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Heat Transfer in Laminar Pulsating Annular Flow of Drag Reducing Dilute Polymer Solutions.

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HEAT TRANSFER IN LAMINAR PULSATING ANNULAR FLOW OF DRAG REDUCING DILUTE POLYMER SOLUTIONS

"انتقال الحرارة في السريان الرقائقي النبضي الحلقي لمحاليل مخففة من البوليمرات المخفضة للجر الاحتكاكي"

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خلاصة :

يقدم هذا البحث دراسة معملية لانتقال الحرارة في السريان النبضي الرقائقي الحلقي لمحاليل مخففة من البوليمرات المخفضة للجر الاحتكاكي. أجريت الدراسة علي مبادل حراري أنبوبي في منصة اختبار مزودة بنظام إلكتروني لتجميع البيانات من خلال تجميع الإشارات الواردة من حساسات قياس درجات الحرارة والضغط والتدفق وتوصيلها بالحاسب الآلي وتخزينها لمعالجتها وتحليلها. وقد أجريت التجارب عند قيم مختلفة لرقم رينولدز، ولمحاليل مخففة من البولي أكريلاميد بتركيزات مختلفة تتراوح ما بين ١٠ الي ١٠٠ جزء في المليون. كما أجريت التجارب علي السريان المنتظم للماء كمائع نيوتوني قياسي بغرض المقارنة.

وقد أوضحت نتائج هذه الدراسة أن انتقال الحرارة للسريان الرقائقي الحلقي المنتظم لا يتأثر بالإضافات المخفضة للجر الاحتكاكي حتى تركيز ١٠٠ جزء في المليون من البولي أكريلاميد، بينما في السريان النبضي للمحاليل المخففة من البولي أكريلاميد فقد لوحظ زيادة معامل انتقال الحرارة (رقم نوسلت) مقارنة بالسريان المنتظم في المدى من ٢٠٠ إلى ١٢٠٠ لرقم رينولدز. وعند مقارنة ذلك بالسريان النبضي للماء تبين أن الإضافات المخفضة للجر الاحتكاكي تخمد تأثير النبض علي انتقال الحرارة في السريان الرقائقي.

ABSTRACT:

Heat transfer in pulsating laminar flow is experimentally investigated for the flow of drag reducing polyacrylamide dilute solutions in the annulus of a tubular heat exchanger. Drag reducing polymer solutions flow through the annulus of the tubular heat exchanger, while hot water as a heating source flows steadily through the inner pipe. Different polymer concentrations are considered: 10, 25, 50 and 100 wppm. Experiments are carried out at a flow pulsation of frequency of 1 Hz. This work covers a range of Reynolds number from Re=200–1200. Steady and pulsating flows of drag reducing polymer solutions as well as steady and pulsating water flows are considered for the sake of comparison. The data of experimental measurements are supplied to a personal computer via a data acquisition system, for further analysis.

The results of this work show that for steady laminar annular flow, it is hardly to detect any difference between Nusselt numbers of polymer solution flow and those of water flow. For the pulsating flow of drag reducing polymer solutions, a noticeable increase in Nusselt number of laminar annular flow is found compared with those of steady flow. Such increase in Nusselt number is slightly dependent on Reynolds number, such that for pulsating flow $Nu \propto Re^{0.65}$ compared with $Nu \propto Re^{0.55}$ for steady flow. When these results are compared with those of the pulsating flow of water, a reduction in Nusselt number is found. This means that drag reducing additives dampen the influence of flow pulsation on heat transfer due to the damping of such local turbulent eddies produced by drag reducing additives.

Key words: Heat transfer, drag reducing, laminar, and pulsating flow.

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1. INTRODUCTION

Drag reduction is a field of study in many engineering disciplines, such as mechanical, aeronautical, aerospace, marine technology, automobile ...etc. The aim of the drag reduction is to improve the fluid-mechanical efficiency using passive and active techniques. The drag is related to flow noise, and heat and mass transfer so that other benefits can also be obtained during the process of drag reduction.

The addition of trace amounts of polymer dissolved into a fluid can reduce frictional losses by as much as 80%. The mechanism however is that the polymer near the wall became fully stretched, due to the large strain rates near the wall, and these stretched polymers increased the elongational viscosity of the fluid in this region. This leads to an increase in the buffer layer thickness and it showed that such a situation can result in a drag reduction.

Drag reducing fluids are found in nature, such as non-Newtonian and viscoelastic fluids. Most of industrial fluids are non-Newtonian with drag reduction characteristics. The excellent reviews by Hoyt (1974) and Virk (1975) gave the necessary fundamentals of the drag reduction phenomenon. Many experimental studies have been carried out to study heat transfer and fluid flow of drag reducing polymer flow. The work of Smith et al (1969), Matthys et al (1987), Kawack et al (1981), Deberule et al (1972), Rabie (1991) and Rabie et al (1986, 1989) are just examples. Most of these studies were carried out at turbulent flow conditions to get the benefit of the enormous frictional drag deductions to associate the turbulent flows of such fluids. A large reduction in heat transfer as well as frictional drag is found. Axouz et al (1996) studied heat transfer characteristics of guar gum and hydroxypropl guar solutions flowing in the inner pipe of a double pipe heat exchanger. Results show a significant difference between the heat transfer coefficient of water and those of the polymer fluids tested. Gasljevic et al (1993) investigated the performance of a plate heat exchanger, a shell-and-tube heat exchanger and a tube-and-fin heat exchanger operating with drag reducing surfactant solutions. The results suggest that the heat transfer and friction characteristics are greatly dependent on geometry and flow conditions and could therefore be controlled. It also shows that an overall high drag reduction in the system could be achieved without sacrificing too much of the heat exchanger performance.

Pulsating flow characteristics have received a considerable attention in the recent years. Pulsating flow is important in biological and industrial applications. Some investigations are carried out to study heat transfer in laminar pulsating flow (Kim et al (1993), Ligrani et al (1996), Moschandreou et al (1997), Guo et al (1997), Hafez et al (2000), Hemeada et al (2000) and Rabie et al (2001)). However, the results are limited and contradicting. None of these investigations considered the influence of flow pulsation on heat transfer characteristics of drag reducing fluids.

Knowledge of the influence of flow pulsation on heat transfer is essential for fluid with drag reduction characteristics. Therefore the objective of the present work is to study, experimentally, the effect of flow pulsation on the hea. transfer in laminar annular flow of drag reducing polymer solutions. Polyacrylamide as a strong drag reducing additive is used. It exerts its maximum effect at dilute concentrations as low as 10-20 wppm.

2. EXPERIMENTAL SET-UP AND PROCEDURE TECHNIQUE

The experimental set-up consists mainly of a tubular heat exchanger, hot water circuit, drag reducing fluid circuit and plunger pump. A schematic diagram for the experimental set-up is shown in Fig. (1). The type of the drag reducing fluid is Polyacrylamide of M.W. (Molecular Weight) over $5*10^6$, diluted with water at different concentrations ranging from 10 to 100 wppm (part per million by weight). The experimental set-up is provided with a data acquisition system, which is connected to a personal computer to collect experimental data for storage and further analysis. The system is provided with sensors to measure the temperatures, pressures and mass flow rates for both hot fluid and drag reducing fluid flows. All details for the tubular heat exchanger, hot water circuit and plunger pump are found in Rabie et al (2001). The drag reducing fluid (polymer solution) flowing through the annulus of the tubular heat exchanger may be pulsating or steady. The pressure at test section inlet is measured as function of time by a pressure sensor, which is connected to data acquisition system. For steady flow case, polymer solutions are allowed to flow through the test section directly from the constant head tank (fixed at 2 m higher than test section inlet).

For each experiment, the experimental set-up is allowed to equilibrate for approximately one hour until steady state condition is reached (the fluctuation in temperatures was about ± 0.1 °C). Once the system reached the desired steady state condition, the required measurements were taken. These measurements are temperatures, pressures and mass flow rates at different positions, as shown in Fig. (1). The uncertainties in the quantities measured directly, including test section dimensions, pressures, temperatures and flow rates for the hot and drag reducing fluid are calculated. The accuracy of K type thermocouples used in temperature measurements is ± 0.1 °C, thus, the uncertainty of temperature difference was estimated to be about 0.142 °C. The accuracy of the electronic turbine flow meters is ±0.01 Lit/min, which is equivalent to 0.3 % of the full scale. The largest calculated uncertainties in the current investigation, were less than 2.5 % for Nusselt number and 3.5 % for Reynolds number.

3. RESULTS AND DISCUSSIONS

The object of the experimental measurements is to determine the heat transfer characteristics of drag reducing, laminar pulsating fluid flow in an annular duct. Allowing the hot water to flow through the inner tube of the tubular heat exchanger carries out heating of the annular flow. The hot water flow conditions are kept constant at Re= 14000 during the experimental work. Therefore, the variation of the inner heat transfer coefficient is almost negligible.

Typical instantaneous pressure at test section inlet versus time for drag reducing fluid at constant frequency 1 Hz is shown in Fig. (2). The variation of Nusselt number (Nu) versus Reynolds number (Re) for steady laminar flow of drag reducing polyacrylamide dilute solutions is shown in Fig. (3) compared with that for water. The concentration of the polymer solutions varies from 10 wppm to 100 wppm. It is clear from this figure that, Nusselt number increases with increasing Reynolds number for both the drag reducing fluid and water. For polymer concentrations considered, results exhibit a slight decrease in Nusselt number compared with that of water flow. However, this decrease in Nusselt number is so small as to be neglected as it is within the experimental error. This result is expected since the influence of drag reducing additives on both momentum and heat transfer is limited to turbulent flow conditions.

The range of Reynolds number considered for both drag reducing fluid and water annular flow is 200-1200. Curve fitting of the experimental results in the considered range of Reynolds number and polymer concentrations shows that Nusselt number is related to Reynolds number for steady flow as:

$$Nu = 0.215\ Re^{0.55} \qquad (1)$$

The independence of Nusselt number of steady laminar annular flow upon polymer is clearly demonstrated when the dimensionless parameter $Nu/Re^{0.55}$ is plotted as function of polymer concentration in figure (4) and as function of Reynolds number in figure (5).

Figure (6) presents the results of Nusselt number of both pulsating and steady annular laminar flow of drag reducing polyacrylamide solutions as function of Reynolds number. Different dilute polymer concentrations are considered. The results show that flow pulsation at a frequency of 1 Hz causes an increase in Nusselt number for laminar annular flow with drag reducing fluid compared with steady flow conditions similar to that of water (Newtonian fluid) given in Rabie et al (2001). The difference in Nusselt number of steady and pulsating flow exhibits slight dependence on both polymer concentration and Reynolds number. In order to clarify the nature of such dependence. the results of the dimensionless parameter $Nu/Re^{0.55}$ for both steady and pulsating flow of drag reducing polymer solutions at different concentrations is plotted as function of Reynolds number, as shown in figure (7). This figure.shows that the difference in Nusselt number of pulsating and steady polymer solutions increases with Reynolds number. This means that the Nusselt number of pulsating polymer solution flow depends on Reynolds number raised to power higher than 0.55. A best fit for the experimental results of pulsating flow polyacrylamide solutions at different concentrations shows that Nusselt number may be related to Reynolds number as:

$$Nu = 0.127\ Re^{0.65} \qquad (2)$$

The dependence of Nusselt number of the pulsating flow of drag reducing polymer solutions upon polymer concentration is demonstrated when $Nu/Re^{0.65}$ is plotted as function of polymer concentration as shown in figure (8). It shows that, polyacrylamide additives dampen the effect of flow pulsation on heat transfer. This is demonstrated by the reduction of $Nu/Re^{0.65}$ for the range of polymer concentration considered, compared with those of water flow (at 0 wppm). This influence is constant and is independent of polymer concentration. This result is in a full agreement with the fact that polyacrylamide solutions exhibits its maximum influence as a turbulent flow drag reducer at concentrations of 10-100 wppm.

Figure (9) shows the results of Nusselt number with laminar pulsating annular flow of polyacrylamide solutions presented as a plot of $Nu/Re^{0.65}$ versus Re, in comparison with those of water flow given by Rabie et al (2001). It is clear that, drag reducing polyacrylamide additives dampen the influence of flow pulsation on Nusselt number by almost 12.5%. This is also demonstrated by the huge damping of high frequency oscillations exhibited in the pressure signal of polyacrylamide solution pulsating flow during suction and delivery phases, as compared with those of water pulsating flow. Such comparison is shown in figure (10).

The power spectrum of the pressure signals is presented in figure (11). This is determined by the Fast Fourier Transformation *"f(k)"* of the fluctuating component of the pressure signal *"F(t)"* as:

$$f(k) = \frac{1}{n} \sum_{j=1}^{n} F(t).exp(2\pi \frac{k}{n} t) \qquad (3)$$

Where:

$$F(t) = \frac{p'(t).p'(t)}{< p'(t).p'(t) >}$$

$$p'(t) = P(t) - < P(t) >$$

The power spectrum of the pressure given in figure (11) clearly demonstrates the large damping of the high frequency fluctuations exhibited in polymer solution pulsating flows compared with that of water pulsating flow. This may suggest that the increase in heat transfer due to flow pulsation is caused by local turbulent eddies generated by flow pulsation. This may lead us to postulate that the reduction in heat transfer in laminar pulsating flow for polymer solutions compared with that of water pulsating flow is attributed to the damping of such local turbulent eddies produced by drag reducing additives.

4. CONCLUSIONS

An experimental investigation was conducted to determine the effect of Reynolds number and polymer concentrations on the Nusselt number for drag reducing fluid in case of pulsating flow compared with steady laminar flow. Water was used as working fluid for the hot fluid and drag reducing fluid (polymer solution) was used as a cold fluid in a tubular heat exchanger. For the considered range of Reynolds number from 200 to 1200 an empirical correlation for Nusselt number as a function of Reynolds number was obtained for pulsating drag reducing fluid.

The results show that, Nusselt number for drag reducing pulsating flow increases than that for steadily drag reducing fluid flow due to local turbulent eddies generated by flow pulsation. But there is no effect for polymer concentration on Nusselt number in pulsating and steady flow compared with water. Nusselt number for drag reducing pulsating flow decreases than that for pulsating water flow in laminar region due to the damping of such local turbulent eddies produced by drag reducing additives.

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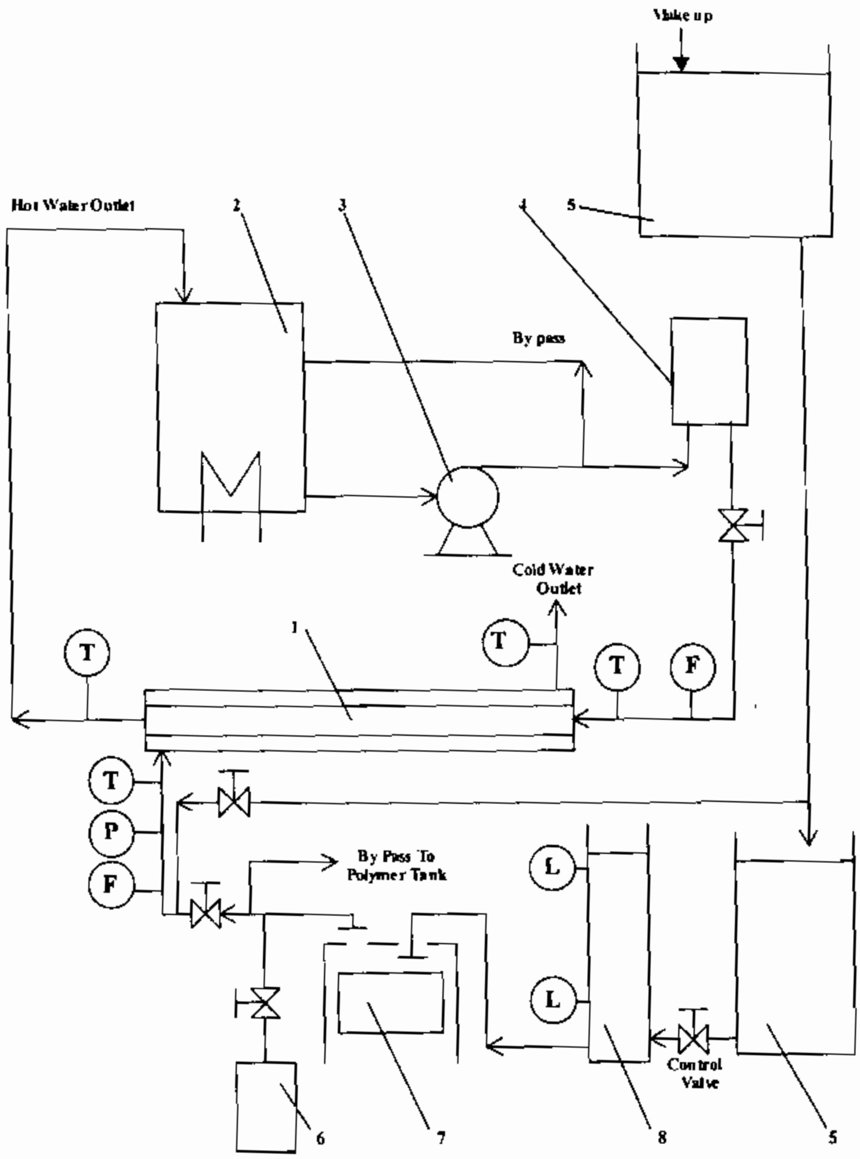
NOMENCLATURE

D : Hydraulic diameter, m
$f(k)$: Fourier transform function (vector containing the FFT coefficients), -
$F(t)$: Fluctuating pressure function (vector), -
h : Heat transfer coefficient, $W/m^2 . ^oC$
k : wave number per second (frequency), 1/s
k : Thermal conductivity, $W/m. ^oC$
n : Number of points in the fluctuating pressure function (vector), -
Nu : Nusselt number (Nu=hD/k), -
$P(t)$: Instantaneous pressure, Pa
$<P(t)>$: Time average (mean) of the pressure $P(t)$, Pa
$p'(t)$: Fluctuating component of the pressure $P(t)$, Pa
$<p'(t).p'(t)>$:Mean square of the fluctuating pressure, $(Pa)^2$
Re :Reynolds number ($Re=\rho uD/\mu$), -
t :Time, s
T : Temperature, ^oC
u : Velocity, m/s
U : Overall heat transfer coefficient, $W/m^2 . ^oC$

Greek symbols

μ : Dynamic viscosity of the fluid, kg/m.s
ρ : Density, kg/m^3



1	Tubular heat exchanger	7	Plunger pump
2	Electric water heater	8	Volumetric tank
3	Hot water circulating pump	T	Temperature sensor
4	Hot water circulator	F	Flow rate sensor
5	Constant head polymer tank	L	Level sensor
6	Pulsation damper	P	Pressure sensor

Fig. (1) Schematic diagram for the experimental set-up

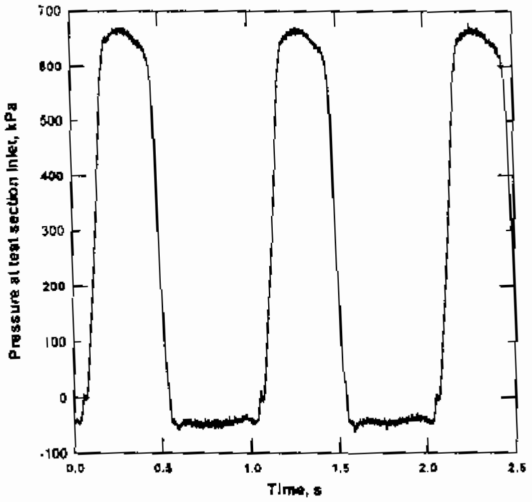


Fig. (2) Typical pressure at test section inlet versus time for drag reducing fluid at constant frequency (1 Hz)

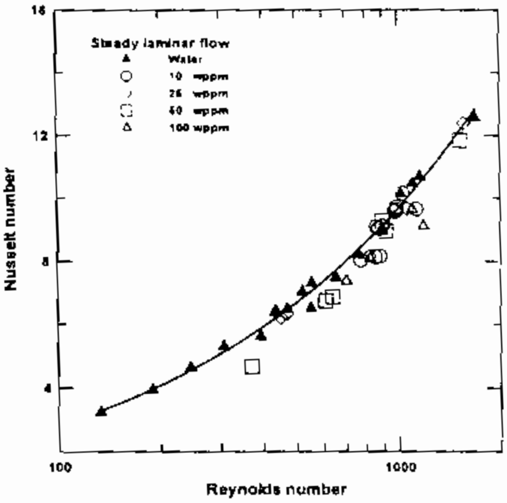


Fig. (3) Nusselt number versus Reynolds number for drag reducing laminar steady flow

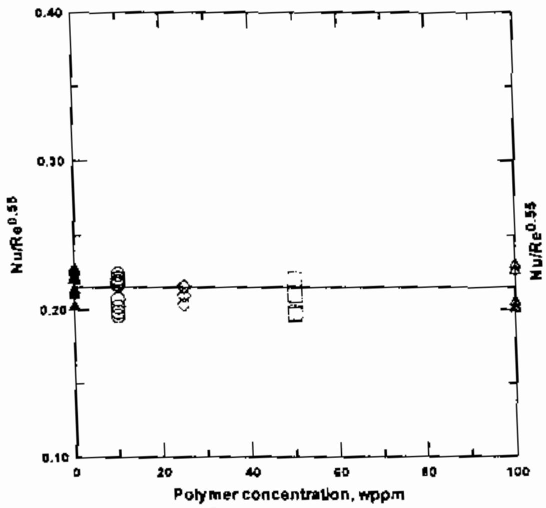


Fig. (4) $Nu/Re^{0.55}$ versus polymer concentration for drag reducing laminar steady flow

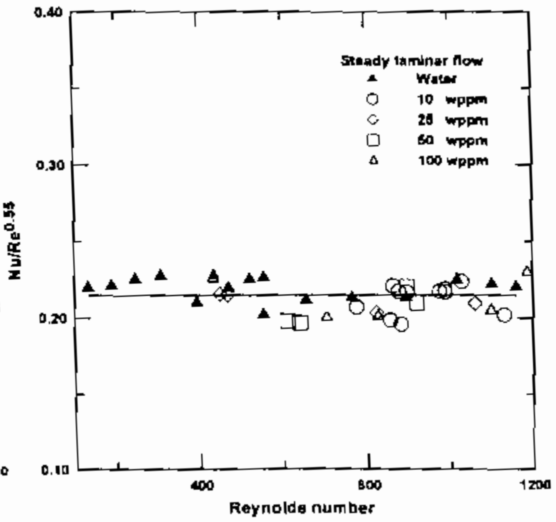


Fig. (5) $Nu/Re^{0.55}$ versus Reynolds number for drag reducing laminar steady flow

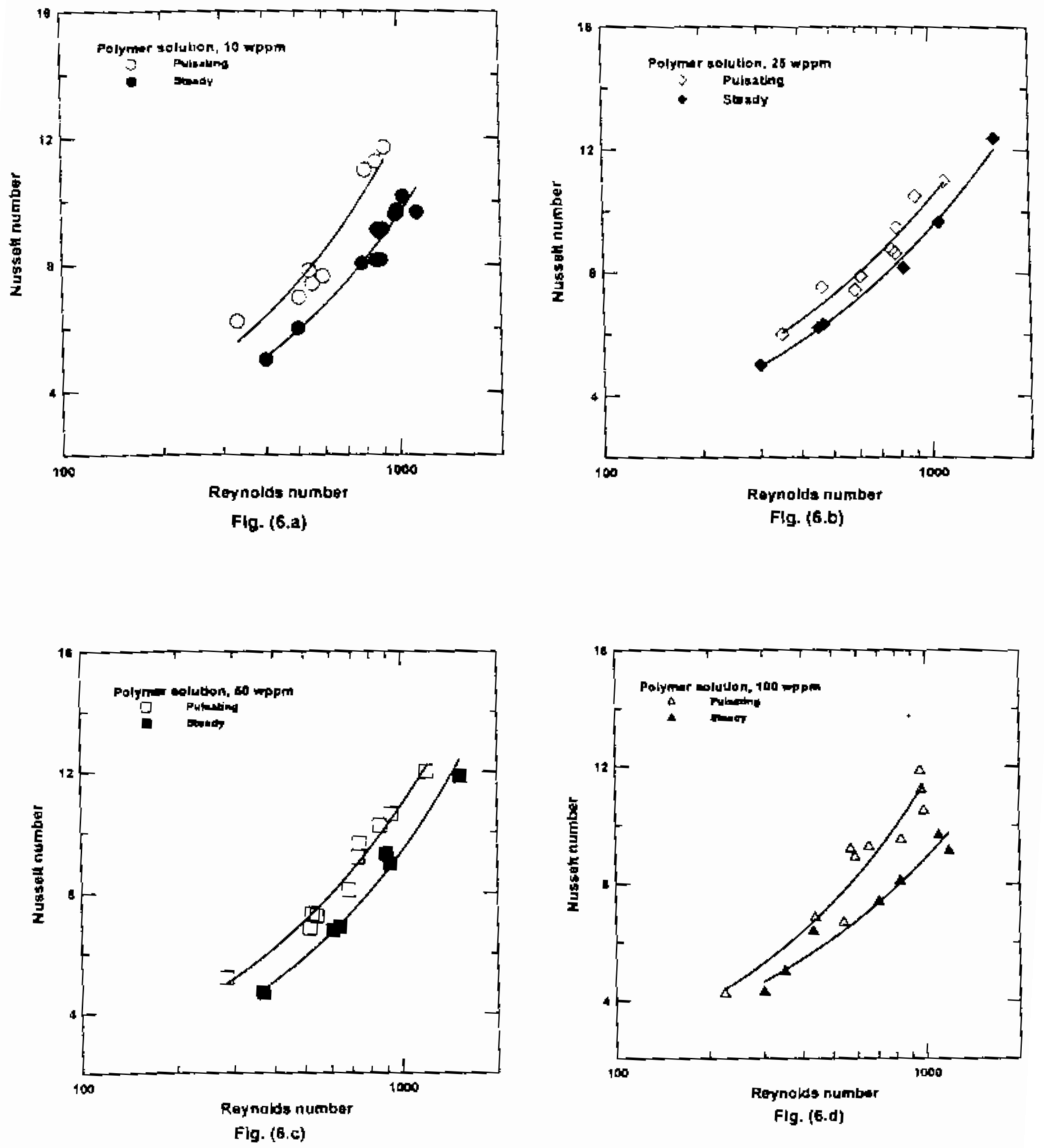


Fig. (6.a)

Fig. (6.b)

Fig. (6.c)

Fig. (6.d)

Fig. (6) Nusselt number versus Reynolds number for drag reducing fluid

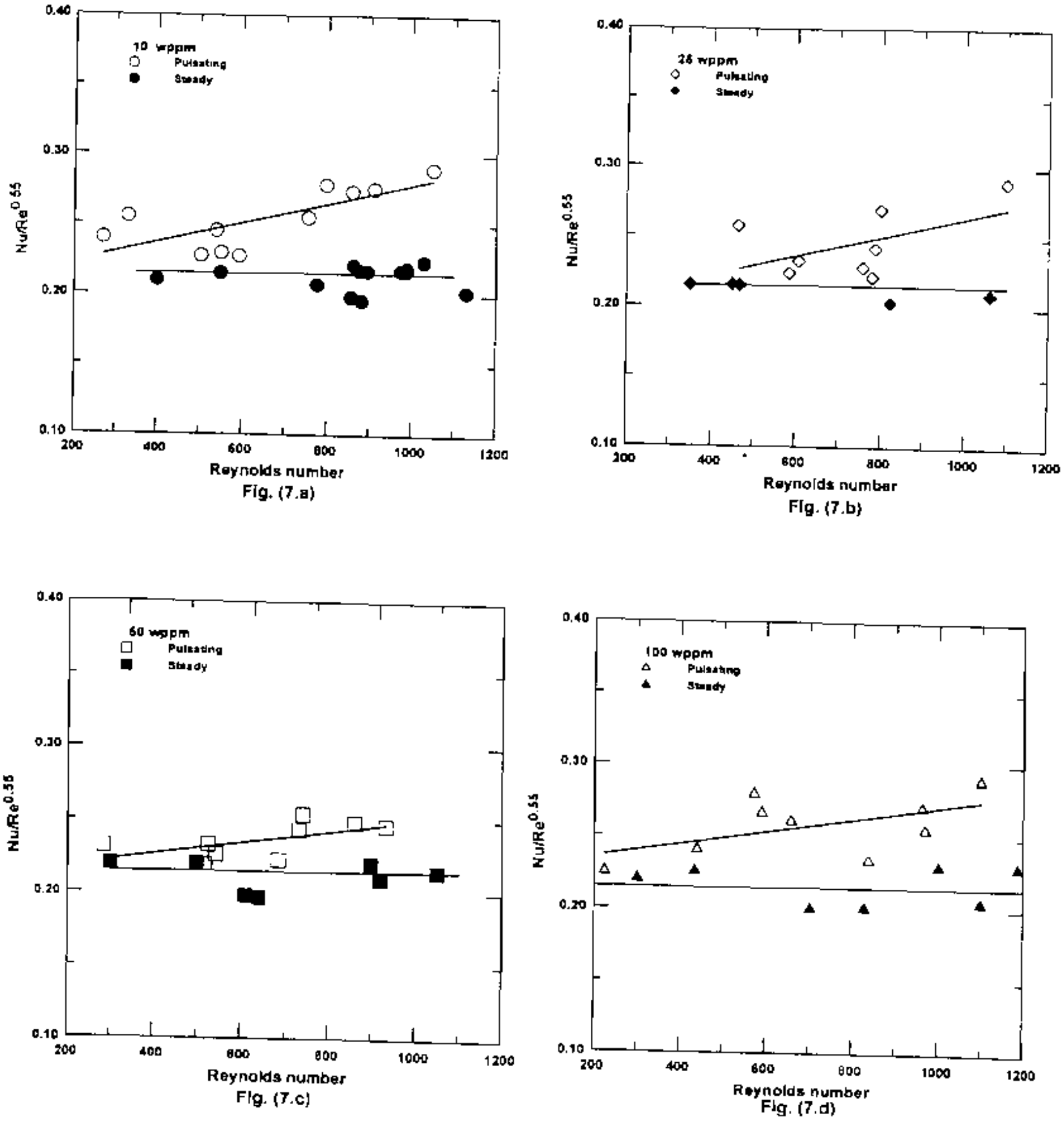


Fig. (7.a)

Fig. (7.b)

Fig. (7.c)

Fig. (7.d)

Fig. (7) $Nu/Re^{0.55}$ versus Reynolds number for drag reducing fluid

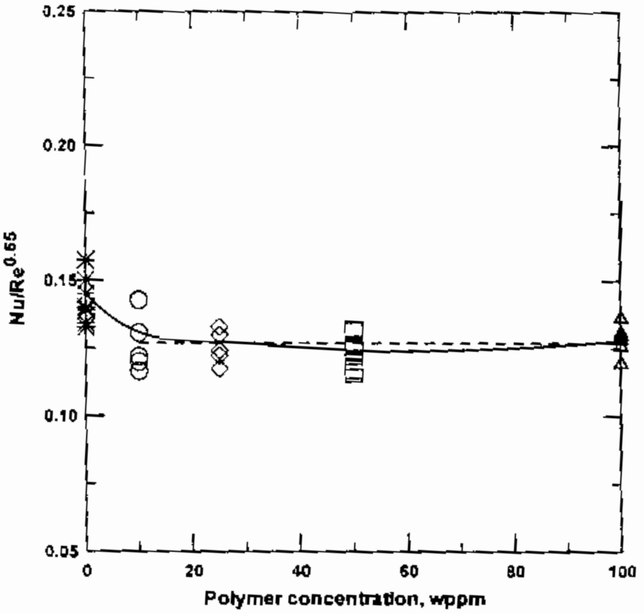


Fig. (8) $Nu/Re^{0.65}$ versus polymer concentration for drag reducing laminar pulsating flow

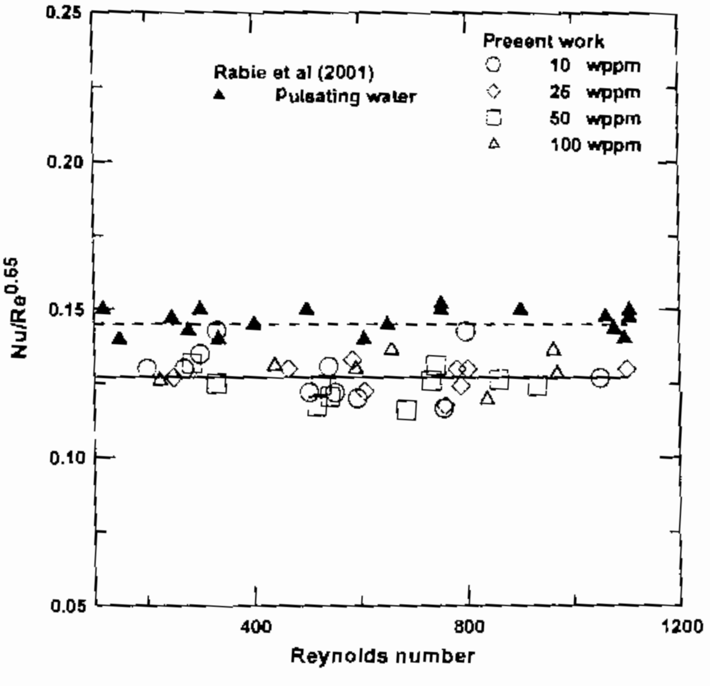


Fig. (9) Comparison between drag reducing pulsating fluid flow with pulsating water flow (Rabie et al 2001)

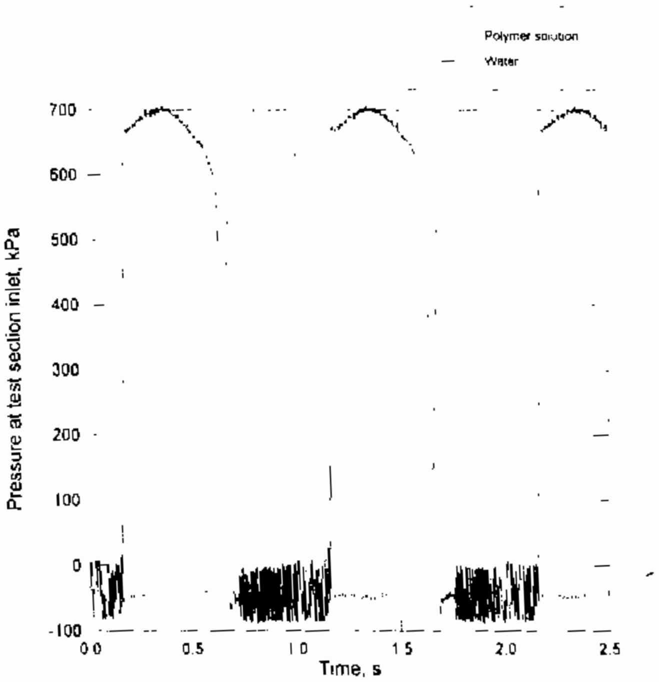


Fig. (10) Instantaneous pressure at test section inlet versus time for polymer solution (50 wppm) compared with water

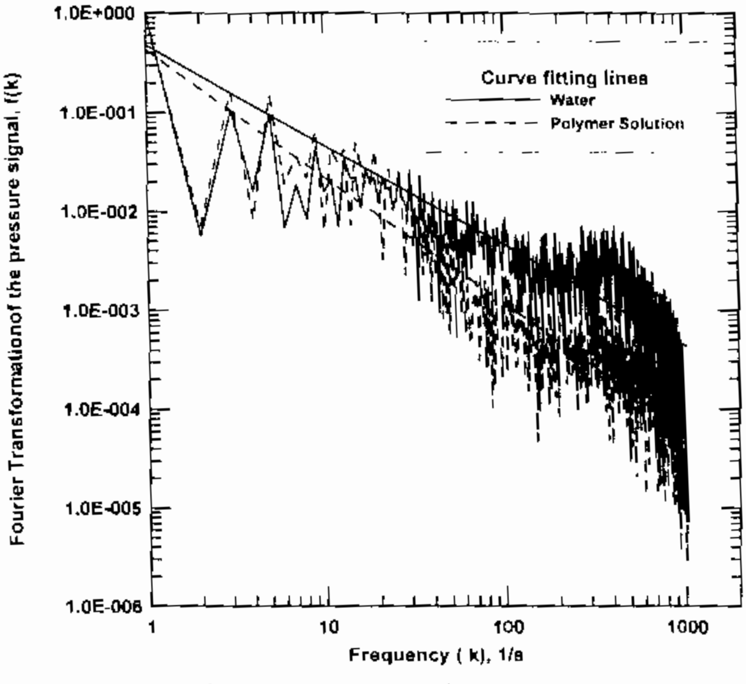


Fig. (11) Power spectrum for the pressure signals