EFFECT OF SALT ADDITION ON THE DRAG REDUCTION BY CATIONIC SURFACTANT

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Abstract :-

In the present paper, an experimental study has been carried out to study the drag reduction in turbulent flow inside a tube by using surfactant with salt additives, where this phenomena used in many industry applications. Therefore, the flow inside a pipe with high volumetric flow rate requires high power to transport it, so this needs large number of pumps to push it for remote distances and this pumps require great amount of fuels and cyclic maintenance ,so the additives reduce the number of pumps that is required to pump the liquids and so this decrease the cost of pumps, the fuel and maintenance or increases the volumetric flow rate at constant pressure drop. The CTAB surfactant has added with concentrations of 1000,1500 and 2000 ppm, and the salt that is NASAl has added for water at 2000 ppm CTAB concentration with 200 and 400 ppm concentration. The study has excuted with different values of Reynolds number that are 33418,44557,55697, 66836, 77976 and 89115,.Different angles of pipe inclinations has used through the work which are 0˚,3˚and 6˚. The experimental results has correlated by using SPSS program, and solved by multiple nonlinear regression analysis. The power law has found to be the optimum relation that may fits with the data that has obtained from the experimental work .

key-Word :- Drag Reduction; Friction Factor; Pressure Gradient; Shear Stress; Reynolds Number; Concentration; Maximum Drag Reduction; Surfactants.

تأثير اضافة الملح على تقليل الاعاقة بالمادة الفعالة سطحيا ذات الشحنة الموجبة

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الخلاصة :-

تم في الرسالة الحالية اجراء دراسة عملية لتقليل الاعاقة في الجريان الاضطرابي داخل انبوب باستعمال بعض المضافات ، تستعمل هذه الظاهرة في كثير من التطبيقات الصناعية. لذلك فان الجريان داخل الانابيب بمعدل تدفق حجمي عالي يحتاج قدرة عالية لنقله ، كما يحتاج عدد كبير من المضخات لكي تضخه لمسافات بعيدة ، وهذه المضخات تحتاج كمية كبيرة من الوقود والصيانة الدورية ، لذلك فان الاضافات تقلل عدد المضخات المطلوبة لضخ السوائل وهذا يقلل كلفة المضخات والوقود والصيانة او زيادة معدل التدفق الحجمي لهبوط ضغط ثابت . المادة الصابونية التي اضيفت هي CTAB بتراكيز1000،1500و 2000جزء بالمليون ، بينما الملح والذي هو NASAl فقد اضيف الى الماء بوجود CTAB بتركيز 2000 جزء بالمليون بتراكيز200 و 400 جزء بالمليون . الدراسة نفذت عند قيم مختلفة لرقم رينولدز وهي33418، 44557،55697، 66836،77976,89115. عدة قيم لزاوية ميلان الانبوب اخذت بنظر الاعتبار خلال الدراسة وهي 0°،3° و6°. النتائج العملية قد صححت باستخدام برنامج SPSS وقد اجريت باستخدام تحليل الانحدار اللا خطي ذو المتغيرات المتعددة .ووجد بان العلاقة الاسية هي افضل علاقة تتلائم مع النتائج المستحصلة من العمل التجريبي .

الكلمات الدلالية :- تقليل الاعاقة؛ معامل الاحتكاك؛ رقم رينولدز؛ التركيز؛ اقصى تقليل اعاقة؛ المادة الفعالة سطحيا .

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Nomenclature

	Meaning	*Units*
Δp	Pressure Drop For Water With Additives	N/m^2
Δp_0	Pressure Drop For Pure Water	N/m^2
∇p	Pressure gradient	N/m3
A	Pipe Cross-Sectional Area	m^2
C_F	Friction Factor	---
CTAB	Cetyltrimethyl Ammonium Bromide	
D	Diameter of pipe	m
DR%	Drag Reduction Percentage	---
NASAL	Sodium Salicylate	
Q	Volumetric Flow Rate	m^3/s
Re	Reynolds Number	----
U	Mean Water Velocity	m/s

Greek Letters

δ	Angle of Pipe Inclination	*Deg.*
ρ	Density of Water	kg/m^3
μ	Water Dynamic Viscosity	*kg/m.s*
τ	Shear Stress	N/m^2

1.INTRODUCTION :-

Since Toms observed the drag reduction phenomenon for the first time in 1948 ,the possibility of obtaining large reductions in friction in turbulent pipe flows by the use of polymer and surfactant solutions have caught the attention of many researchers. However, despite five decades of research, a full understanding of the fundamentals of this phenomenon is still far from complete(G.Aguilar and K. Gasljevic 2006)

The drag reducers has been used in a wide range of applications in a several fields such as oil transportation, in transportation of solids in water, in fire fighting applications, treatment of wastewater and heating and cooling loops. The use of drag reduction to increase flow in petroleum pipelines has received great attention due to its large commercial success in reducing cost and energy consumption.

Mysels (1949) was the first one that studied the drag reduction by surfactant solution. However, the field of surfactant drag reduction did not receive great attention until it was studied by Dodge and Metzner (1959). Surfactants can be classified into four types: cationic, anionic, zwitterionic, and non-ionic. Recently biodegradable surfactants had received sparticular attention as a drag reduction agents. Surfactants appear lower mechanical degradation and most of them are safe chemicals for environment (Harwigsson and Hellsten 1996). It is believed that threadlike or wormlike micelles of are necessary for surfactant solution to perform as a drag reducer. The shape of micelles changes from spherical to rodlike by adding some additives such as a surfactant with opposite charge, organic counterions, or non-charged small compounds like alcohols to the solution of cationic surfactants.

The micelle shape is dependent on system conditions, where it can be globular or spherical , cylindrical or rod / worm /thread-like, disk-like, bilayer spherical (vesicle), cubic crystal , lamellar and hexagonal which can transform from one shape to another when the solution conditions change (Zhang et al. 2009). The shape and the size of the aggregate can be determined by using the surfactant packing parameter which is the ratio of the hydrophobic group area to the hydrophilic head area ($p= v/a_0 l_c$). The ν and l_c are the volume and length of the hydrophobic tail in the surfactant aggregate, while a_0 is the head group cross-section area. Figure (1) shows the surfactant aggregate.

Surfactants are powerful drag reducers in turbulent flow in pipes and can hence contribute to significant energy savings. Their drag reduction ability at concentrations as low as a few millimolar is ascribed to the rod-like micelles present in the solution. These micelles play a dominant role in the mechanism of turbulence suppression and in the significant friction decrease which can be even higher than in some high polymer solutions. A comprehensive review of properties and abilities of these surfactants was provided by Zakin et al. (1998).

Surfactant solutions with rodlike or threadlike micelles usually act as Newtonian fluids at low shear rates because the micelles rotate freely in the solution .While for higher shear rates, micelles start to align in the shearing direction causing shear thinning (Hartmann and R. Cressely 1997). A particular phenomenon may occur for some solutions at a critical shear rate the shear viscosity and elasticity have a sudden increase. This phenomenon is called shear-induced structure (SIS) . The SIS structure is orders of magnitude larger than the individual rodlike micelles (S. Koch 1996) and the solution is like a viscoelastic gel (Wunderlich, Hoffmann 1987) . **Fischer** (2000) observed oscillations in the first normal stress difference and shear stress indicating that elastic structures were formed and destroyed with SIS and the induced new phase was more elastic than the initial one . The shear stress becomes independent of shear rate while a second phase appears . As shear rate further increases, shear thinning occurs (Rehage and H. Hoffmann 1988). However, as shear rate increases, the SIS is no longer stable and viscosity begins to decrease with shear rate. At the viscosity peak, it is believed that micelles are fully aligned in the flow direction **. Many** variables have been considered during studying the field of drag reduction: the type of drag reducing additive, additive concentration, mean velocity and angle of inclination of pipe .

The objective of the present research is to obtain the parameters of drag reduction by CTAB surfactant with and without NASAL salt addition. For different concentrations of surfactant and salt and different mean velocities and angles of inclination of pipe.

2.EXPERIMENTAL WORK :-

The experimental rig is described in figure (2), and the schematic diagram is presented in figure (3) while the description of its components is shown in table (1).

2.1.Experimental Procedure :

Firstly we must calculate the amount of mother solution required for each concentration according to the equation:

Quantity added of mother

$$\text{Solution} = \frac{fluid\ mass\ in\ the\ tank * desired\ concentration}{concentration\ of\ mother\ solution} \qquad (1)$$

After that it will be mixed with the water in the major tank. In order to obtain flow data against which the various predictive methods could be tested ,experiments were carried out in pipe whose nominal diameter 38.1 mm with three angles of inclination which are(0 , 3 and6 degrees) and with eight values for flow rates which are(60 , 80 , 100 and 120 , 140 , 160 , 180 and 200 L/min).The additive solution concentration tested where (1000,1500 and 2000 ppm) for CTAB surfactant and (200 and 400 ppm) for NASAL salt at 2000 ppm CTAB concentration. The tank will be filled with enough quantity of water and operating the pump ,the valve is opened to the required flow rate. The fluid is allowed to flow through the pipe and wait for 5 minute until steady state will be attend. Then connect the four pressure taps with sensors and with the interface and personal computer to recording the pressure of the four points. The same procedure is repeated in order to obtain more data at various flow rates ,angles of inclination and various concentrations of additives.

2.2. Determination of Flow Parameters :

Reynolds number for turbulent flow is given by :

$$Re = \frac{\rho U D}{\mu} \qquad (2)$$

Where:

ρ:water density(kg/m^3).

U:mean velocity of water inside the pipe(m/s).

D:pipe diameter(m).

μ:water dynamic viscosity (Pa.s).

The mean velocity can be calculated from the flow rate from the equation:

$$U=\frac{Q}{A} \tag{3}$$

Where $A=\frac{\pi}{4}\times D^2$ (4)

Where:

A: cross-sectional area of pipe(m^2)

Pressure gradient has been found from the equation:

$$\nabla p=\frac{\Delta p}{L} \tag{5}$$

Friction factor can be found from the equation:

$$C_F=\frac{\tau}{\frac{1}{2}\rho D^2} \tag{6}$$

Where :

$$\tau=\frac{D}{4}\times\frac{\Delta P}{L} \tag{7}$$

Where:

C_F: friction factor

τ : shear stress (N/m^2)

ΔP: pressure drop (Pa)

L:length between pressure taps (m)

Drag reduction percent can be found for the equation:

$$DR\%=\frac{C_{F0}-C_F}{C_{F0}} \tag{8}$$

or

$$DR\%=\frac{\Delta po-\Delta p}{\Delta po} \tag{9}$$

Where:

DR%:Drag reduction percentage.

C_{F0}:friction factor for pure water .

C_F: friction factor at any additive concentration

Δp_0: Pressure drop for pure water (Pa).

Δp: Pressure drop for water with additive(Pa).

The range of variables in the present study and the several drag reducing polymers that have been reported in literature are maintained in table 2.

3. RESULTS AND DISCUSSION :-

The surfactant is cetyltrimethyl ammonium bromide (CTAB) which is cationic surfactant that has a molecular weight of 364 g/mol, while the counter ion salt which used is sodium salicylate (NASAL).

Figure (4) explains the effect of Reynolds number on the pressure gradient for various concentrations of additives for pipe of 4m length. It is observed from figure (4) that the pressure gradient increases with increasing Reynolds number until reach a maximum increase at Re= 66836, After this critical value drag reduction falls off due to the increase in turbulence which causes degradation in the micelles, because the SIS is no longer stable and viscosity begins to decrease with shear rate. Increase of additives concentration lead to a decrease in pressure gradient due to damping of near wall vortices and sustain turbulence by imparting energy into the stream wise velocity component in the very near wall region.

It is noticed from figure (4-a) that the difference in pressure gradient for the four CTAB concentrations starts from 5.3 Pa/m at Re= 33418, then increases gradually until reaches the value 15.87 Pa/m at Re= 89115. It can be seen that the slope of curves is approximately parallel.

It is noticed from the figure (4-b) that pressure gradient decrease with increase in salt concentration because the salt is counter ion to cationic surfactants. Where high salt concentrations.

Figure (5) shows the effect of additive concentration on pressure gradient for different angles of inclination .It can be observed from figure (5) that increasing the concentration leads to decrease in pressure gradient as discussed in figures (4),while increasing angle of inclination of pipe increases the pressure drop due to the additional force from tangential component of solution weight.

It is observed from figure (5-a) that the difference in pressure gradient between the 0˚ and 6˚ angles is 134.92 and 140.21 Pa/m for the 1000 and 2000 ppm concentration respectively. While the pressure gradient for figure (5-b) decreases from 44.97 to 33.07 Pa/m and from 185.185 to 166,667 when concentrations increases from 1000 to 2000 ppm for the 0˚ and 6˚ angles respectively.

Figure (6) presents the effect of mean velocity on wall shear stress for different additive concentrations . It is observed from the figure that the wall shear stress increases with increase in velocity for Newtonian and non-Newtonian flow due to suppression of more eddies which make great contact of water particles with each others that leads to high shear stress.

It can be noted from figure (6-a) that the difference in shear stress for pure water and water with the two concentrations of CTAB begins from minimum value at the start then increases until reaches maximum increase in the velocity 2.047 m/s where has a value 0.2014 Pa then decreases after that.

From figure (6-b) we can see that the difference in shear stress for CTAB solution without and with NASAL salt addition begins from the minimum value which is 0.088 Pa then decreases in a fluctuated behavior to the minimum value 0.088 Pa at the velocity 2.047 m/s then increases to maximum value after that. From figures (6-a) and (6-b) it can be noticed that the slope of curves starts from small value then increases sharply after the velocity 1.17 m/s ,then decreases to smaller value after that.

Figure (7) presents the effect of additive concentration on the drag reduction at different solution velocities. It is observed from the figure that drag reduction increases as additive concentration increases. This increase is probably due to increasing the number of additive molecules which cause the damping of more turbulent eddies. The increase in velocity causes increase in drag reduction until reaches the velocity 1.754 m/s that called critical velocity, then decreases after that.

It is observed from figure (7-a) that drag reduction at the velocity 1.754 m/s increases from 8.33% to 29.17% when CTAB concentration increases from 1000 to 2000 ppm.While from figure (7-b) we see that the drag reduction at 400 ppm NASAL concentration increases from 43.75% to 47.91% when velocity increases from 1.17 to1.754 m/s.

Figure (8) explains the effect of Reynolds number on drag reduction for different additive concentrations .Its noted that drag reduction increases with increase in Reynolds number until reaches a critical Reynolds number which is about 55000-66000. After this critical value drag reduction falls off as discussed in figure (4).

From figure (8-a) we can see that minimum difference in drag reduction for the three concentrations occurs at the start which have a value 7.14% ,while maximum difference that have a value 23.1% occurs at the Reynolds number 55697.

Also we can see from the figure (8-a) that the difference in drag reduction between 1000 ppm and 1500 ppm is larger than the difference between 1500 ppm and 2000 ppm. While from the figure (8-b) that the difference in drag reduction between the three salt concentrations starts from the value 25% at the start , then decreases until reaches minimum value which has a value of 13.43% at Reynolds number 55697,then increases after that.

Figures (9) shows the effect of additive concentration on the drag reduction at different angles of inclination. It is noticed from the figure that increasing angle leads to decrease in drag reduction due to high increase in pressure drop in the direction of flow as discussed in figure (4)

It can be observed from the figure (9-a) that the drag reduction increases from 8.33% to 29.17% and from 3.85% to 10.26% when CTAB concentration increases from 1000 to 2000 ppm at the 0° and 6°angles respectively. Also it can be seen that the difference between drag reduction for the 0° and 6°angles at 2000 ppm CTAB concentration is 18.91%.

It can be noticed from figure (9-b) that the slope of drag reduction with salt concentration is approximately constant for the 0° and 3° angles. Also it is noted that the difference in drag reduction starts at the value 18.91%,then increases to 28.68% at the concentration 400 ppm.

Figures (10) shows the effect of Reynolds number on friction factor for Newtonian and non-Newtonian flow for different additives concentrations. It can be seen that friction factor decreases with increase in Reynolds number for Newtonian and non-Newtonian flow and decrease with increase in concentration.

From figure (10-a) we can observe that the difference in friction factor for the pure water and the three concentrations of CTAB solution in water begins from the value 0.131×10^{-3} ,then decreases until reaches minimum value at Re=89115 that has a value of 0.055×10^{-3}.

It can be observed from figure (10-b) that the difference in friction factor for CTAB solution in water without and with salt addition for the two concentrations starts from the value 0.229×10^{-3}, then decreases until reaches maximum decrease at Re=77976,then increases after that.

4. DRAG REDUCTION AND FRICTION FACTOR MATHEMATICAL ORRELATION:

The obtained data of experimental work for all parameters that have been concluded in our study are used for developing an empirical correlation for drag reduction percentage and friction factor. The SPSS program has been used for correlate the data that have been obtained. The drag reduction percentage and friction factor are correlated in terms of Reynolds number Re, additive concentration C (ppm) and angle of inclination of pipe δ (˚).The power low that is Dr% and $C_F = C_1 \times (Re - C_2)^{n1} \times (C - C_3)^{n2} \times (\delta + C_4)^{n3}$ was used to correlate the experimental results because it is the only relation that gave the higher maximum correlation coefficient for all additives. The values of C_2,C_3 and C_4 were evaluated by try and error until the optimum maximum correlation coefficient is obtained, While the constants C_1, n_1,n_2 and n_3 were found by the program according to the input data for each type of polymer. The obtained empirical relations can be expressed as follows:

1- CTAB Surfactant:

$$DR\%=0.07(Re-33000)^{-0.429}(C-700)^{-0.901}(\delta+0.5)^{-0.003} \quad (10)$$

With maximum correlation coefficient 0.936.

$$C_F=72364.608Re^{-1.844}C^{-0.088}(\delta+3)^{1.469}. \quad (11)$$

With maximum correlation coefficient 0.997.
Where $33418 < Re < 89115$, $1000 < C < 2000$ and $0^\circ < \delta < 6^\circ$.

2- CTAB-NASAL:

$$DR\%=0.067Re^{0.171}(C+350)^{0.889}(\delta+4)^{-0.927} \quad (12)$$

With maximum correlation coefficient 0.965 .

$$C_F=59281.336Re^{-1.869}(C+150)^{-0.086}(\delta+3)^{0.212}. \quad (13)$$

With maximum correlation coefficient 0.997 .

Where $33418 < Re < 89115$, $0 < C < 400$ and $0^\circ < \delta < 6^\circ$.

5. CONCLUSIONS:-

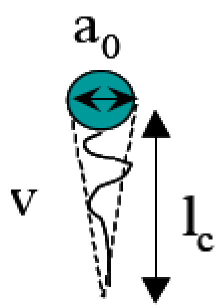
From the research above we can conclude that:
1-Addition of salt increases drag reduction significantly due to forming rodlike micelles that increases the viscosity of solution considerably.
2- Drag reduction decreases as angle of inclination of pipe increases. Where the angle influence on drag reduction considerably.
3-Drag reduction increases with increase in Reynolds number until reaches a critical value of Reynolds number over which the drag reduction decreases.

Table (1): The rig components and its description

No	Components	Description
1	Major fluid tank	A liquid tank of 300L capacity, with length of 1m ,width of 0.5m and height of 0.6m is used to store the water for recirculation flow in the pipe.
2	Gear pump	The pump used is Hitachi Ltd type with power of 3.7KW ,voltage of 380V, head of 20m and with maximum flow rate of 0.4m^3/min.
3	Flow meter	rotameter F.M.91426 type used for water flow rate measuring at 20 C° with range of (20-200 L/min).
4	Minor fluid tank	provide uniform stream flow for water and get ride off the pulse created by the pump which will affect the measurement taken because of non uniformity.
5	Test pipe	The test pipe is made of glass with 4m long ,38.1mm internal diameter
6	Sensors	The pressure range of such sensors from (0-1) bar
7	Interface	Its function is receiving signals from pressure sensors as a voltage then converting it to data on the personal computer.
8	Personal computer	Is used to read the data from the interface
9	Electric crane	The electric crane is used to change the angle of inclination of test pipe.

Table(2): Range of variables.

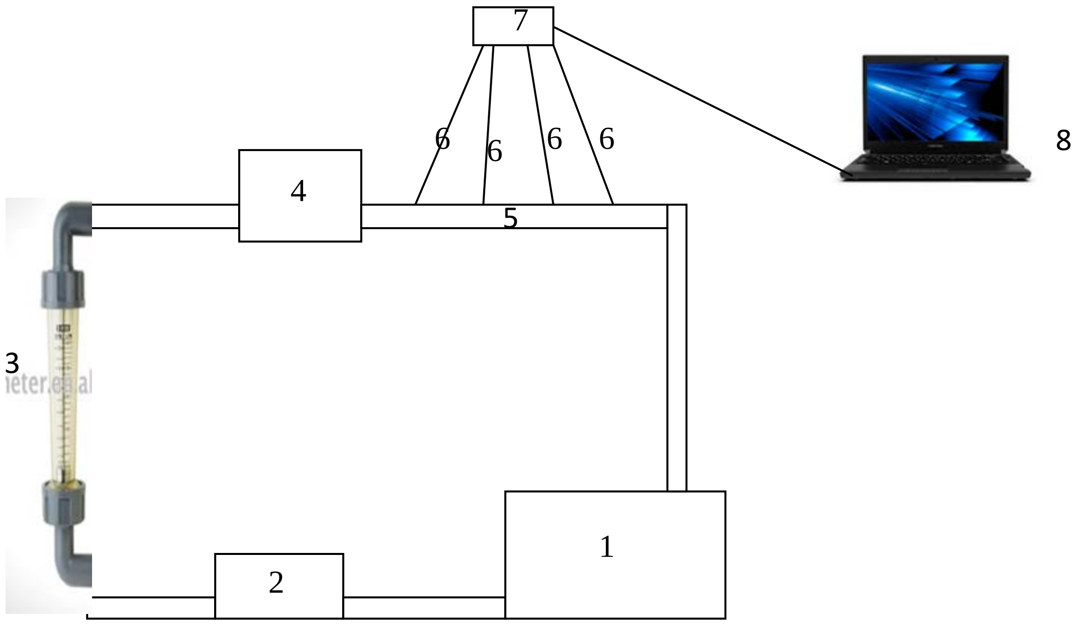
S. No	Variable	Minimum	Maximum
1	Mean velocity(m/s)	0.877	2.924
2	Reynolds number	33418	111394
3	CTAB concentration (ppm)	1000	2000
4	NASAL concentration (ppm)	200	400
5	Angle of inclination of pipe (º)	0	6



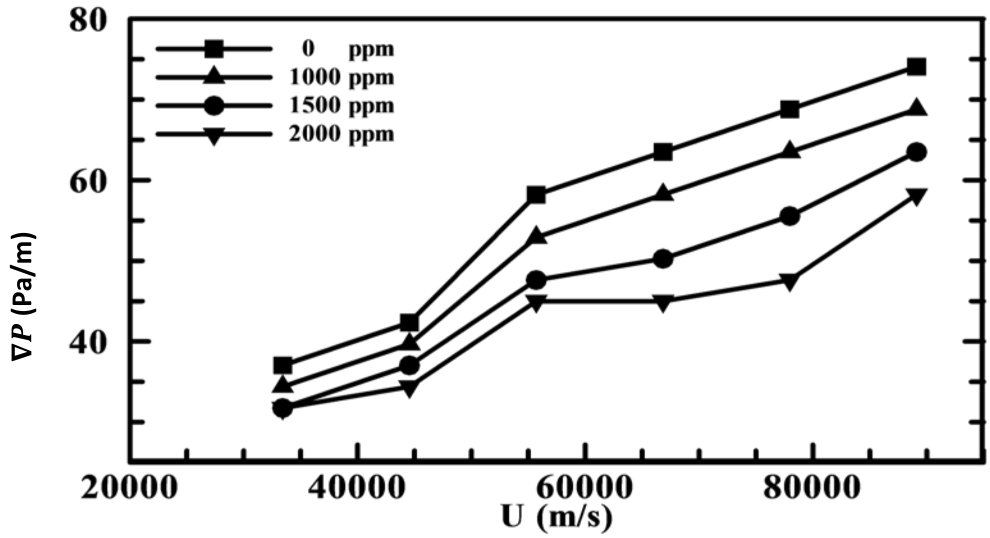
$$p = \frac{v}{a_0 l_c}$$

Figure(1): Surfactant Aggregate.

Fig.(2) The Test Rig



Figure(3) Schematic diagram for the test rig



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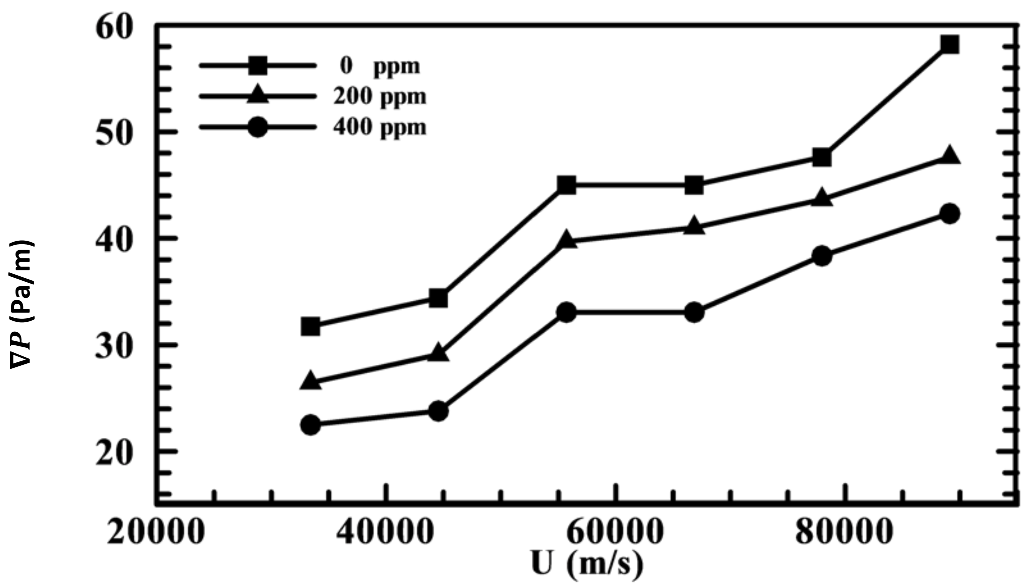
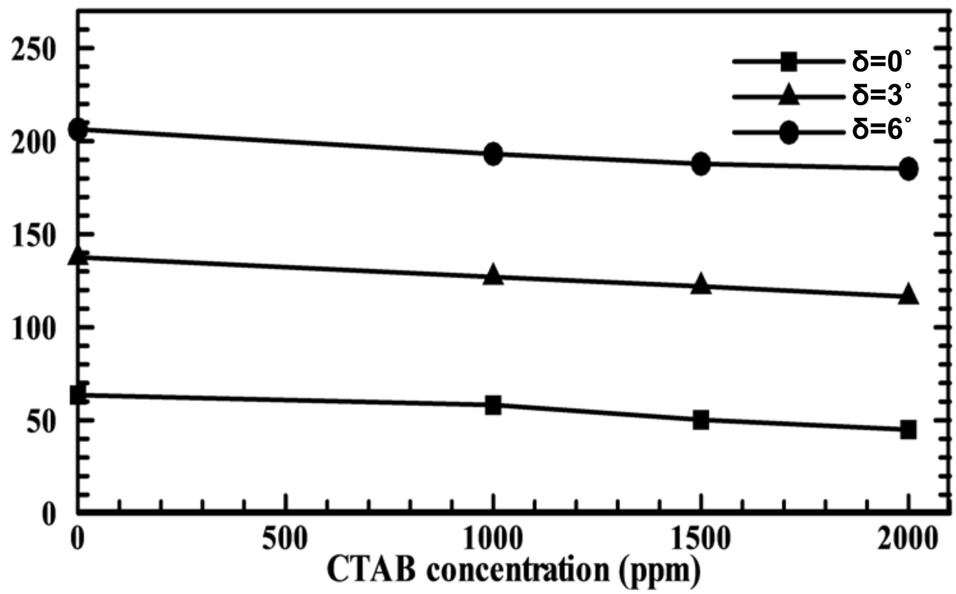


(b)

Fig.(4) Variation of Pressure gradient with Reynolds number at δ=0° for different concentrations of (a) CTAB, (b) NASAL at 2000 ppm CTAB concentration for different at δ=0°.



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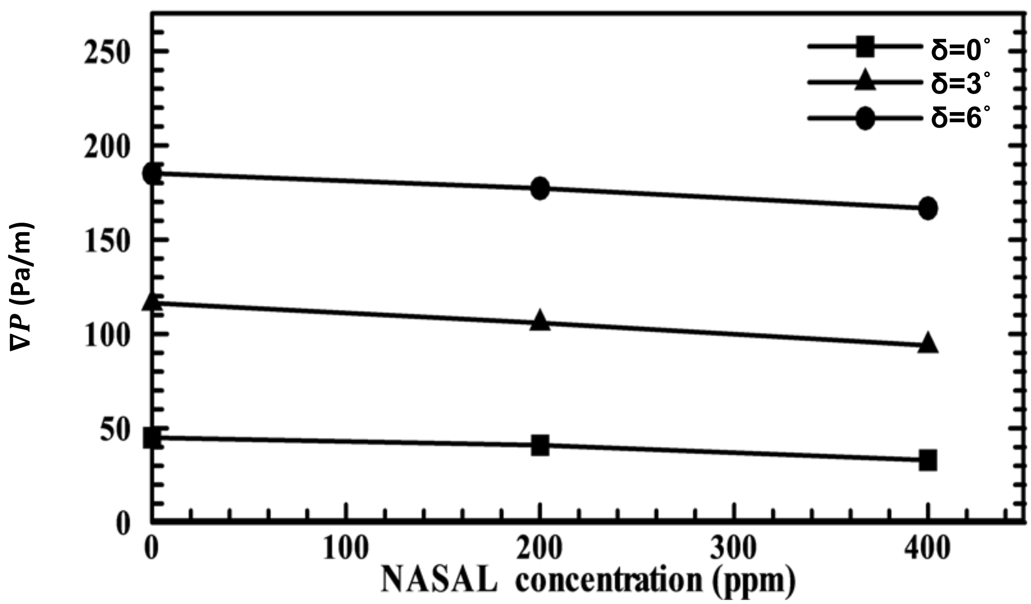

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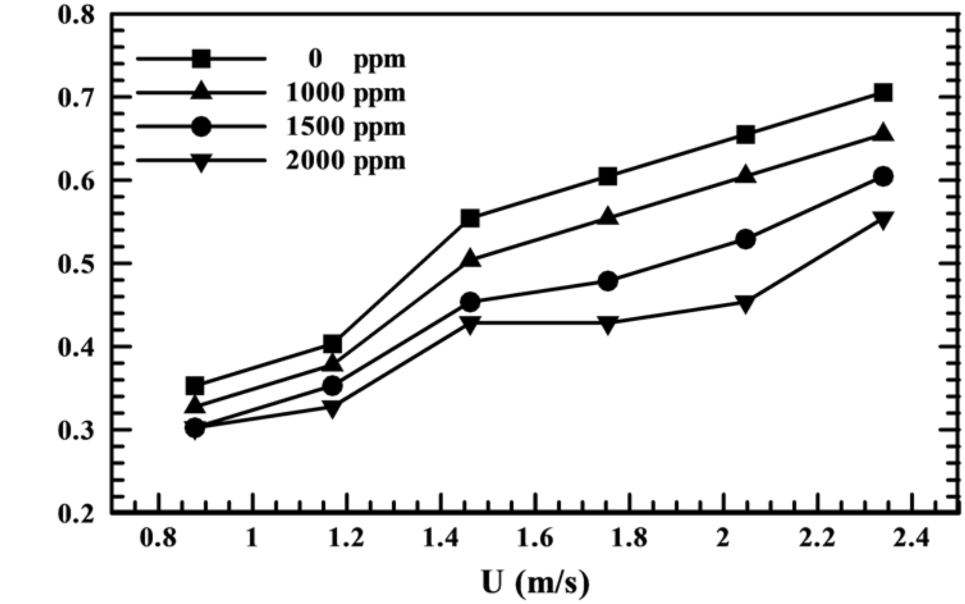
Fig.(5) Variation of Pressure gradient with concentration for different angle values at Re=66836 for (a) CTAB , (b) NASAL at 2000 ppm CTAB concentration.



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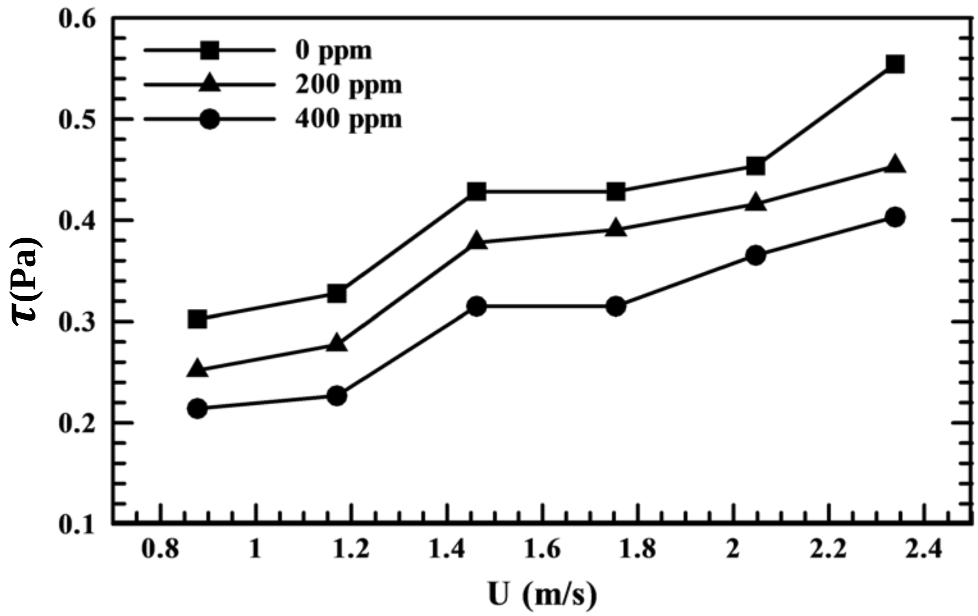
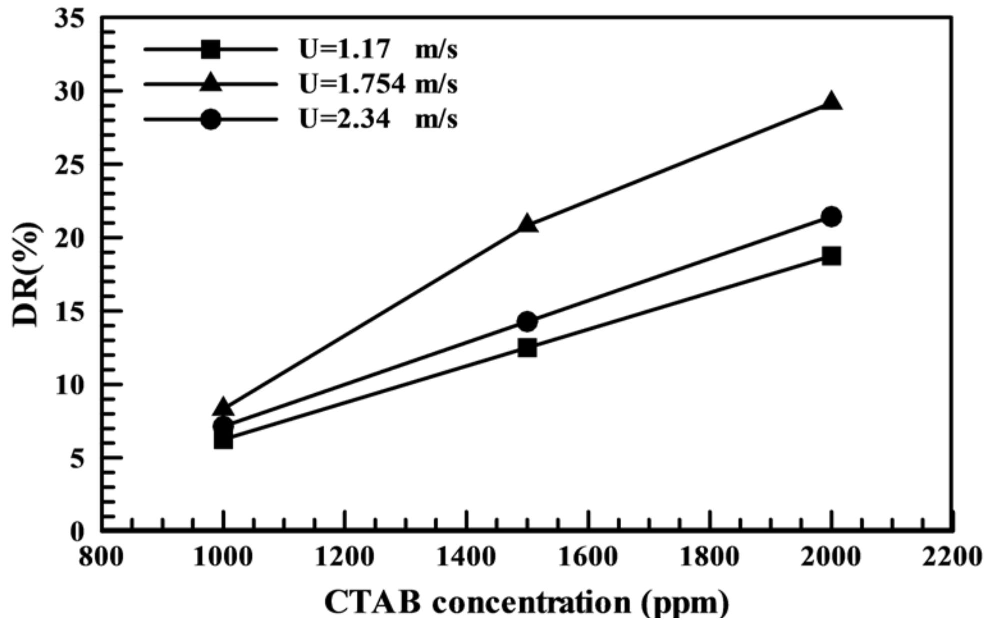


(b)

Fig.(6) Variation of shear stress with mean water velocity at δ=0° for different concentrations of (a) CTAB , (b) NASAL at 2000 ppm CTAB.



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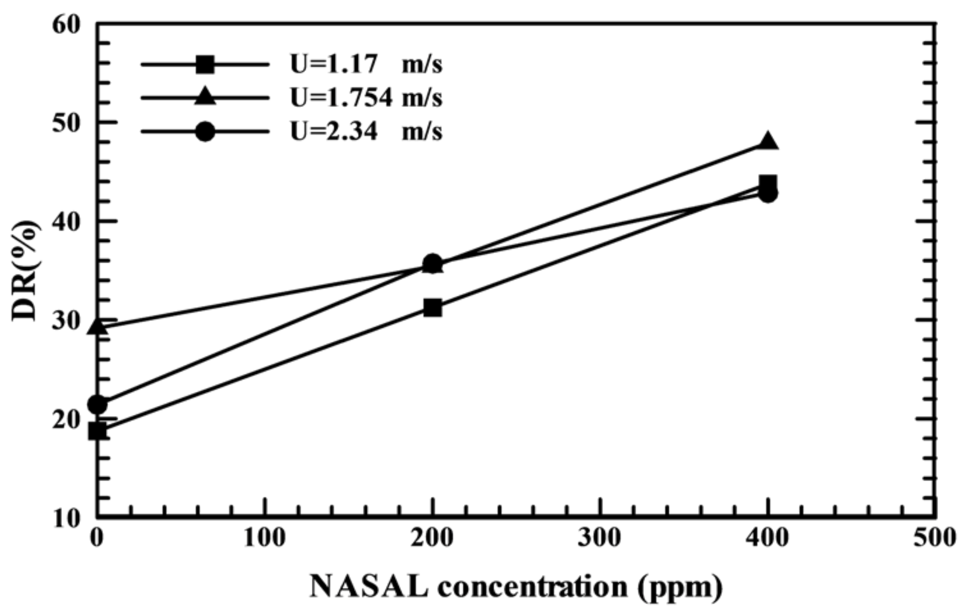
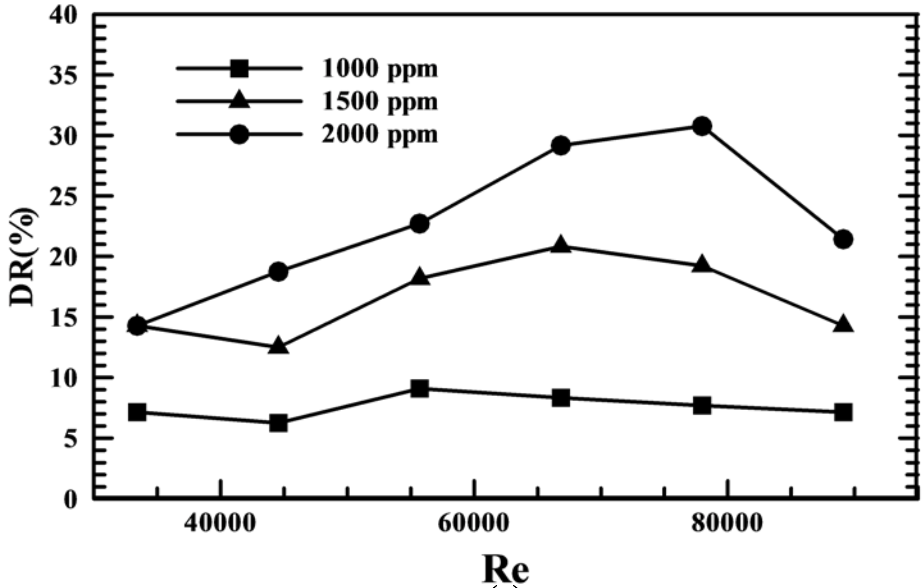


(b)

Fig.(7) Variation of drag reduction with concentration for different mean water velocities at $\delta=0°$ for (a) CTAB concentration, (b) NASAL concentrations at 2000 ppm CTAB concentration.



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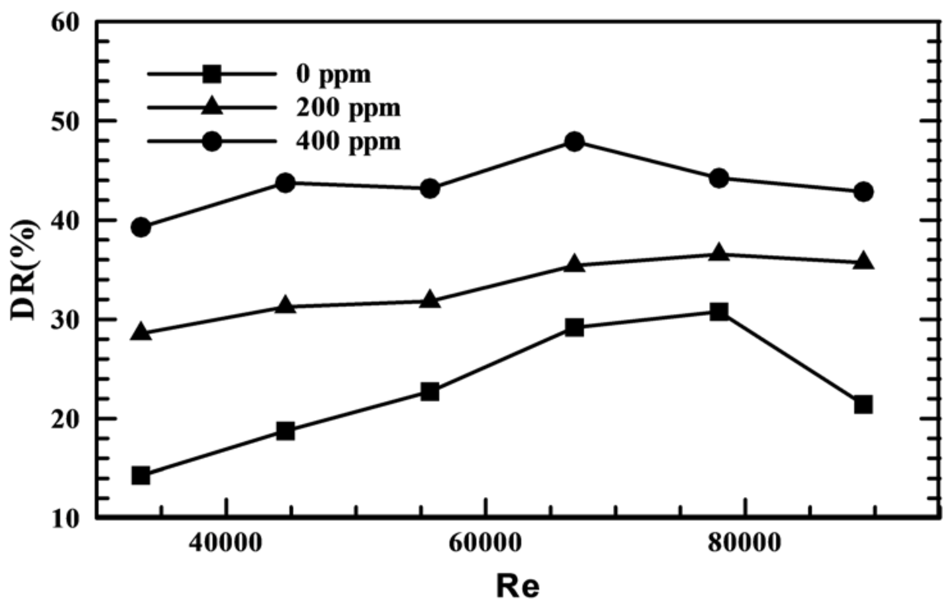

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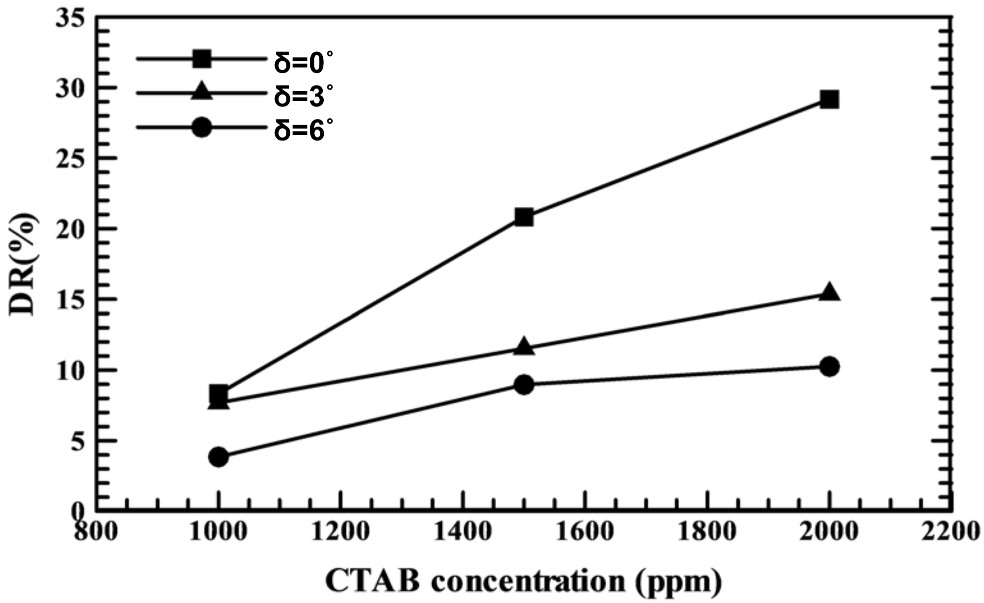
Fig.(8) Variation of drag reduction with Reynolds number at δ=0° for different concentrations of (a) CTAB , (b) NASAL at 2000 ppm CTAB concentration.



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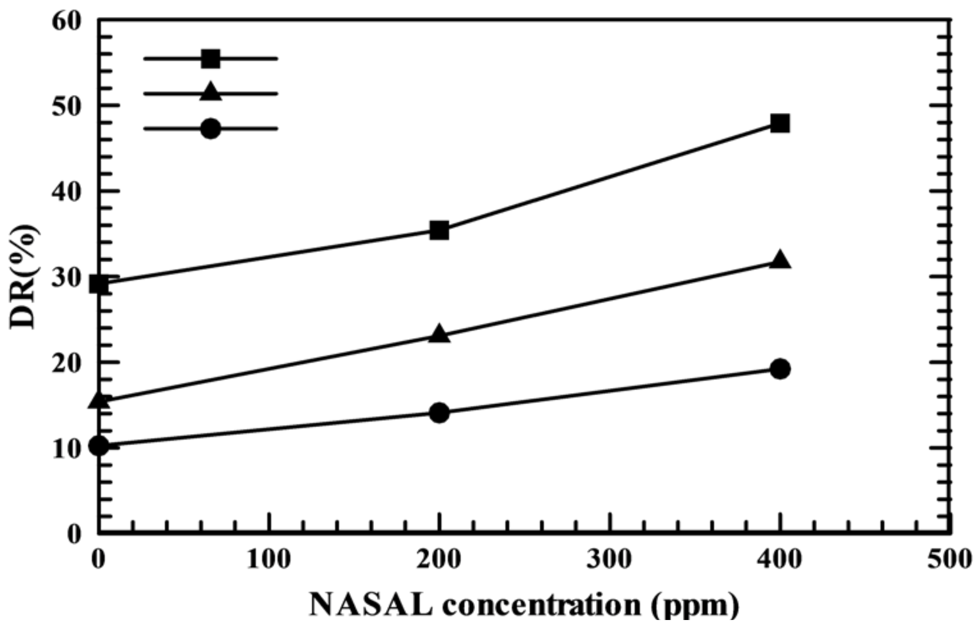
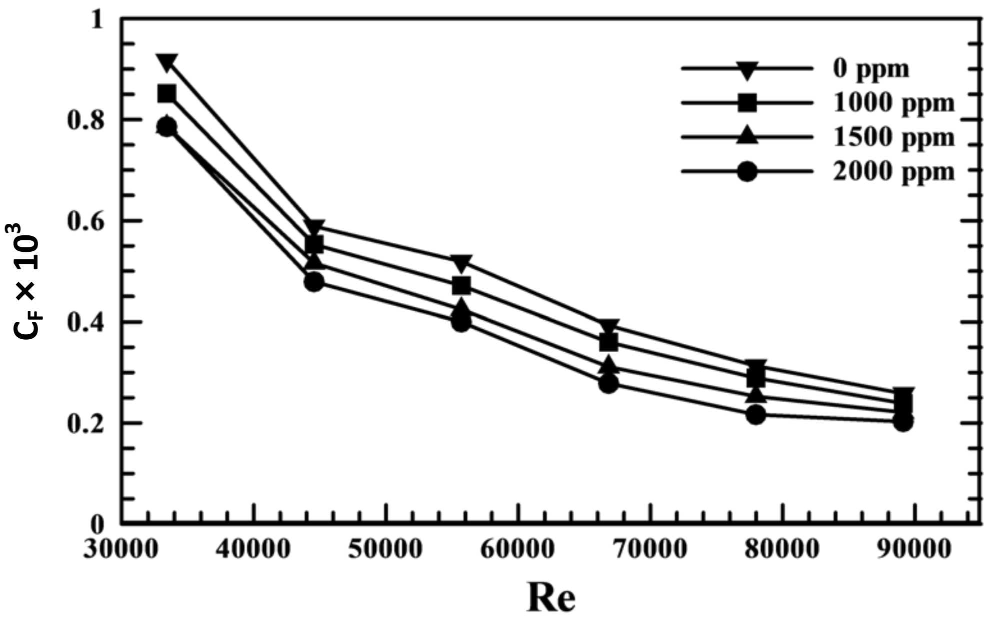


(b)

Fig.(9) Variation of drag reduction with concentration for different angle values at Re=66836 for (a) CTAB , (b) NASAL at 2000 ppm CTAB concentration.



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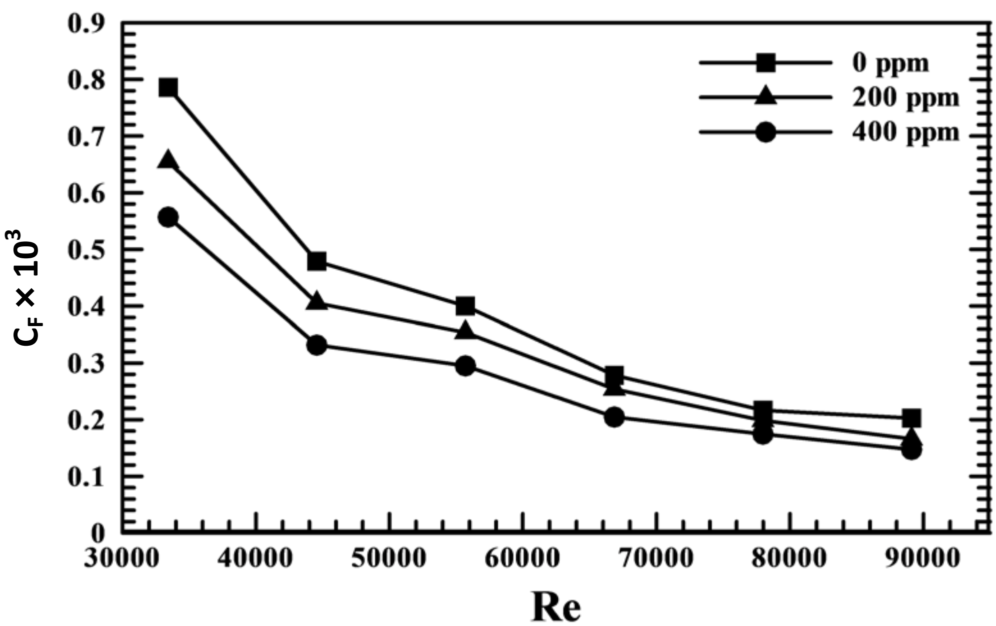

(b)

Fig.(10) Variation of friction factor with Reynolds number for different concentrations of (a) CTAB , (b) NASAL at 2000 ppm CTAB concentration at $\delta=0°$.

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