KUFA JOURNAL OF ENGINEERING
ISSN 2071-5528
PRINTED IN IRAQ

Volume 4, Number 1 pp.97- 112, 2012

Drag Reducing Flow of water in forced closed loop circulation system by using Sodium dodecyl sulfate additive

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(Received: 15/1/2012 ; Accepted :September/2012)

Abstract

The turbulent flow friction of a water solution with a small amount of surfactant additive is dramatically reduced when compared to that of pure water. This effect offers a significant reduction in pumping power and energy consumption. Commercial implementation of drag reducing fluids have proved successful for oil pipeline transportation, district heating and cooling systems, fire fighting, sewer throughput, jet cutting, etc.

The investigation was carried out on a facility with a forced closed loop for pressure drop measurements. A type of anionic surfactant (Sodium dodecyl sulfate) mixed with same weight of counter ion material (Sodium nitrate) was used as a drag reducing additive to tap water at a mass concentration ranged from 50 to 2000 ppm. Pressure drop data was collected over a 1668 mm flow pipe of carbon steel with 15.8 and 26.6 mm internal diameter and different solution flow rate (up to 8 m^3/h) at constant temperature of 30℃ (ambient temperature).

The paper focused on calculation of friction factor from experimental data. It was found that the friction factor values lies near Blasuis asymptote for pure solvent, while they positioned towards maximum drag reduction asymptotes when surfactant is added. A maximum drag reduction percent of about 66% was obtained by using 2000 ppm surfactant – counter ion aqueous solution. Also, it was concluded that there is a critical Reynolds number equals to about 96000 not to be exceeded because any further increasing leads to decrease in drag reduction. In addition, a correlation equation was found to correlate wall shear stress as a function of bulk mean fluid velocity. This correlation equation is of value in scale up of results obtained in small laboratory equipments to larger diameter pipes and different operating conditions. Another objective was to investigate the mechanism behind a possible drag reduction.

Key Words: Sodium dodecyl sulfate, Tap water, Drag reduction, Friction factor, Sodium nitrate.

الجريان منقوص السحب للماء في نظام حلقي قسري الدوران باستخدام كبريتتات الدوديسايل صوديوم كمادة تفعيل سطحي

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الخلاصة:

إن احتكاك الجريان المضطرب لمحلول مائي يحتوي على كمية قليلة من مادة التفعيل السطحي يكون قليل بشكل كبير عند مقارنته مع ذلك للماء النقي. هذا التأثير يعطي تأثير ملحوظ في قدرة الضخ و استهلاك الطاقة. إن التطبيقات العملية للموائع منقوصة السحب أثبتت نجاحها في خطوط نقل النفط وأنظمة التسخين والتبريد المركزي و مكافحة الحرائق ونقل المياه الثقيلة والقطع بالنوازل الخ.

الدراسة قد تم إجراءها بواسطة جهاز ذو حلقة مغلقة قسرية و ذلك لإجراء قياسات هبوط الضغط. نوع من مواد التفعيل السطحي الأيوني خلط مع نفس الوزن من مادة معادلة للايونات (نترات الصوديوم) تم استخدامها كمضاف لتقليل السحب في الماء الموزع عند تراكيز كتلية تتراوح من ٥٠ إلى ٢٠٠٠ جزء من المليون. بيانات هبوط الضغط تم جمعها على أنبوب جريان ذو ١٦٦٨ ملم طول من الفولاذ الكربوني ذو أقطار داخلية ١٥,٨ و ٢٦,٦ ملم ومعدل جريان مختلف للمحلول (يصل إلى ٨ م^{٣}/سا) عند درجة حرارة ثابتة هي ٣٠ مْ (درجة حرارة معتدلة).

البحث يتركز على حساب معامل الاحتكاك من البيانات المختبرية. لقد وجد إن قيم معامل الاحتكاك تقع بالقرب من محاذي بلازيس للمذيب النقي، بينما إنها تتجه نحو محاذيات منقوص السحب العليا عندما يتم إضافة مادة التفعيل السطحي قيمة عظمى لتقليل السحب حوالي ٦٦ % قد تم الحصول عليها باستخدام ٢٠٠٠ جزء من المليون من هذا المحلول المائي لمادة التفعيل السطحي – المعادل الأيوني. كذلك قد تم استنتاج إن هنالك رقم رينولد حرج مساوي لحوالي ٩٦٠٠٠ والذي لا يجوز تجاوزه بسبب إن أي زيادة أخرى تؤدي إلى نقصان في تقليل السحب. بالإضافة إلى ذلك، معادلة ربط قد تم إيجادها لربط إجهاد قص الجدار كدالة لمعدل سرعة الجريان الكلي. هذه المعادلة لها أهمية في عملية تكبير النتائج التي تم الحصول عليها من أجهزة مختبريه صغيرة إلى أنابيب اكبر قطراً وظروف تشغيلية مختلفة. هدف آخر هو لدراسة الميكانيكية وراء تقليل السحب الممكن.

Nomenclature

Symbol	Meaning	Unit
C	Concentration of surfactant in aqueous solution	ppm
D	Diameter of test section of pipe	m
Dr	Drag reduction	-
f	Fanning friction factor	-
f_s	Fanning friction factor for pure solvent (water)	-
f_p	Fanning friction factor for drag reducing solution	-
L	Length of test section of pipe	m
Re	Solvent based Reynolds number	-
u_s^*	Shear velocity	m/s
V	Bulk mean fluid velocity	m/s
ΔP_{corr}	Corrected pressure drop	Pa
ΔP_s	Pressure drop for pure solvent (water)	Pa
ΔP_p	Pressure drop for drag reducing solution	Pa
μ	Viscosity of pure solvent (water)	kg/(m.s)
ρ	Density of solvent or solution	kg/m^3
σ	Surface tension of solvent or solution	N/m
τ_w	Wall shear stress	Pa

INTRODUCTION

The drag reduction effect is extremely interesting from a practical point of view. Liquids are mostly transported through pipes and frictional drag reduction offer large economic advantages and a large effectiveness of this transport. Many techniques for reducing drag were suggested by many researchers for large number of applications. One of these techniques depends on suppressing turbulent eddies by using baffles with different heights in turbulent flow region (Rashidi and Baner, 1990). Other techniques used layers of greasy materials or bubble layers to reduce skin friction (Aguilar et al., 2006). But the most effective technique in drag reduction is by the addition of minute quantities of chemical additives to liquids transported in turbulent flow through pipelines (Zakin et al., 1996).

Polymers were initially used as drag reducing additives for turbulent water flow to reduce the frictional drag. This is due to the viscoelastic properties of the polymer solution. In a turbulent flow region, the friction factors of viscoelastic fluids are much smaller than those of pure viscous fluids. But because polymer solutions are strongly affected by thermal and mechanical irreversible degradation which may result in shorter life time of drag reduction effectiveness, an alternative additives were examined. Surfactants were found in the last two decades also to reduce the frictional drag but to be less affected by chemical, mechanical and thermal degradation. They suffer only temporal degradation when a certain critical wall shear stress is exceeded, but the structures were repairable through regaining their drag reducing abilities when the shear stress is reduced (Brostow et al., 2007). Therefore, surfactants are now being considered as practical drag reducing additives.

Surfactants are molecules that consist of a polar head group and non-polar tail. The non-polar tail consists of a long carbon chain. Surfactants are divided into four groups depending on the way the head group is charged. The head group can be: uncharged (non ionic), positively charged (cationic), negatively charged (anionic) or with both a positive and negative charge on opposite sides (zwitterionic). In practice, the utility of anionic surfactants available in industry would meet the requirements of long-term stability of the drag reducing effect. Although, these conventional soaps are relatively inexpensive and mechanically and thermally stable (Gyr and Bewersdorff, 1995).

It is not completely understood which rheological behavior is responsible for the drag reduction occurring in turbulent shear flows of surfactant solutions (Aguilar et al., 2006). Many drag reducing solutions are non-Newtonian fluids with strong viscoelasticity and high ratio of extensional to shear viscosity (Zhang et al., 2005). Gyr (1990) suggested that shear induced structure is responsible for drag reduction. But some surfactant drag reducing systems do not necessarily show shear-induced structure (Lin et al., 2001). Lu et al. (1997) found that a non-viscoelastic fluid also has a good drag-reducing ability. They suggested that extensional viscosity appears to be the key property controlling drag-reducing flows. Li et al. (2004) found that elongational viscosity of their solution has no visible difference from that of the pure solvent, even though the drag reduction can be seen clearly in his work. Anyway, the existence of thread like micelles seems to be necessary for drag reduction effectiveness. Zhang et al. (2005) directly observed the microstructure of thread like micelle by cryo-TEM in ethylene glycol/water solution and correlated it with drag reduction effectiveness. Furthermore, by adding some salts (i.e. electrolytes), the electrolytic repulsion forces of the head groups can be suppressed, the molecules can be packed more densely facilitating the formation of micelles (Gyr and Bewersdorff, 1995).

Data on the drag reduction with Sodium dodecyl sulfate surfactant additive are scare in the literature (Michels and Waton, 2000). Even for these, there is a dearth of quality data published with enough information to be useable for comparison and analysis. They are often based on limited ranges of operating conditions and are not externally verified. Therefore, large parts of these data is not ordinarily considered practical from a commercial standpoint.

The present work focuses on obtaining a fundamental data for Sodium dodecyl sulfate - sodium nitrate aqueous solution. Sodium nitrate salt was added as counter ion due to its power in facilitating micelles formation and because it is known to be an effective anticorrosion inhibitor

(Bardal, 2004). In order to acceptably narrow the experimental focus and provide practical relevance, the flow conditions and facilities are chosen from works done on fire fighting/department at Aldewanya city, Iraq. Flow rate and concentration effects were investigated by flowing Sodium dodecyl sulfate – Sodium nitrate aqueous solutions with four different concentration (50, 100, 400 and 2000 ppm) in pipe with two kinds of diameters 15.8 and 26.6 mm under adiabatic conditions at 30℃ (ambient temperature).

EXPERIMENTAL WORK

The experiments were carried out in a re-circulatory forced closed loop flow facility. The flow sheet and a photographic picture of the system are shown in Figures (1) and (2), respectively. The experimental apparatus includes: concentric double pipe test section, solution main centrifugal pump, small conditioning water pump, two fluid storage tanks (each has capacity of 1 m^3), analog flow meters, U manometer, thermometers, valves, elbows and pipes. The double pipe test section allows us to operate the experiments under adiabatic conditions, since the solution flows in the inner carbon steel tube while the constant temperature conditioning water flows in the annulus space between the two pipes. This was done due to the large effect of temperature variation on the pressure drop and as a result, the friction factor values (Li et al., 2004). The pressure drop was measured across a 1668 mm long test section of the pipe with a diameter of 15.8 and 26.6 mm using a U manometer. The reading from this manometer is the frictional pressure drop along that test section of pipe; the drops due to acceleration and gravity are negligible. The pump (Begemann, MGH 3500), which had a maximum setting of 36 m^3/h, drove the flow of solution through the system. The flow rates were measured and controlled by a variable area flow meters (Liquatec, PMF 0505) and valves attached to the pipe near the region of the pressure drop measurements. The flow meters were calibrated by conventional method using a bucket and stop watch.

In order to obtain the fully established friction factors, it is essential to measure the pressure drop between two pressure taps in the fully developed flow region. At a distance of 10 mm from test section entrance, a trip ring was inserted in the pipe to accelerate transition to turbulence. The trip ring causes a sudden narrowing of the pipe diameter in the stream wise direction. However, the entrance length for turbulent flow of Newtonian fluids is fairly short and 20 pipe diameters are usually sufficient (Choi et al., 1987). Therefore, the pressure holes were located at entrance length equal to 535 mm for both pipes. The entrance length is defined as the length measured from piping element (elbow) to the pressure hole.

The surfactant solution used in this study was Sodium dodecyl sulfate (Santa Cruz Biotechnology, Inc.) dissolved in tap water. Sodium dodecyl sulfate (M=288.38) has the chemical formula [$C_{12}H_{25}O_4S{\cdot}Na$]. This surfactant is an anionic surfactant, which is known to be very effective for drag reduction. The advantages of using this surfactant over other types of surfactants are: it is locally available; cheap in price and less affected by potassium, sodium, or calcium ions that may naturally found in tap water. Sodium nitrate (Lab Chem, Inc.) was added to enhance rod like micelles structure formation, which is thought to be the key to give complicated rheological fluid properties including viscoelastisity. Since, it acts to reduce ion radius of sodium dodecyl sulfate to deform micellar shape from globular to rod like. Furthermore, it is active anticorrosion inhibitor (Bardal, 2004). Concentrations of 50, 100, 400 and 2000 ppm were used to achieve the static surface tensions listed in Table 1. A tensiometer (Krüss, K20S) was used for surface tension measurements with an accuracy of 8%. Furthermore, a swirl decay time measurements were performed to give a rough estimate of the viscoelasticity of the solutions. 100 ml sample of solution was placed in a beaker. The beaker was covered with parafilm and placed on a magnetic stirrer (Heidolph, MRHeis). The stirrer was turned on and allowed to stir for 5 minutes, after which it was promptly turned off. A stopwatch was started when the stir bar stopped spinning. The stopwatch was stopped when the fluid began to recoil. This was designated the swirl decay time. Solutions with lower swirl decay times often had higher drag reduction.

Approximately, 0.75 m^3 of solution was prepared for each set of tests. Dry sodium dodecyl sulfate and sodium nitrate were weighed and mixed with warm de-ionized water for 6 – 12 hours by an electric mixer (Caframo, BDC2002). Same weight concentration of sodium nitrate and sodium dodecyl sulfate are always included in the solution, since this ratio was experimentally confirmed to be the most suitable for drag reduction effectiveness (Myska and Mik, 2006). After pouring the solution into the tank, it was forced to flow in all sections of the installation. Once fully assembled, the solution flow is regulated to the desired rate and the experiments begun. The liquid flow rate is increased slowly and given time to reach equilibrium before taking each data point. The pressure readings are time averaged over a minute of recorded values, though the fluctuations are typically slight.

Pressure drop readings through testing section before and after drag reducer addition, were needed to calculate the percentage drag reduction (Indartono et al., 2005) which is quantified as follows:

$$\%Dr = \frac{\Delta P_s - \Delta P_p}{\Delta P_s} \times 100 \tag{1}$$

Drag reduction can be also expressed in terms of fanning friction factor as follows (Indartono et al., 2005):

$$\%Dr = \frac{f_s - f_p}{f_s} \times 100 \qquad (2)$$

The fanning friction factor is determined using the following equation (Yoon et al., 2002):

$$f = \frac{\tau_w}{\rho \cdot V^2 / 2} = \frac{\Delta P_{corr} \cdot D}{2\rho \cdot V^2 \cdot L} \qquad (3)$$

The friction factor is essentially a dimensionless pressure gradient, and it is a function of the Reynolds number for a fully developed flow of Newtonian fluid. Blasius equation correlates friction factor and Reynolds number in fully developed turbulent flow (McComb, 1990):

$$f = 0.0791 Re^{-0.25} \qquad 3 \times 10^3 \langle Re \langle 1 \times 10^5 \qquad (4)$$

Maximum drag reduction asymptote limits the maximum drag reduction that can be achieved by a drag reducing fluid. The well-known maximum drag reduction asymptote for dilute polymer solutions is that proposed by Virk (Virk et al., 1970):

$$\frac{1}{\sqrt{f}} = 19.0 \log\left(Re\sqrt{f}\right) - 32.4 \qquad 2.3 \times 10^3 \langle Re \langle 6 \times 10^4 \qquad (5)$$

A fairly good power law approximation to this implicit equation is given by (Aguilar et al., 2001):

$$f = 0.58 Re^{-0.58} \qquad 2.3 \times 10^3 \langle Re \langle 6 \times 10^4 \qquad (6)$$

This asymptotic correlation has been confirmed by a great amount of experimental data with regard to dilute polymer solutions, and it has shown to be independent of pipe diameter, concentration, molecular weight, etc.

There is almost an unanimous consensus that the maximum drag reduction asymptote for surfactants should be higher than that of polymers (Aguilar et al., 2001). Zakin et al. (1996), proposed a maximum drag reduction asymptote for surfactants:

$$f = 0.315 Re^{-0.55} \qquad 4 \times 10^3 \langle Re \langle 1.3 \times 10^5 \qquad (7)$$

RESULTS AND DISCUSSION

In order to ensure that the test setup is performing acceptably, tap water data is collected over the relevant ranges of flow rates and pipe diameters as seen in Figures 3 and 4. The recorded pressure drop data is used to calculate the friction factor and is compared to the theoretical prediction (Blasius equation). There is an average 4.9% deviation between the data and theoretical prediction, however the data relies on measured values for the pipe diameters and fluid flow rates. If the measurement uncertainty is included then there is good agreement between the theoretical and experimental and the test setup could be considered to be operating acceptably. The experimental uncertainty for pipe dimensions are measured to be 1668 ± 1.9 mm for length and 15.8 ± 0.2 mm and 26.6 ± 0.5 mm for the two diameters, respectively. There is a ± 2℃ uncertainty in the fluid temperature, ± (0.01 – 0.08 m^3/h) in the liquid flow rate (dependent on flow rate values) and 1.0% in pressure drop measurement. Any remaining disparity between experimental and theoretical data may be attributed to slight imperfections in test section machining.

Figures 3 and 4 show the friction factor measurements for the surfactant – counter ion solution measured in two pipes of different diameters (15.8 and 26.6 mm) and concentrations of (50, 100, 400 and 2000 ppm) plotted as a function of the solvent based Reynolds number. The friction factor lines corresponding to turbulent Newtonian flows (Blasius) as well as Virk and Zakin maximum drag reduction asymptotes are also plotted as references. Blasius line describes the vicinity of the onset of drag reduction, where the experimental data show the first signs of reduction in friction factor; while Virk and Zakin lines describes the asymptotic region, where none of the experimental data shown herein reached any of these lines. In this work, Reynolds number was calculated based on solvent viscosity. Since, it is very difficult to predict the proper viscosity from rheometric measurement for these solutions in turbulent flows (Bewersdorff, 1996), due to the time dependent rheological material properties in the shear induced structure. At shear induced structure, viscosity increase of surfactant solution is a function of slit width of viscometer (Gyr, 1990).

The experimental data shows that the friction factor values are progressively reduced as Reynolds number increases, but the slope of friction factor curves reduction increases with solution concentration increasing. This is a normal result because high concentration of additive means high concentration of micelles in the solution, which is the main element in drag reduction phenomena. This agreed well with the results of Zhang et al. (2005) who noticed a clear relation between micellar network occurrence and friction factor values and concluded that thread like micelle is responsible for drag reduction. In addition, Table 1 shows that there exists a clear interaction between additive concentration and solution surface tension. As the concentration of additives increases, the surface tension of the solution decreases. This leads to decrease in fluid motion resistance and as a result decreasing in pressure drop and friction factor values, since the surface tension essentially acts as a resistance to the motion of a water droplet as it is being blown along a solid surface. However, in turbulent flow region, both of the above-mentioned factors and many others could affect the viscoelastic properties of the solution. There are a large number of studies in literature indicates that the friction factor of viscoelastic fluids are much smaller than those of Newtonian or pure viscous fluids (Yoon et al., 2002). Also, it can be seen from comparing Figures 3 and 4, that there exists a diameter effect on the curves of friction factor against Reynolds number. There is a general agreement in literature pertaining to flow in pipes that the surface tension has an increasing effect on the flow behavior and pressure drop as the pipe diameter decreases for same flow rate (Indartono et al., 2005).

At certain Reynolds number (critical Reynolds number), the friction factor values begin to increase after reaching a minimum value. This increasing in friction factor values is usually related to fluid degradation, which implies that the properties of the fluid may be different in different diameter pipes at the same Reynolds number. As the pipe diameter increases, the critical Reynolds number value increases. This is due to the fact that as pipe diameter increases, the bulk mean velocity as well as shear stress (main driving force for fluid degradation) decreases, that led to increase in critical Reynolds number value.

Figures 5 and 6 show drag reduction percentage as a function of shear velocity with four different surfactant – counter ion concentrations (50, 100, 400 and 2000 ppm) for 15.8 and 26.6 mm pipe diameters. These figures indicate that all data points seem to be well correlated by four similar curves corresponding to four different solution concentrations independent on the pipe diameter. In addition, it could be concluded from these figures that there is a unique critical shear velocity equals to 0.21 m/s for all concentrations and pipe diameters. This value corresponding to approximately 6.9 m/s bulk mean fluid velocity and 71 Pa wall shear stress. This critical velocity should be never reached in practical applications, since the benefit of adding surfactant to solution begins decreasing as the velocity increasing from this critical value. This is agreed well with several published works that proposed critical wall shear stress (at critical Reynolds number) as the upper bound of drag reduction effectiveness for surfactant drag reducing systems (Usui et al., 1998; Gyr, 1990). This could be explained from the interesting stress controlled drag reduction effect in the surfactant solutions. Drag reduction increased with increasing shear stress up to a critical value. Beyond the critical value, the drag reduction of the surfactant solution became indistinguishable from that of the surfactant free solution. This is agreed well with several published works (Zakin et al., 1996). This occurs because of a temporary disentanglement of the network induced by turbulent vortices and eddies in fully developed flow. If the wall shear stress is increased from below to above the critical value, the network of micelles collapses and if it is reduced from above to below the critical value, the network bonds reform and the reducing ability of the solution is restored. In the present case, drag reduction (Onset) occurred at relatively high Reynolds number. However, one could concluded that the critical region for friction factor or drag reduction percentage depends mainly on fluid velocity not on additive concentration nor pipe diameter. This critical velocity is not to be exceeded under any operation conditions using sodium dodecyl sulfate – sodium nitrate aqueous solution pumping process because any further increasing in velocity leads to decrease in drag reduction and as a result decreasing in pumping flow rate.

Figures 7 and 8 show wall shear stress as a function of bulk mean fluid velocity with various solution concentrations for pipe diameters equal to 15.8 and 26.6 mm, respectively. It could be concluded from these figures that there is a clear linear relationships between wall shear stress and bulk mean fluid velocity in logarithmic scales for various solution concentration and pipe diameters. Also, it could be shown that these linear relationships are close enough to be represented by a single line for all solution concentrations and pipe diameters. In the present work, the relationship was found to be:

$$\tau_w = 1.078V^{16.056} \tag{8}$$

The average relative error was examined and found to be equals to 11.34%.

CONCLUSIONS

1. Maximum drag reduction percentage of about 66% was obtained using aqueous solution of sodium dodecyl sulfate – sodium nitrate.
2. The critical Reynolds number for aqueous sodium dodecyl sulfate – sodium nitrate solution was calculated to be equals to 96000 not to be exceeded under any operational conditions.
3. A simple linear correlation between wall shear stress and bulk mean fluid velocity was proposed and proved to be successful in scale up calculations since it is independent on pipe diameter nor solution concentration (50 – 2000 ppm).

ACKNOWLEDGMENTS

We wish to acknowledge the University of Alqadissya / College of Engineering for its permission to construct the experimental system in its owned laboratories.

The author would like to acknowledge the support provided by Civilian defense office, fire-fighting department at Alqadissya city, Iraq.

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Table 1, Surface tension for pure water and the surfactant solutions

Concentration of surfactant, ppm	Surface tension, N/m
0	0.074
50	0.068
100	0.064
400	0.051
2000	0.042

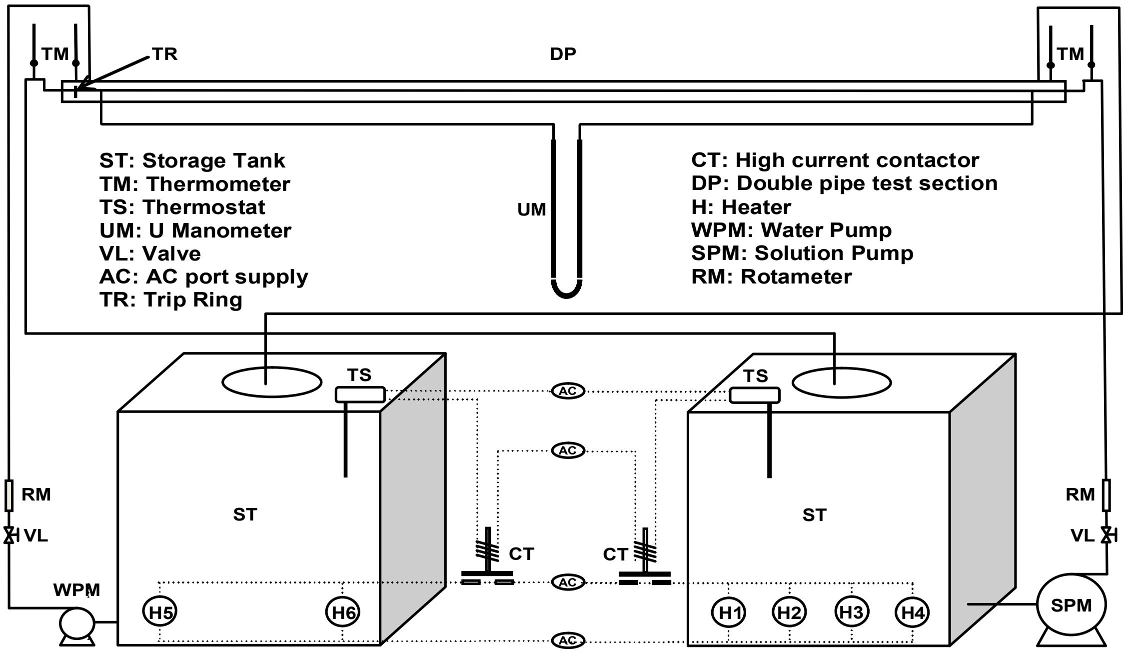

Figure (1), Flow sheet of the experimental apparatus

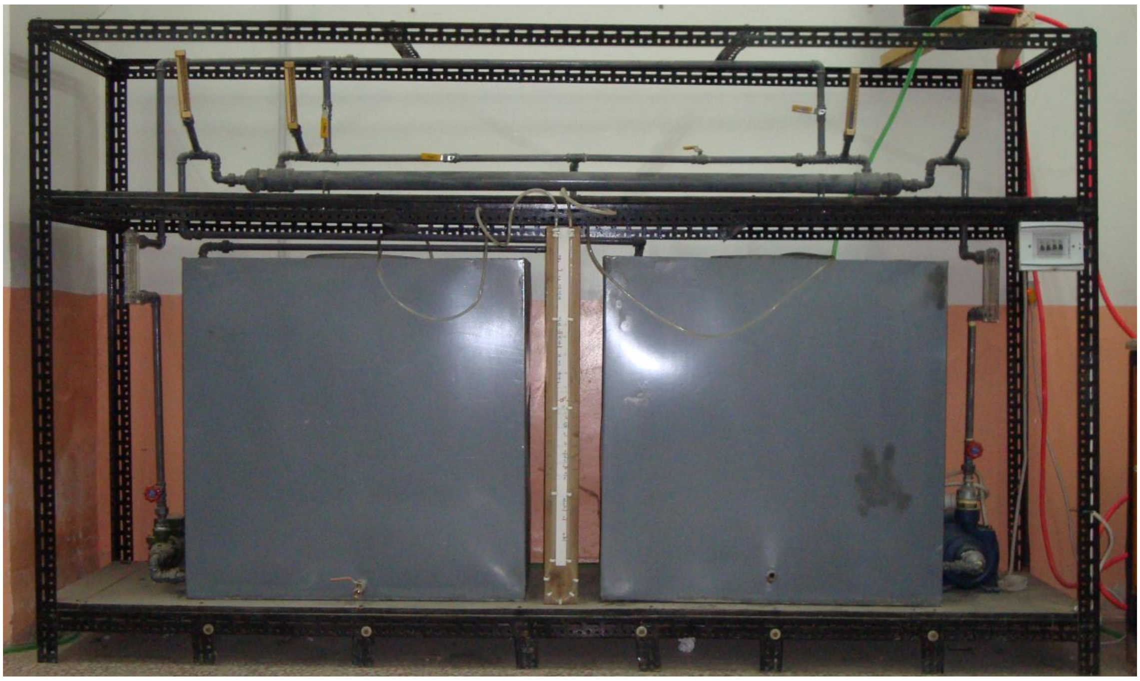

Figure (2), Photographic picture of the experimental apparatus

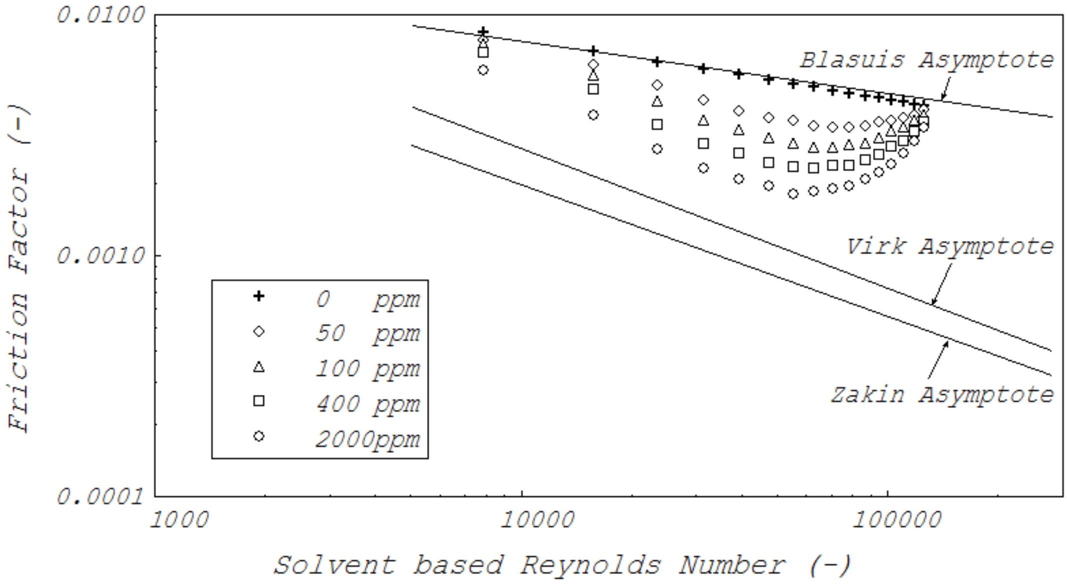

Figure (3), Friction factor as a function of solvent-based Reynolds number with different solution concentration for pipe diameter equals to 15.8 mm.

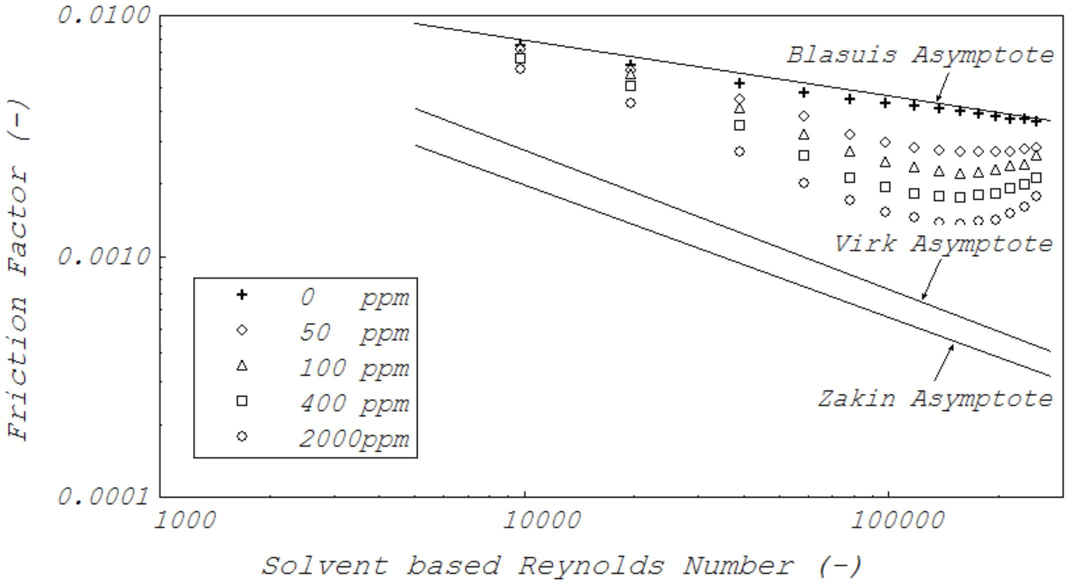

Figure (4), Friction factor as a function of solvent-based Reynolds number with different solution concentration for pipe diameter equals to 26.6 mm.

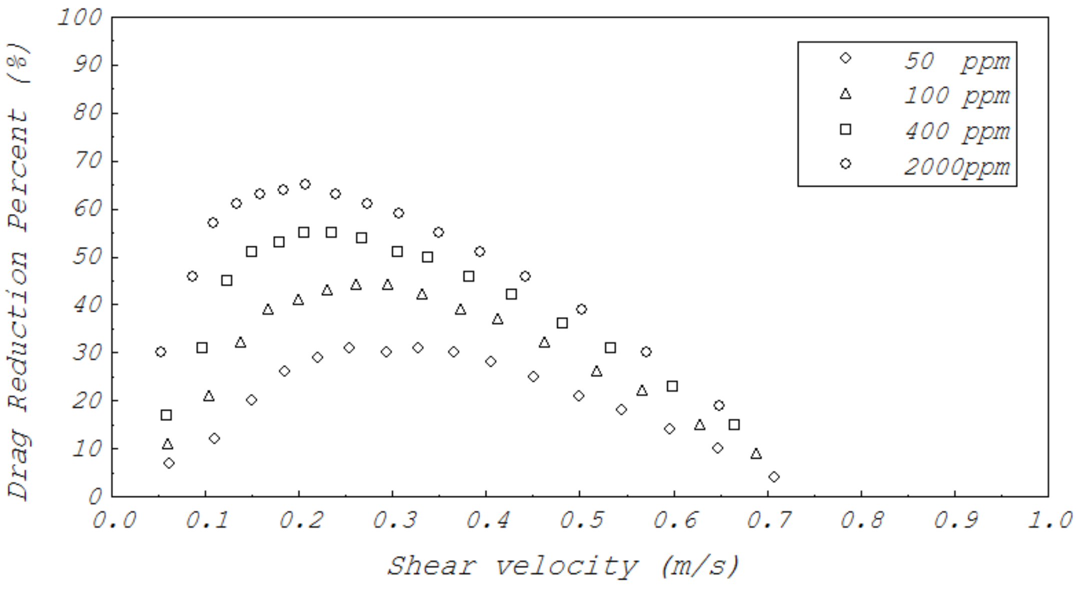

Figure (5), Drag reduction percentage as a function of shear velocity with different solution concentration for pipe diameter equals to 15.8 mm.

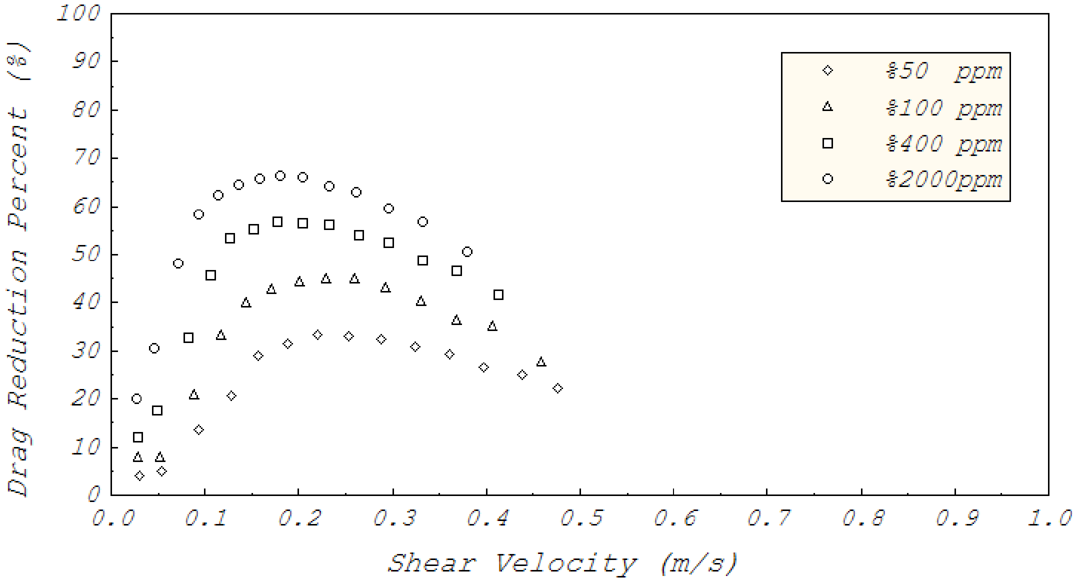

Figure (6), Drag reduction percentage as a function of shear velocity with different solution concentration for pipe diameter equals to 26.6 mm.

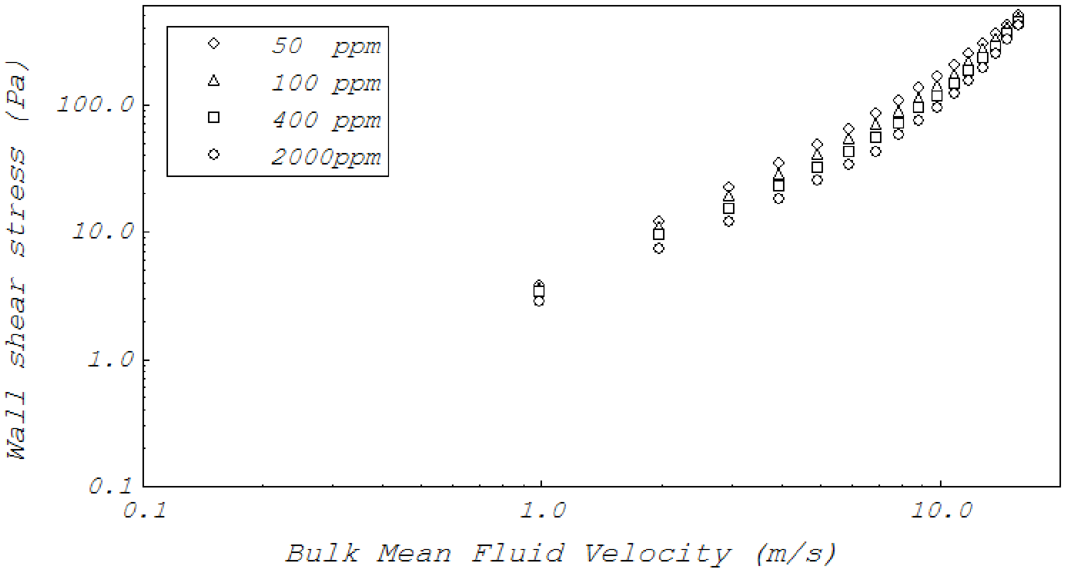

Figure (7), Wall shear stress as a function of bulk mean fluid velocity with different solution concentration for pipe diameter equals to 15.8 mm.

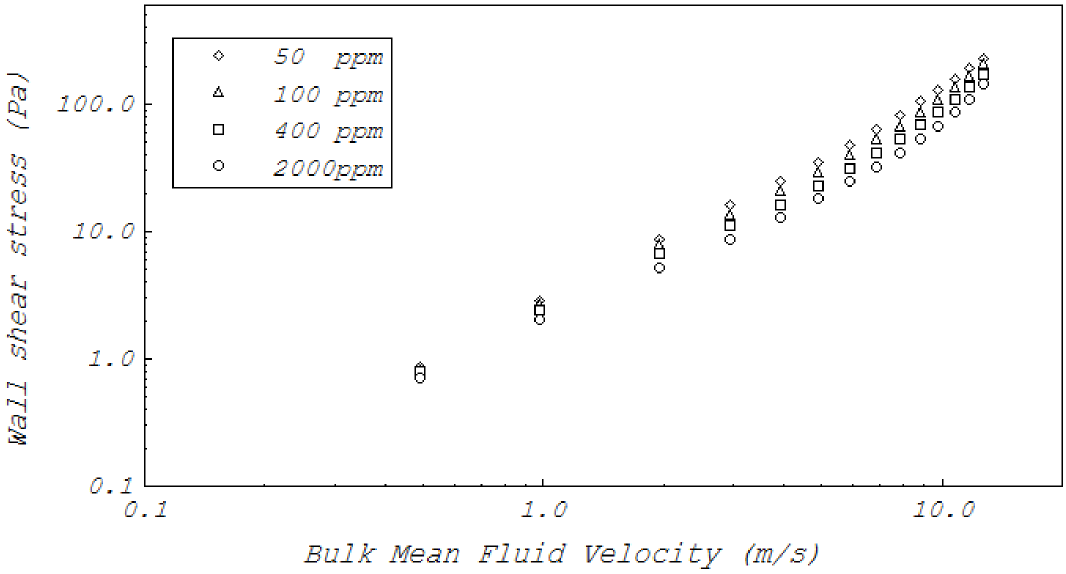

Figure (8), Wall shear stress as a function of bulk mean fluid velocity with different solution concentration for pipe diameter equals to 26.6 mm.