynolds number at all inlet temperatures causing the steep decreases in heat transfer reduction. Below the critical Reynolds numbers for break down of the microstructure, heat transfer reduction increased with Reynolds number for all inlet temperatures with little difference between the heat transfer reductions at the different entering temperatures. However, after the Reynolds number exceeded some critical value, heat transfer reduction decreased rapidly. The drops in heat transfer reduction occur at lower Reynolds number for lower inlet temperatures. At inlet temperatures of 50°C and 55°C, the critical Reynolds number for heat transfer reduction in the fluted tube-in-tube heat exchanger is about 30,000.

The behavior of the SPE98330 (1500 ppm) solution flowing through the fluted tube heat exchanger is quite different from that of the Ethoquad T13-50 solution. The aggregated rod-like super-ordered micelle structure

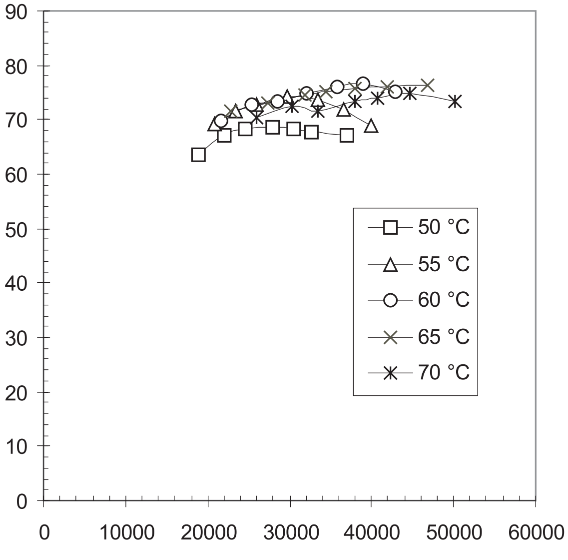


Fig. 10. Drag reduction results of SPE98330 (1500 ppm) with Trilon A (500 ppm) and formaldehyde (150 ppm) – 2 days after the solution was prepared.

in the Ethoquad T13-50 solution is too strong to be broken up by the shear stress in the flow field in the fluted tube at the Reynolds numbers in these experiments. Gasljevic and Matthys [14] reported that a pressure drop of more than 1 bar was needed to break down the microstructure of Ethoquad T13-50/NaSal (5 mM/12.5 mM) solution. The spiral fluted tube adds swirls to the main flow and periodic disturbances to the viscous boundary layer of any fluid flowing through it and thus increases the heat transfer ability of the solution. For the SPE98330 solution, the aggregated rod-like micelle super-ordered structure is not as strong as that of the Ethoquad T13-50 surfactant solution and it is at least partly broken up in the fluted tube. In another set of experiments with destructive devices installed at the inlet to the tube-in-tube heat exchanger, break down of the SPE98330 solution microstructure was also observed. Thus, the spirally fluted tube not only adds swirls to the main flow and disturbances to the viscous boundary layer of the SPE98330 surfactant solution but also causes at least partial break down of the super-ordered microstructure of the surfactant solution when stresses at which the critical wall shear stress for breakdown are exceeded.

As noted above, the maximum heat transfer reduction of the SPE98330 solution passing through the fluted tube is only about 40%. With the same calculation as for the Ethoquad T13-50 solution, the heat transfer ability of the SPE98330 solution in the fluted tube-in-tube heat exchanger is about 1.4 times that of water in a straight tube-in-tube heat exchanger at the maximum heat transfer reduction of 40%.

Fig. 11 presents pressure drop data for the SPE98330 solution flowing through the fluted tube at different inlet temperatures and Reynolds numbers together with pressure drops for water in the fluted tube and in a straight tube at 60°C. The pressure drop of the SPE98330 solution at 50°C, 55°C, 60°C and 65°C ranges from 7 times that of water at 60°C in a straight tube of equivalent diameter at low Reynolds number to as little as 2.5 times that of water in the straight tube at high Reynolds number. The pressure drop of the SPE98330 solution in the fluted tube is about two times that of water in the fluted tube at low Reynolds number. At high Reynolds number, it is near or even lower than that of water in the fluted tube. This surprising result was confirmed by repeating the experiment several times.

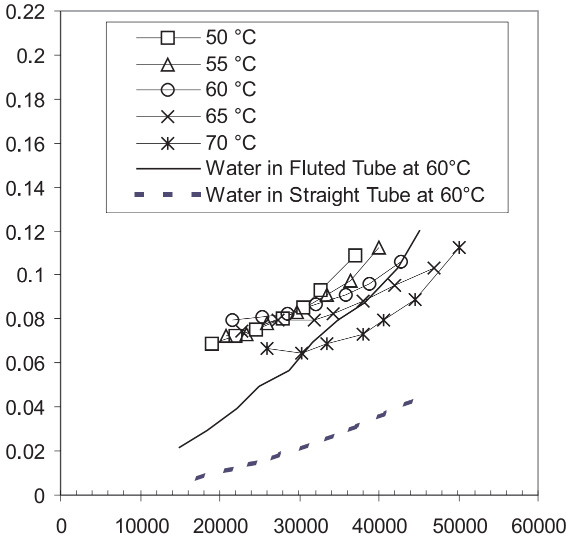


Fig. 11. Pressure drop of SPE98330 (1500 ppm) with Trilon A (500 ppm) and formaldehyde (150 ppm) in the fluted tube heat exchanger – 2 days after the solution was prepared.

The fluted tube effectively enhances the heat transfer of the SPE98330 solution with a relatively modest pressure drop penalty. However, as shown in Fig. 5(b), we did encounter a serious degradation problem with SPE98330 after seven days including 60 h circulation.

5. Summary

Drag reduction tests and heat transfer reduction and enhancement tests in a fluted tube-in-tube heat exchanger were conducted for cationic surfactant solution Ethoquad T13-50/NaSal (5 mM/8.75 mM) and zwitterionic/anionic surfactant solution SPE98330 (1500 ppm).

(1) For the fresh Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution at Reynolds numbers from 10,000 to 50,000 and temperatures ranging from 45°C to 70°C, maximum drag reduction of 70% was observed which increased to 80% after 18 days (48 h circulation). The upper temperature limit for drag reduction was 65°C. (Fig. 4). The upper temperature limit for drag reduction decreases if the solution is continually exposed to mechanical shear (Figs. 4 and 7). The drag reduction ability of the solution increases with Reynolds number and decreases with increasing temperature. The solution was partly degraded in 45 days including 120 h of circulation.

(2) Drag reduction tests on the fresh SPE98330 solution show maximum drag reduction of 80% in the temperature range of 55–70°C and Reynolds numbers from 10,000 to 50,000 (Fig. 5(a)). The upper temperature limit for drag reduction for the solution could not be obtained because of the upper temperature limit of our equipment. The drag reduction ability of this solution was also found to increase with Reynolds number in the range tested. The effect of temperature on the drag reduction ability of the solution is small at temperatures above 55°C. This solution was partly degraded in seven days which includes 60 h of circulation (mechanical shear) (Fig. 5(b)).

(3) Heat transfer tests for cationic surfactant solution Ethoquad T13-50/NaSal (5 mM/8.75 mM) in the fluted tube-in-tube heat exchanger show that the Nusselt

number of the Ethoquad T13-50 solution is more than 1.2 times that of water in a straight tube (Fig. 6). At 60°C, the ratio of pressure drop for Ethoquad T13-50/NaSal solution in the fluted tube to that of water in a smooth tube of equivalent diameter varies from 2.6 to 3.5. At 50°C and 55°C , this ratio is much larger (Fig. 8). Therefore, the practical use of fluted tubes to enhance the heat transfer ability of Ethoquad T13-50 solution depends on the details of the circulation system. It was also found that heat transfer reduction of the solution decreases slowly with Reynolds numbers. There is a surprising increase of heat transfer reduction at an inlet temperature of 60°C which approaches the upper temperature limit for drag reduction even though the pressure drop of the solution across the fluted tube heat exchanger at this temperature is close to that of water in the fluted tube.

(4) Heat transfer enhancement at least 1.4 times of water in straight tubes was observed in the heat transfer tests of SPE98330 (1500 ppm) solution in the fluted tube-in-tube heat exchanger with only modest pressure drop penalties (Figs. 9 and 11). These are very encouraging results. The super-ordered micelle structure of this solution may experience a breakdown by the shear stress induced by the spirally fluted tube. This was not found in the experiments for Ethoquad T13-50/NaSal solution in the same tube and indicates that the Ethoquad T13-50/NaSal (5 mM/8.75 mM) solution has a stronger microstructure than the SPE98330 (1500 ppm) solution, which also degraded significantly with continuous circulation.

Acknowledgements

This 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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