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Experimental and Theoretical Investigation of Polymeric Drag Reducing Agent in Turbulent Pipe Flow

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Abstract

In the present work, the drag reduction effectiveness of water soluble Carboxyl methyl cellulose (CMC) was studied as a function of polymer concentration and flow rate. Drag reduction results were assessed by measuring pressure drop over a one meter test section from the selected pipe. The effect of additives concentration was investigated over a range of 0 – 85 wppm, the solvent (water) flow conditions that were studied included higher flow rates. The experimental work was performed in a constructed re–circulating closed loop system. Maximum drag reduction percent (MDR%) of 17.3 % was obtained by using 85 wppm of CMC. The friction factor was calculated from experimental data with an acceptable average absolute percent Deviation. Correlation equation for fanning friction factor was suggested as a function of Re. The drag reduction results have been correlated based on an modification of a theoretical model available in the literature. The functional form of the model requires knowledge of the velocity profile, ratio of mixing length, friction factor, and the additive concentration as dependent variables.

Keywords: Drag reduction, Turbulent pipe flow, Polymer, Velocity profile.

دراسة تجريبية ونظرية لمقللات الاعاقة في محلول بوليمري في انابيب الجريان المفترض

الخلاصة

تم في هذا البحث العلمي دراسة فاعلية تقليل الاعاقة باستخدام نوع خاص من البوليمر (CMC) في منظومة تدوير مختبريه مغلقه وعند ظروف جريان مختلفه تم الحصول على الجريان الإضطرابي بواسطة مضخة الإزاحة الموجبة. تم استنباط نتائج تقليل الإعاقة من قياسات هبوط الضغط في مقطع واحد وبطول متر واحد في ألانبوب. تم دراسة تركيز المواد البوليميرية المضافة بمعدل يتراوح بين (20 – 85)جزء لكل مليون / نسبة وزنية، وبمعدلات جريان عالية القيم. تم ملاحظة زياده مستمره في تقليل الإعاقة مع زيادة تركيز البوليمر ومعدل سرعة الجريان.تقع قيم معامل ألاحتكاك للماء المعامل مع 85 wppm بوليمر بأتجاه محاذي للفرك الممثل للحدود القصوى لتقليل الإعاقة. تم تقدير معامل ألاحتكاك كدالة لرقم رينولدز، وأعطت نتائج مطابقه الى حد ما للنتائج المستحصله عمليا. تم ربط نتائج تقليل الاعاقة بادخال تطوير على الموديل الرياضي المتوفر في الادبيات وان الدالة الشكلية للموديل تتطلب معرفة الشد السطحي، هبوط الضغط وتركيز المضافات كمتغير, النتائج تؤشر الى توافق مقبول مع القيم المستحصله عمليا، للانبوب.

الكلمات الدالة: تقليل الاعاقة، الجريان المضطرب في الانابيب، بوليمر، توزيع السرعة.

Nomenclature

a,b,c,d	Constants in Eq.(13)
A, B, C	Coefficients depends on CMC
CMC	Carboxymethyl Cellulose
f	Fanning Friction Factor
μ_{eff}	Effective Viscosity
L	Entrance length
lp	Mixing Length with polymer
l	Mixing Length without polymer

Con. Concentration of polymer
M Molecular weight
Rc Ratio of mixing length
Re Reynolds number
%DR Percent drag reduction

Introduction

It is well known that a small amount of chemicals such as water-soluble polymers or surfactants cause dramatic suppression of turbulence when they are added to the liquid flow at large Reynolds number. In 1948, Toms[1], observed that a substantial reduction of the frictional pressure gradient in one-phase turbulent flow could be achieved by the addition of such a small amounts of long chain polymers into a solvent. Dodge [2], noticed that friction factors measured in the turbulent flow of aqueous carboxymethyl cellulose (CMC) solutions through pipes were abnormally low as compared to the curves correlating the results for other non-Newtonian purely viscous fluids. It was hinted that viscoelasticity could be the cause of the phenomenon.

At the same time, turbulent friction factors for non-Newtonian fluids were correlated by Shaver and Merrill [3].This technological achievement requires a new designing strategy for pipe line network, fittings and heat exchangers to handle the drag reduction flow. For the case of Newtonian fluid, the knowledge to design fluid system is well accumulated and the accuracy of numerical prediction is sufficient.

Predicting friction factors systematically lower than the ones proposed by Dodge and Metzner [4]. Shaver and Merrill's results refer to different liquids, the only solution used in both investigations being the CMC solution. This suggests that all of Shaver and Merrill's liquids are in the category of the anomalous liquids, whose existence was acknowledged by Dodg and Metzner. The velocity distribution for the turbulent flow of purely viscous fluids through round tubes is well known and has been adequately correlated in dimensionless form [5]. It has been shown that the same correlation can be extended to non-Newtonian purely viscous liquids by simply evaluating the viscosity at the wall shear rate [4,5].In contrast with this, the same correlation does not fit the velocity distributions measured by Shaver and Merrill [3] ;this is not surprising, because once the velocity distribution is known. the friction, factor-Reynolds number curve can be calculated, and vice versa [6].The velocity profiles measured by Shaver and Merrill are markedly steeper than the purely viscous ones; should the wall slip be the cause of the lower friction loss, flatter velocity profiles would be observed.

Various drag-reducing additives are available, such as flexible long-chain macromolecules, colloidal surfactants, and suspensions of fine, insoluble fibers or particles. Among these, macromolecules, which possess a linear flexible structure and a very high molecular weight, have been widely investigated as drag reducers. In spite of a large amount of experimental and simulational data. The fundamental mechanism has remained under debate for a long time [7]. Since polymers tend to stretch in a turbulent flow, thus increasing the bulk viscosity, it appears contradictory that they should reduce the drag. L'vov [8], proposed that the polymer stretching gives rise to a self-consistent effective viscosity that increase with the distance from the wall. Such a profile reduces the Reynolds stress (i.e., the momentum flux to the wall) more than it increases the viscous drag; the result is drag reduction.

The dependence of DR efficiency is known to be a function of polymer molecular weight, polymer concentration, and the degree of turbulence. Since solvent molecules take time to establish introductions with polymer molecules, maximum drag reduction, as a function of time, is obtained when the polymer–solvent interaction reaches the state of homogeneity.

The main objective of the present work is concerned with studying the effect of concentration and solution flow rate on effectiveness of ahigh molecular weight carboxy methyl cellulose CMC as drag reduction agent in the laboratory built-up closed turbulent flow loop system as drag reducing agent. Also to investigate the theoretical interaction between turbulent flow and polymer molecules, with the ultimate goal of providing a reliable prediction technique for percent drag reduction results.

Theoretical Approach

As mentioned above, one of the objectives of the present study is the interaction between polymer concentration and turbulence. The simplest form of turbulence modeling is the mixing length theory of Prandtl [9]. An attempt will be made here to find the effect of polymer concentration on the mixing length of turbulence. For this purpose a numerical algorithm is developed to calculate the velocity field in a circular pipe starting from its inlet and down to the fully developed region. The boundary layer equation is assumed to be adequate for this simplified analysis. Thus, for steady state incompressible turbulent flow, the governing equations are:

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}+\frac{v}{r}=0 \quad \text{....................................(1)}$$

Momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}=\frac{-1}{\rho}\frac{\partial p}{\partial x}+\frac{1}{\rho}\frac{1}{r}\frac{\partial}{\partial r}\left(\mu\frac{\partial u}{\partial r}-\overline{\rho u'v'}\right) \quad \text{.......................(2)}$$

The effective viscosity μ_{eff} includes the effect of turbulence. Using the mixing length theory the effective viscosity is calculated from:

$$\mu_{eff}=\mu+\rho l^{2}\left|\frac{\partial u}{\partial r}\right| \quad \text{..........................(3)}$$

Where l is the mixing length which can be calculated from the empirical relation of Nikuradse [9]:

$$\frac{l}{R}=0.14-0.08\left(1-\frac{y}{R}\right)^{2}-0.06\left(1-\frac{y}{R}\right)^{4} \quad \text{....(4)}$$

The above relation works well in the core region of the pipe. In the wall region it is modified by the Van Driest model[10].

$$l=0.41y\left(1-e^{y^{+}/26}\right) \quad \text{............................(5)}$$

Where $y^{+}=yu_{\tau}/v$ and

$$u_{\tau}=\sqrt{\tau_{w}/\rho}$$

Equations (1) and (2) are solved by an implicit marching integration procedure. The pressure gradient term for each marching step is calculated iteratively a secant method. Details of the solution algorithm can be found in [10]. Once the solution is obtained, the pressure gradient and the coefficient of friction are compared with the experimental values.

For a given flow rate, or Reynolds number, the experimental and theoretical results for the pressure gradient and friction coefficient will be different due to the effect of additives. To make the results match, a mixing length ratio, R_c, is introduced as:

$$R_{c}=\frac{l_{p}}{l} \quad \text{...(6)}$$

Where lp is the mixing length of the treated fluid. The value of Rc is varied in ad-hoc manner to obtain the experimental results.

Experimental work

The drag-reducing polymer was CMC with high molecular weight, which supplied from Petroleum North Company. Water was used as pipelining liquid, to dissolve the carboxyl methyl cellulose (CMC). The method of solution preparation adapted here, 2.4 gram for 15 wppm of corresponding CMC type was placed in a (500ml) conical flask and mixed with 500 ml of water under laboratory temperature. The container was placed in a stirring device, hence the arm of stirring device has no sharp edge that could expose the polymers to high shear force. A homogenous solution was obtained, after 30 minute for carboxyl methyl cellulose (CMC). The drag reduction experiments were carried out in an available laboratory circulation loop, as shown in Figure (1). The 160 liter reservoir tank with the dimensions (120 * 50 * 26.6 cm) was supported with pvc pipe inside diameter

(21.4 mm) in addition to by-pass pipe to control the flow. The test section of 100 cm long was placed away from the entrance length required (the distance based on Desissler equation [11], for minimum entrance length). A Submersible pump was used to deliver the fluid at high turbulence.

Percentage: drag-reduction (%DR) was calculated based on pressure drop data through the test section, as follows [12]:

$$\%DR. = \frac{\Delta P_{untreated} - \Delta P_{treated}}{\Delta P_{untreated}} * 100 \quad \text{.........(6)}$$

Where:

$\Delta P_{untreated}$: is the friction pressure drop for untreated water

$\Delta P_{treated}$: for treated water, both measured at the same volumetric flow rate.

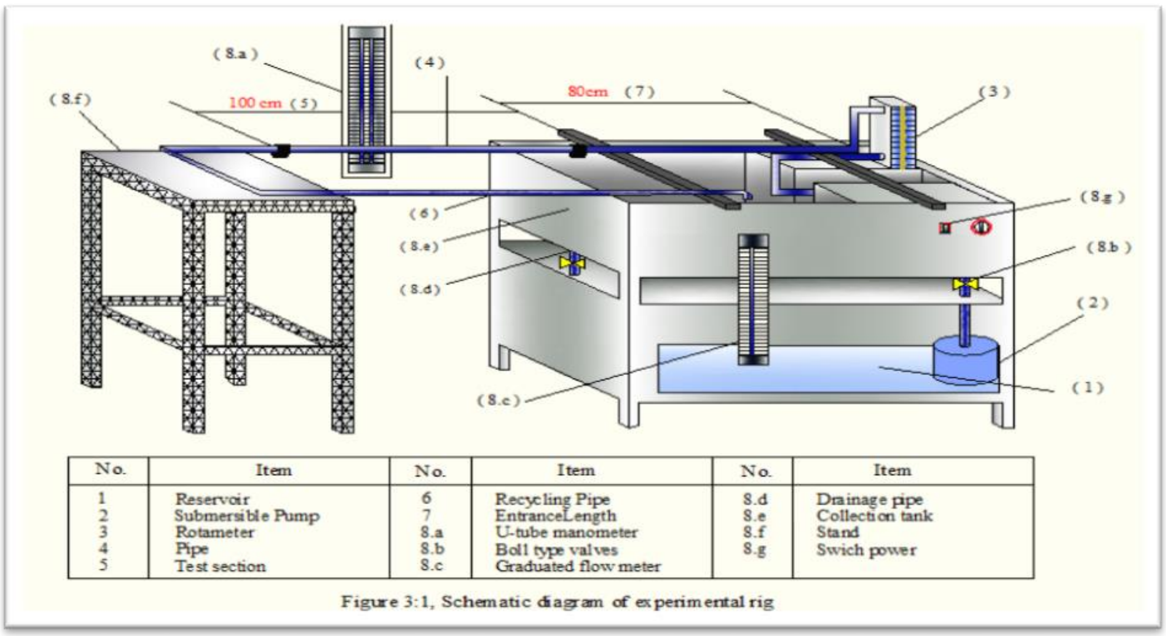

Fig. 1. Schematic diagram of experimental rig

Results and Discussion

A laboratory circulation closed loop system was used to investigate the effectiveness of drag-reducing additive in water solution under turbulent pipe flow. Since turbulent flow is necessary for drag reduction to occur, the system was designed for high Reynolds numbers. Drag-reduction efficiency of CMC, dissolved in water had been studied in turbulent flow as a function of polymer concentration. This concentration ranged from 20 up to 85wppm which might have been economically feasible for commercial applications [13]. Within the concentrations used, Newtonian behavior was observed for all polymer solutions. Higher concentrations could lead to Non-Newtonian fluids, which have different behavior, as pseudo plastic or diluents.

Figure (2) shows that percentage drag-reduction increases gradually as polymer concentration increases for used pipe . This phenomenon can be explained by the elastic-sub layer model theory of Virk [14]. This sub layer starts to grow with increasing additive concentrations, due to an increase in the number of available polymer molecules.

The trend of percentage drag reduction increase with concentration increase is about the same for all flow rates studied as shown in Figure (2) .The maximum percentage drag-reduction about 17.3 %, was achieved in 21.4 mm I.D pipe diameter at 85wppm and Reynolds number equal to 36873 as shown in Figure (3). This behavior agrees with Berman and his workers [15,16], who reported, that an increase in Reynolds number leads to an increase in the strain rate and a decrease in the time scale

Figure (2), summarizes the effect of polymer concentration on percentage throughput increase at different flow rates. A noticeable increase in the pumpability of solvent was achieved, which is caused by addition of small amounts of CMC to the fluid. Polymer concentration effect is initial for increasing flow rate capacity.

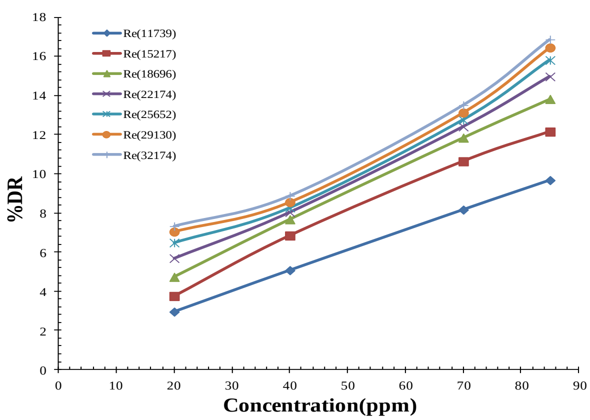

Fig. 2. Effect of concentration on percent drag reduction through 21.4 mm I.D pipe

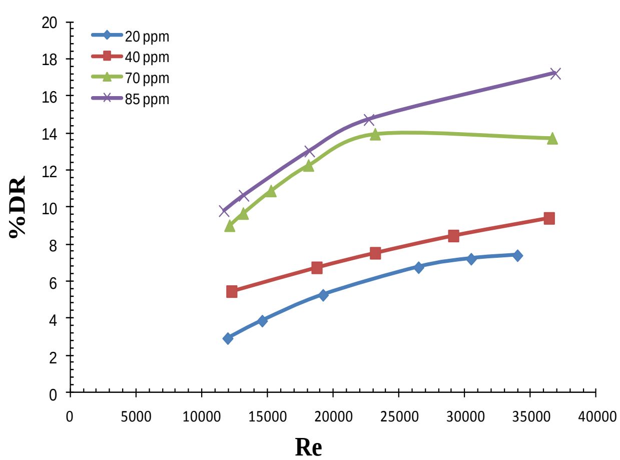

Fig. 3. Effect of Reynolds number on percentage drag reduction

Moreover, these polymer threads have a high viscoelasticity and they may cause on interaction with turbulent eddies and consequently, a remarkable drag-reduction was observed. It is fair to say, that this effect is not well clear in Figure (3), because of low polymer concentration.

The drag-reduction properties of solutions could be explained as the fanning friction factor versus solvent Reynolds number. The use of Reynolds number based on the solvent viscosity and pipe diameter provides a direct indication of the degree of drag-reduction. An attempt was made to correlate the friction factor as a function of Reynolds number, for the considered polymer concentrations and pipe diameters. The friction factor was calculated as follows:

$$f = \frac{\Delta h * 2 * g}{1} \frac{1}{u^2} \frac{D}{L} \quad \text{.............................(8)}$$

The friction factor is usually correlated as a function of Reynolds number as shown in the following formula:

$$f = a(\mathrm{Re})^b \quad \text{.....................................(9)}$$

In accordance with the above formula and by using appropriate software program, the constants a, b had been found of untreated of water Equation (11) and treated with polymer Equation (12) therefore, the formula becomes:

$$f = 0.316(\mathrm{Re})^{-0.25} \quad \text{..............................(10)}$$

$$f = 0.2566(\mathrm{Re})^{-0.25} \quad \text{..............................(11)}$$

$$f = 0.783(\mathrm{Re})^{-0.38068} \quad \text{...........................(12)}$$

The effect of polymer additives with different concentrations on friction factor as function of Reynolds number are plotted in figures (4) for (21.4mm), I.D pipe. This figure, show that for untreated solvent friction factor values lies near Blasuis asymptote, while by adding a minute amounts of polymer into the flow, the friction factor values were positioned below Blasius asymptote towards the maximum drag reduction region which is represented by “Virk asymptote”.

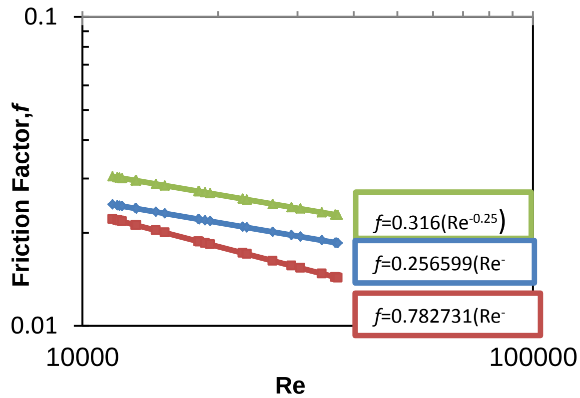

Fig. 4. Effect of polymer additives with different concentration on friction factor as function of Re for 21.4 mm pipe diameter

The Mixing Length Ratio

The procedure described earlier is used to find the values of R_c for a given Reynolds number and a given polymer concentration such that the numerical and experimental results coincide. The value of R_c obtained in this manner are correlated with Re and CMC concentrations as follows:

$$COFF.=a(Con.)^3+b(Con.)^2+c(Con.)+d \quad ......(13)$$

Where
Con.: Concentration of CMC in ppm
a,b,c&d : Constants

For each value of coefficient and concentration, the ratio of R_c as function of Reynolds number, were found by the equation listed below

$$R_c=A\,Re^2 + B\,Re + C \quad ....(14)$$

The values of Rc for each Reynolds number are summarized in Table (2) depending on the coefficients values for each concentration.

Table 1. The values of constants of equation (13&14)

Coef.	Constants			
	A	b	c	d
A_i	-6.364E-15	1.012E-12	-4.878E-11	8.205E -10
B_i	2.614E-10	-4.293E-08	2.128E-06	-4.134E -05
C_i	-1.81E-06	0.0003	-0.018	1.316

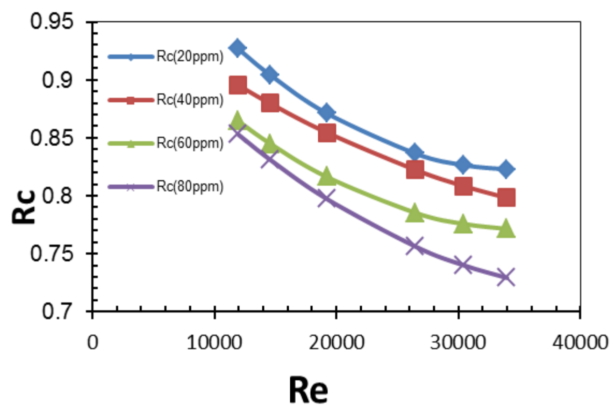

Fig. 5. Effect of Reynolds number on Ratio (lp / l) of CMC

Velocity Profile

Figure (6), shows the velocity distributions of the flow for both the treated and untreated fluids. it has already been seen that the treated fluid has a friction factor lower than that of the untreated fluid .This is attributed basically to the velocity profile near by the wall of the pipe and its gradient according to the shear stress law, the velocity profile for the treated fluid should be less step than that of the pure fluid. This is quite clear in the enlarged view of the velocity profiles shown in Figure (7). The additive has retarded the fluid in the wall region.

According to conservation principles the flow maintains its rate by accelerating its particles in the core region of the pipe. This fact can be seen very clearly in the enlarged view of the velocity profile near the pipe centerline as show in Figure (8-a,b).

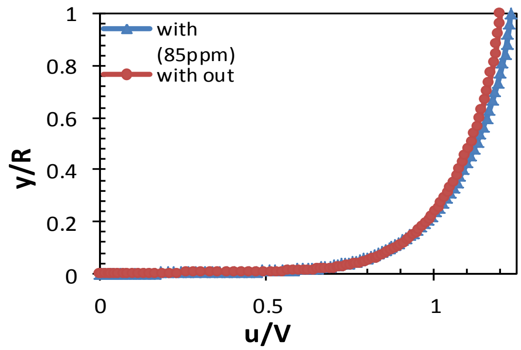

Fig. 6. Effect of Reynolds number on velocity profile with and without polymer for values of u/V ranged (0-1.2)

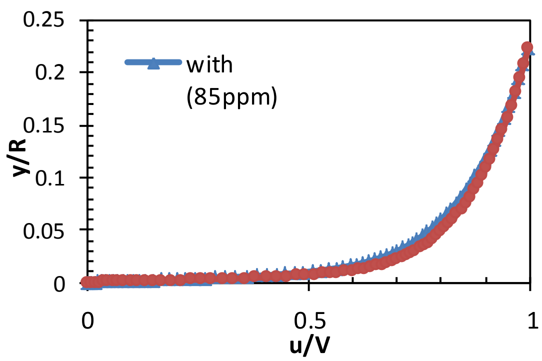

Fig. 7. Effect of Reynolds number on velocity profile with and without polymer for values of u/V ranged (0- 1.0)

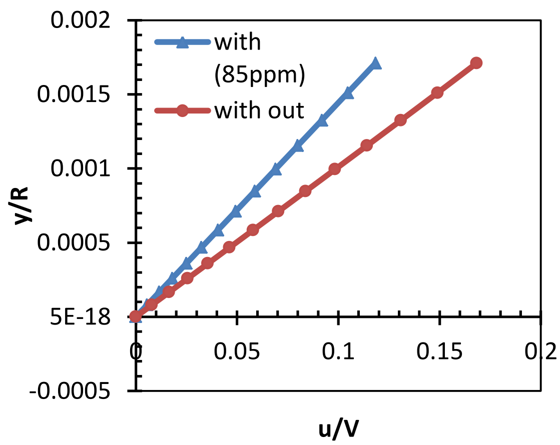

Fig. 8a. Effect of Reynolds number on velocity profile with and without polymer for values of u/V ranged (0- 0.2)

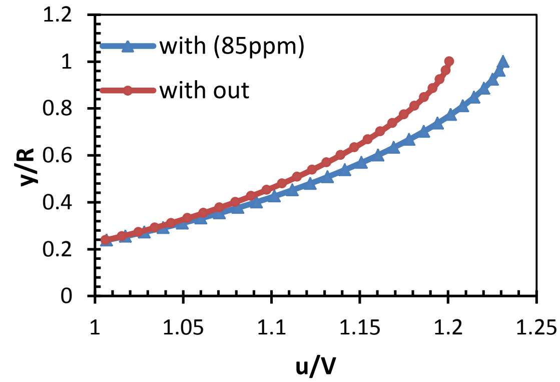

Fig. 8b. Effect of Reynolds number on velocity profile with and without polymer for values of u/V ranged (1- 1.25)

Conclusions

The efficiency of CMC as drag-reducing agents is strongly dependent on its concentration and flow velocity.

Percentage drag-reduction increases with increasing in concentration at given velocities. Values of calculated fanning friction factor for CMC treated water positioned toward Virk line for maximum drag-reduction, especially for high concentrations in 21.4mm I.D pipe. The fanning friction factor correlated as function of Reynolds number, resulted in good agreement with experimental observations. A mixing length ratio R_c is introduced to include the effect of the drag reducing agent to the turbulence mixing length. An empirical correlation for R_c has been obtained as a function of Reynolds number and the drag reducing agent calculation. It is found that the equation has acceptable values of AAPD as it is compared with experimental data.

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