

Turbulent heat transfer of polyacrylamide solutions in the thermal entrance region of circular tube flows

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Abstract—The purpose of this article is to investigate experimentally the heat transfer characteristics of drag reducing polymer solutions in the thermal entrance region of circular tube flows. Two stainless steel tubes with $L/D = 710$ and 1100 are used for the heat transfer tests. Testing fluids are aqueous polyacrylamide solutions of Separan AP-273 with concentration ranging from 300 to 2000 w.p.p.m. The main assertion of the present study is that the order of magnitude of the thermal entrance length of the maximum drag reducing polymer solutions is much higher than that of Newtonian fluids in turbulent tube flows. Also, by introducing a new dimensionless parameter, the product of Reynolds number and Graetz number, all experimental data are recast in a newly defined parameter.

INTRODUCTION

THE THERMAL entrance length of the turbulent tube flow for a drag reducing polymer solution is an important factor in designing heat exchangers. Yoo and Hartnett [1] reported that the turbulent thermal entrance length of a viscoelastic fluid is much longer than that of a Newtonian fluid and a purely viscous non-Newtonian fluid. Ng *et al.* [2] who used heat transfer test sections with dimensionless lengths (L/D) of 430, 475 and 620, could not reach the fully developed region until $L/D = 430$. Cho and Hartnett [3], who employed a heat transfer test section with an L/D of 620, concluded that the dimensionless thermal entrance length of viscoelastic fluids is about 400–500, and also presented the minimum heat transfer asymptote based on the heat transfer results measured at $L/D = 430$. Toh and Ghajar [4] showed that the thermal entrance length of the viscoelastic fluid might be longer than $L/D = 600$. Reviewing the experimental works in the literature there needs to be some more experimental surveys on the thermal entrance length of a drag reducing viscoelastic fluid corresponding to the maximum heat transfer reduction asymptote.

An aqueous polymer solution which exhibits viscoelastic characteristics is degraded notably while the polymer solution is forced to flow in the flow loop. The degradation results in increases of the friction factor and heat transfer coefficient. Major discrepancies of the reported experimental results in the above litera-

ture are probably caused by variations of the fluid properties and the flow characteristics due to degradation. To minimize the degradation effects in the heat transfer experiments, Kwack *et al.* [5] conducted experiments with the once-through system and concluded that the polymer solution of Separan AP-273 500 (w.p.p.m.) approached the minimum heat transfer asymptote. Kwack and Hartnett [6], by employing the recirculating flow loop system, reported that the effect of degradation on the friction factor is not serious for a fairly long time, but the effect on heat transfer is quite serious from the beginning. To present the results of the degree of degradation, Kwack and Hartnett [6] introduced the critical Weissenberg number. Most importantly, the degree of degradation can clearly be shown by measuring the characteristic time of a drag reducing polymer solution experimentally in viscometric flows [7].

The purpose of the present study is to determine the order of magnitude of the thermal entrance lengths and heat transfer coefficients of drag reduction polymer solutions corresponding to the maximum drag reduction asymptote of turbulent circular tube flows and to show the change of apparent viscosity and the characteristic time of the working fluids due to degradation.

EXPERIMENTAL

The flow system consists of a pump, two reservoirs, two test tubes, two mixing chambers, and a Venturi

NOMENCLATURE

| | | | |
|------------|--|----------------|---|
| C_p | specific heat at constant pressure | Re | Reynolds number, $\rho VD/\mu$ |
| D | tube diameter | V | mean velocity |
| f | fanning friction factor, $\tau/(\rho V^2/2)$ | w.p.p.m. | weight parts per million |
| g | gravitational acceleration | x | axial distance. |
| Gz | Graetz number, $(Re Pr D)/x$ | Greek symbols | |
| h | heat transfer coefficient | $\dot{\gamma}$ | shear rate |
| j_h | dimensionless heat transfer coefficient, $(Nu Pr^{2.3})/(Re Pr)$ | λ | characteristic time |
| k | thermal conductivity of fluid | μ | viscosity |
| L | tube length | μ_a | apparent viscosity |
| n | power law exponent | μ_0 | apparent viscosity at zero shear rate |
| Nu | Nusselt number, hD/k | μ_∞ | apparent viscosity at infinite shear rate |
| Nu_x | local Nusselt number | ρ | density of fluid |
| Nu_x | Nusselt number in the fully developed region | τ | shear stress. |
| ΔP | pressure difference | Subscript | |
| Pr | Prandtl number, $C_p\mu/k$ | a | based on the apparent viscosity. |

meter. The schematic diagram of the system is shown in Fig. 1. Test tubes are made of smooth stainless steel tubes, one of which with i.d. = 8.5 mm and $L/D = 712$, and the other with i.d. = 10.3 mm and $L/D = 1158$. They are directly heated by d.c. power supply to impose uniform heat flux boundary conditions on the wall. The flow system is constructed in such a way that the hydrodynamic and thermal boundary layers are developed simultaneously from the beginning of the test sections. The copper-constantan thermocouples are attached to the wall of test tubes with copper oxide cement to measure the local outside wall temperature. Thermocouple readings are recorded with a data logger which comprises 32 channels (Digistrip III). Details of the experimental set-up and the experimental procedure are given in ref. [8].

A capillary tube viscometer and falling ball viscometer are used to measure the viscous properties of fluids. Samples of the working fluids were regularly taken out of the flow loop during heat transfer experiments. Details of the capillary tube viscometer and

the falling ball viscometer are given in refs. [9] and [10], respectively.

Fluids tested are aqueous solutions of the high molecular weight polymer, Polyacrylamide Separan AP-273 (Dow Chemical Co. Ltd.), which is known to be very effective in reducing drag and heat transfer. Test fluids were made by dissolving the polymer powder in tap water and the concentration of polymer ranged from 300 to 2000 w.p.p.m.

RHEOLOGICAL PROPERTIES OF POLYMER SOLUTIONS

The viscous characteristics of viscoelastic fluid may be expressed by the power law model with two constants:

$$\tau = K(\dot{\gamma})^n. \quad (1)$$

The rates of shear and shear stress for laminar circular tube flow are given by

$$\dot{\gamma} = \frac{3n+1}{4n} \frac{8V}{D} \quad (2)$$

$$\tau = \frac{D\Delta P}{4L}. \quad (3)$$

The flow behavior index n is determined by the following equation:

$$n = \frac{d\{\ln(D\Delta P)/4L\}}{d\{\ln(8V/D)\}}. \quad (4)$$

The apparent viscosity is defined as the ratio of shear stress and shear rate at any given shear rate. The Reynolds number and the Prandtl number for a non-Newtonian fluid are defined on the basis of the apparent viscosity.

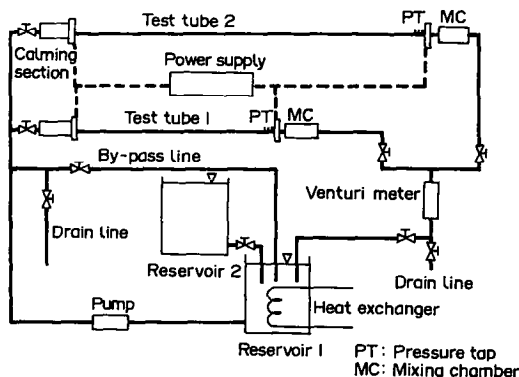


FIG. 1. Schematic diagram of the flow loop.

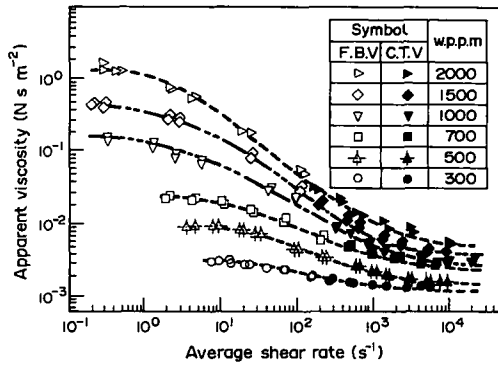


FIG. 2. Apparent viscosity vs average shear rate for aqueous polymer solutions.

$$\mu_a = \frac{\tau}{\dot{\gamma}} \quad (5)$$

$$Re_a = \frac{\rho V D}{\mu_a} \quad (6)$$

$$Pr_a = \frac{C_p \mu_a}{k} \quad (7)$$

The apparent viscosities of polymer solutions over the concentration range from 300 to 2000 w.p.p.m. are measured by a falling ball viscometer and a capillary tube viscometer. Viscosities at the high shear rate range are determined by the capillary tube viscometer (C.T.V.) and those at the low shear rate range by the falling ball viscometer (F.B.V.). The experimental results are illustrated in Fig. 2. The differences of zero shear rate viscosity and infinite shear rate viscosity increase as the concentration of polymer solution increases. The apparent viscosities decrease as the shear rate increases and for shear rates above 10 000 s⁻¹, the apparent viscosities show nearly constant values depending on polymer concentrations.

FRICION AND HEAT TRANSFER RESULTS

Experiments with water were conducted to confirm the validity of the experimental system. The friction factors are compared with the Blasius formula and the heat transfer results with the relations reported by Petukhov [11], Nu_p , and Sleicher and Rouse [12], Nu_{s-r} :

$$f = 0.079 Re^{-0.25} \quad (8)$$

$$Nu_p = Re Pr (f/2) / [1.07 + 12.7 (Pr^{2/3} - 1) \sqrt{f/2}] \quad (9)$$

$$Nu_{s-r} = 5 + 0.015 Re^a Pr^b \quad (10)$$

where

$$a = 0.88 - 0.24 / (4 + Pr)$$

$$b = 0.333 + 0.5 \exp(-0.6Pr).$$

The experimental results and the correlations are

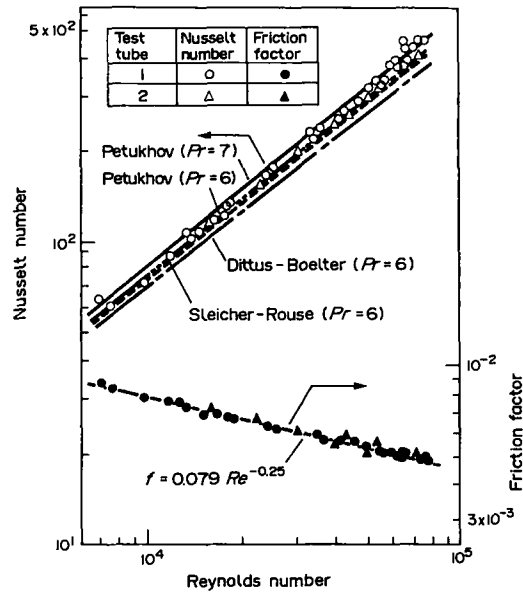


FIG. 3. Fully developed Nusselt numbers and friction factors vs Reynolds numbers for water.

shown in Fig. 3. The maximum deviations of friction factors compared with the Blasius formula range within ±5% and the Nusselt numbers range within ±6% to the Petukhov relation. The thermal entrance length of turbulent flow with a Newtonian fluid varies about 30–40 times the tube diameters from the entrance. The experimental results of a Newtonian fluid confirm the adequacy that the experimental system is suitable for experiments with polymer solutions.

Friction factors of polymer solutions as a function of Reynolds number are given in Fig. 4. Virk *et al.* [13] presented the maximum drag reduction asymptote for viscoelastic fluids, and Cho and Hartnett [3] presented another convenient correlation equation:

$$1/\sqrt{f} = 19.0 \log (Re_a \sqrt{f}) - 32.4 \quad (11)$$

$$f = 0.20 Re_a^{-0.48} \quad (12)$$

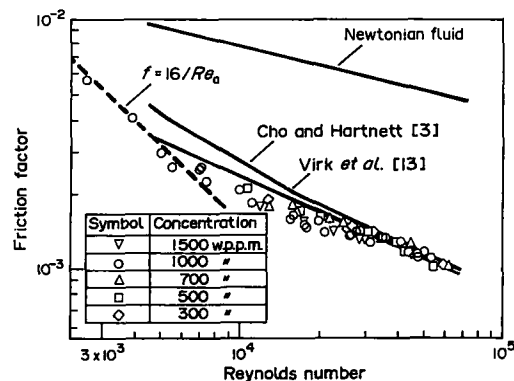


FIG. 4. Friction factors vs Reynolds numbers for drag reducing polymer solutions at $x/D = 1100$.

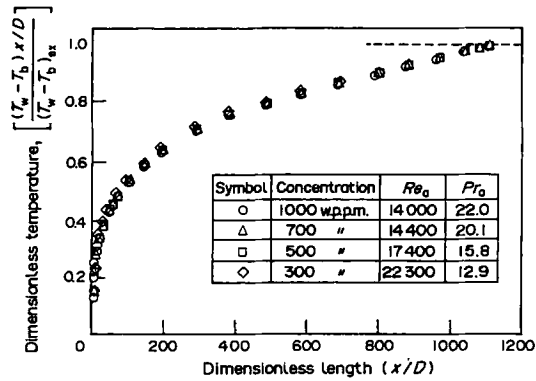


FIG. 5. Wall temperature distribution along the dimensionless length for polymer solutions.

Experimental friction factors of undegraded polymer solutions are lower than the maximum drag reduction asymptote in the range of Reynolds numbers below 30 000. In the range of Reynolds numbers above 30 000, however, the experimental friction factors follow the curve of the maximum drag reduction asymptote.

The temperature distribution along the tube wall of undegraded polymer solutions of 300–1000 w.p.p.m. is presented in Fig. 5. From this figure the thermal entrance length cannot be determined, since the wall temperature distribution is not parallel to the line of the mixing-cup temperature rise of polymer solutions. The dimensionless thermal entrance lengths of drag reducing viscoelastic fluids corresponding to the maximum drag reduction asymptote may be said to exceed 1000.

Cho and Hartnett [3] reported that the thermal entrance length was approximately 400–500 diameters and the minimum heat transfer asymptote based on experimental data at 430 diameters could be expressed by

$$j_h = 0.03 Re_a^{-0.45}. \quad (13)$$

On the other hand, the formula suggested by Toh and Ghajar [4] is based on the experimental results of concentrations of up to 500 w.p.p.m.:

$$j_h = 0.15(x/D)^{-0.29} Re_a^{-0.43}. \quad (14)$$

Experimental heat transfer results for relatively undegraded polymer solutions are shown in Fig. 6. The results for relatively fresh polymer solutions in the present study may be expressed by

$$j_h = 0.093(x/D)^{-0.34} Re_a^{-0.36}. \quad (15)$$

Equation (15) is in good agreement with the experimental results ranging from 10 to 1100 of the dimensionless length. Comparison between formulas (14) and (15) manifests that the maximum deviation of equation (15) is $\pm 16\%$ in the range of dimensionless lengths of 10–600.

The order of magnitude of the Nusselt numbers

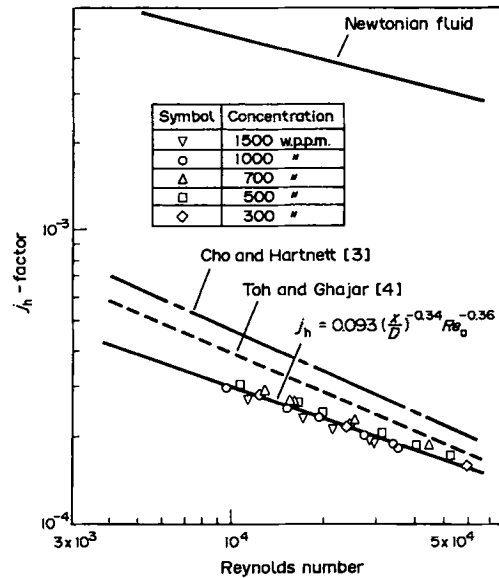


FIG. 6. Heat transfer j -factors vs Reynolds numbers for drag reducing polymer solutions at $x/D = 1100$.

of the maximum drag reducing polymer solutions is considerably lower than that of Newtonian fluids in the thermal entrance region for turbulent flow. It appears that the turbulent tube flow behavior of the maximum drag reducing polymer solutions is quite different from that of the Newtonian turbulent flow in the range of Reynolds number of 10^3 – 10^4 . Interestingly enough, the turbulent heat transfer characteristics of viscoelastic fluids may be expressed as a function of the Graetz number, which is an important dimensionless number for laminar heat transfer in the entrance region. The Nusselt number of a non-Newtonian fluid in terms of the power law model is shown in equation (16) for the entrance region and equation (17) for the fully developed region, respectively [14]:

$$Nu_x = 1.30 \left[\frac{3n+1}{4n} \right]^{1/3} Gz^{1/3} \quad (16)$$

where $Gz = (Re Pr D)/x$ and

$$Nu_\infty = \frac{8(3n+1)(5n+1)}{1+12n+31n^2}. \quad (17)$$

The analysis of the present experimental data suggests a modified form of the Graetz number. The modified form of Graetz number, which may be called the viscoelastic turbulent Graetz number, Gz_v , is defined as the product of Reynolds number and Graetz number:

$$Gz_v = Re_a Gz. \quad (18)$$

In the thermal entrance region, the Nusselt number for drag reducing viscoelastic fluids may be correlated in the form of

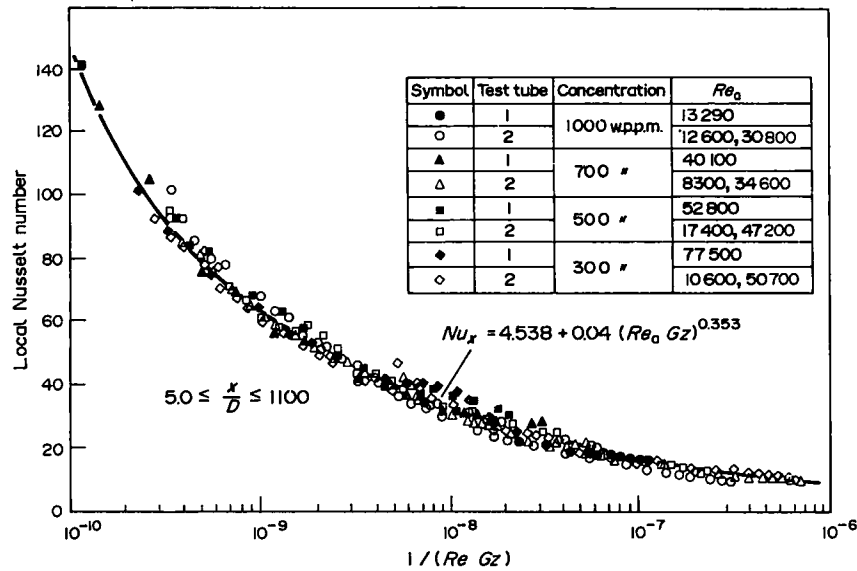


FIG. 7. Local Nusselt numbers vs the product of Reynolds number and Graetz number in the entrance region for polymer solutions.

$$Nu_x = Nu_\infty + C(Re_a Gz)^m \quad (19)$$

The local Nusselt numbers are shown as functions of Nu_∞ and the product of Reynolds number and Graetz number in Fig. 7. The Nusselt number for thermally fully developed flow, Nu_∞ , equals 4.538 for a flow behavior index n of 0.7. With a value of $Nu_\infty = 4.538$, the experimental results may be expressed as

$$Nu_x = 4.538 + 0.04 (Re_a Gz)^{0.353} \quad (20)$$

This correlation may be used for the prediction of heat transfer of drag reducing viscoelastic fluids corresponding to the maximum drag reduction asymptote in the thermal entrance region over the Reynolds number range of 10 000–70 000 and over the dimensionless length (x/D) range of 5–1100. Using equation (20) within the given ranges, the maximum deviation of the experimental results ranges within $\pm 18\%$. Equation (20) can be applied regardless of test tube diameter.

DEGRADATION OF POLYMER SOLUTIONS

The heat transfer behavior and variation of apparent viscosity of degrading polymer solutions in the recirculating flow loop were studied experimentally. The apparent viscosity and characteristic time of the Separan AP-273 (1000 w.p.m.) solution are shown in Fig. 8 as a function of recirculation time. $\lambda_1(s)$ and $\lambda_2(s)$ in Fig. 8 denote the characteristic time of the polymer solution derived from the rheological model of Powell–Eyring [14] and the diffusion time [15], respectively. The apparent viscosity and characteristic time decrease as the recirculation time increases. The apparent viscosity in the low shear rate range decreases more rapidly than that in the high shear rate

range at the beginning of degradation. However, as time lapses, the rate of decrease of apparent viscosity becomes gradually smaller, and presumably, the apparent viscosity approaches a constant value.

The changes of zero shear rate viscosity and infinite shear rate viscosity vs time lapse for two polymer concentrations are shown in Fig. 9. At the initial stage of degradation, the decrease of zero shear rate viscosity is quite pronounced, but that of the infinite shear rate viscosity is not. As the degradation of polymer solutions continues, the characteristic time and apparent viscosity decrease. Any given polymer solution exhibits quite different characteristic time and viscosity depending on the degree of degradation. So, it is crucial to measure the viscous property and the characteristic time of the working fluid while it is in use.

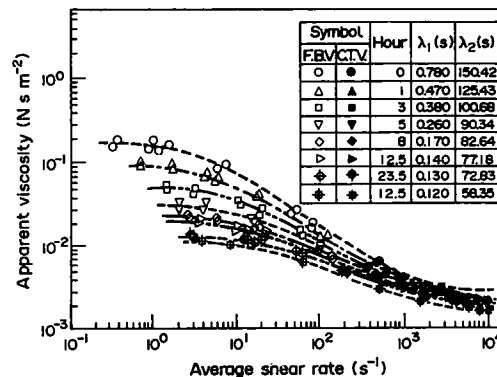


FIG. 8. Degradation effects on the apparent viscosity for 1000 w.p.m. polymer solutions.

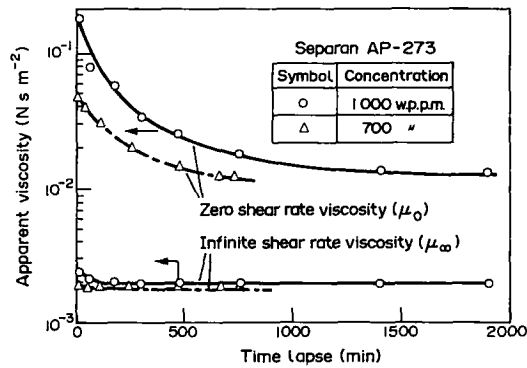


FIG. 9. Degradation effects on the zero shear rate and infinite shear rate viscosities.

CONCLUSIONS

(1) Dimensionless thermal entrance lengths of the maximum drag reducing polymer solutions are longer than 1000, which is larger than the entrance length of Newtonian fluids by an order of magnitude.

(2) The dimensionless heat transfer parameter j_h -factor in the turbulent thermal entrance region for drag reducing polymer solutions corresponding to the minimum heat transfer asymptote may be correlated by the following formula :

$$j_h = 0.093(x/D)^{-0.34} Re_a^{-0.36}.$$

(3) The local turbulent Nusselt number of viscoelastic fluids corresponding to the minimum heat transfer asymptote in the entrance region can be represented as a function of flow behavior index n and the product of Reynolds number and Graetz number :

$$Nu_x = Nu_\infty + 0.04(Re_n Gz)^{0.353}.$$

(4) The degradation effect of polymer solutions on the zero shear rate viscosity is more remarkable than that on the infinite shear rate viscosity. In addition, as a polymer solution degrades, the characteristic time and apparent viscosity decrease, approaching the asymptote values.

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