

# Heat transfer in the thermal entrance region for viscoelastic fluids in turbulent pipe flows

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(Received 7 July 1987 and in final form 10 November 1987)

**Abstract**—Experimental results for the effects of polymer concentration, polymer type, solution flow rate, and pipe diameter on the thermal entrance length and heat transfer reduction are presented. The experiments were conducted for Separan AP-273 and AP-30 solutions with concentrations ranging from 10 to 500 p.p.m. flowing turbulently in the test sections of 1.11 and 1.88 cm i.d. under constant wall heat flux. An empirical correlation for the minimum heat transfer asymptote was established which predicts the present experimental data with a maximum deviation of 8%.

## INTRODUCTION

A NUMBER of experimental studies on turbulent heat transfer for non-Newtonian fluids in the thermal entrance region of a pipe with uniform heat flux have appeared in the literature [1-6]. In general, these studies reveal that the thermal entrance length and consequently the rate of heat transfer reduction is a function of the solution concentration, the polymer type, the solution flow rate, and the pipe diameter. However, most of these studies were limited to a small concentration range [1-3], a single polymer type [3-5], a fixed Reynolds number [6], and a single pipe diameter [3, 4]. Consequently, no conclusive results are available with respect to the influence of these parameters on the thermal entrance length and the rate of heat transfer reduction. The aim of this study is to provide a new and reliable data base in order to resolve some of these deficiencies. For this purpose experiments will be conducted in the thermal entrance region for two different polymer solutions (Separan AP-273 and AP-30) with concentrations ranging from 10 to 500 p.p.m. flowing turbulently ( $Re_a \approx 10\,000-56\,000$ ) in two pipes with diameters of 1.11 cm ( $L/D = 1046$ ) and 1.88 cm ( $L/D = 617$ ) under constant wall heat flux condition.

In addition, some of the above mentioned inves-

tigators [3, 5, 6] have correlated their experimental data in the thermal entrance region for the minimum heat transfer asymptote (Table 1). These correlations satisfactorily correlated the experimental data from which they were developed. However, none of these correlations have been compared with one another or with a different set of experimental data. Therefore, in order to establish the validity of these correlations, they will be compared with our recent experimental data. Furthermore, using our experimental data for the minimum heat transfer asymptote, a heat transfer correlation will be developed and compared with the available correlations given in Table 1.

## EXPERIMENTS

A schematic diagram of the flow circulation system is shown in Fig. 1. The test sections used have inside diameters of 1.88 cm ( $L/D = 617$ ) and 1.11 cm ( $L/D = 1046$ ). These test sections are long enough for the study of heat transfer characteristics of viscoelastic fluids with a wide range of concentrations in the whole thermal entrance region. To minimize mechanical degradation of polymer solutions, the overall flow system was operated with pressurized air using the once-through mode. The constant wall heat flux

Table 1. Types of minimum heat transfer asymptote heat transfer correlations in the thermal entrance region

Investigator(s)	Year	Fluid	Range of application		Correlation
			$Re_a$	$x/D$	
Kwack <i>et al.</i> [5]	1981	Separan AP-273 Polyox WSR-301 Polyox FRA	$6000 \leq Re_a \leq 60\,000$	$\leq 450$	$j_h = 0.13(x/D)^{-0.24} Re_a^{-0.45}$
Ng [6]	1983	Separan AP-273 Polyox WSR-301 Polyox FRA	$6000 \leq Re_a \leq 40\,000$	$\leq 450$	$j_h = 0.12(x/D)^{-0.25} Re_a^{-0.43}$
Matthys [3]	1985	Separan AP-273	$6000 \leq Re_a \leq 90\,000$	$35 < x/D < 560$	$j_h = 0.377(x/D)^{-0.293} Re_a^{-0.523}$

## NOMENCLATURE

$C_p$	specific heat of fluid	$Re_a$	apparent Reynolds number, $\rho_f UD/\eta_a$
$D$	inside diameter of test section	$St$	Stanton number, $Nu/(Pr_a Re_a)$
$h$	local heat transfer coefficient	$T_{bx}$	local bulk mean temperature
$HTR$	heat transfer reduction, $(Nu_n - Nu_p)/Nu_n$	$T_{wi}$	inner wall temperature
$j_h$	Colburn $j$ -factor, $St Pr_a^{2/3}$	$U$	average velocity
$k_f$	thermal conductivity of fluid	$x$	local axial distance.
$L$	test section length		
$Nu$	Nusselt number, $hD/k_f$		
$Nu_n$	Nusselt number for Newtonian fluid, from equation (1)	Greek symbols	
$Nu_p$	Nusselt number for polymer solution, from experimental data	$\eta_a$	apparent viscosity at the wall
$Pr_a$	apparent Prandtl number, $\eta_a C_p/k_f$	$\theta$	dimensionless temperature, $(T_{wi} - T_{bx})_{x/D}/(T_{wi} - T_{bx})_{exit}$
		$\rho_f$	fluid density.

boundary condition was maintained by a Lincoln DC-600 welder. In the present experiments, a hydrodynamic starting length ( $x/D = 110$ ) is provided so that the velocity profile is fully developed before heat transfer starts. The temperatures along the heat transfer test section were measured with 28 #30 gage copper-constantan thermocouples. The flow rate was measured by a 1 in. turbine meter located upstream from the test section. The viscoelastic fluids used were the well-mixed homogeneous aqueous solutions of polyacrylamide (Separan AP-273 and AP-30) with concentrations ranging from 10 to 500 p.p.m. Apparent viscosities of these solutions were measured at a wide range of shear rates ( $0.36-2 \times 10^4 \text{ s}^{-1}$ ) with the use of two Couette viscometers (Brookfield Synchro-Electric Model LVT with UL adaptor and a Fann model VG) and a capillary tube viscometer (0.94 mm i.d. and  $l/d = 325$ ).

The reliability of the flow circulation system and the experimental procedures were checked with several calibration runs with tap water and the results were compared with the well-established Newtonian cor-

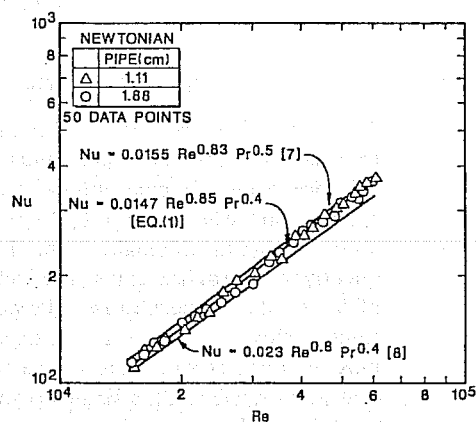


FIG. 2. Calibration data for a Newtonian fluid (tap water).

relations [7, 8] for the fully developed region (Fig. 2). From Fig. 2 it is clear that the calibration data are in excellent agreement with the Newtonian correlations. The experimental data presented in Fig. 2 were correlated (within 7%) with the following expression:

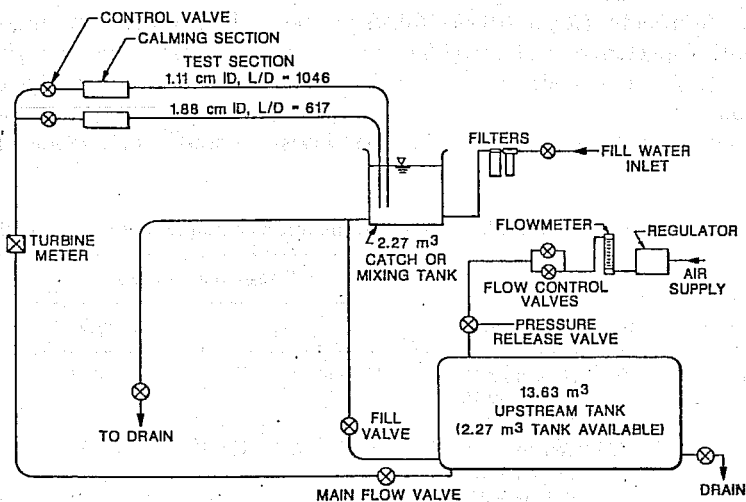


FIG. 1. Schematic of the flow circulation system.

$$Nu_n = 0.0147 Re^{0.85} Pr^{0.4} \quad (1)$$

This correlation will be used as a reference for the calculation of the relative magnitude of heat transfer reduction for different polymer solutions flowing in the two test sections. The uncertainty analyses of the overall experimental procedures for Newtonian and viscoelastic fluids showed that there is a maximum of about 14% uncertainty for Nusselt numbers. More detailed descriptions of the experimental apparatus and procedures are presented elsewhere [9, 10].

### THERMAL ENTRANCE LENGTH

The temperature measurements in the thermal entrance region for Separan AP-273 and AP-30 in the 1.11 cm test section are presented in terms of dimensionless temperature ratio ( $\theta$ ) and the dimensionless axial distance ( $x/D$ ) in Figs. 3–6. The effect of polymer concentration on the development of the temperature profile for an approximately fixed value of Reynolds number ( $Re_a \approx 15000$ ) is shown in Figs. 3 and 4 for Separan AP-273 and AP-30, respectively. These figures clearly demonstrate that the thermal entrance length is a strong function of polymer concentration. For example, the thermal entrance length for dilute polymer solutions (10–20 p.p.m.) is only 10–20 pipe diameters which is comparable to the thermal entrance length for Newtonian fluids. However, for 500 p.p.m. of Separan AP-273 (Fig. 3), the thermal entrance length is approximately 550 pipe diameters. The presented thermal entrance length results for Separan AP-273 (Fig. 3) are shorter than those reported by Kwack *et al.* [5]. For example, at 100 p.p.m. they reported a thermal entrance length of about 420 pipe diameters at  $Re_a = 10000$  compared with 300 pipe diameters for the current study at  $Re_a = 15000$ . The difference is because Kwack *et al.* [5] used a flow system in which the hydrodynamic and thermal entrance lengths developed simultaneously from the beginning of the test section, therefore, a greater length is required for the thermal profile to achieve the fully established condition.

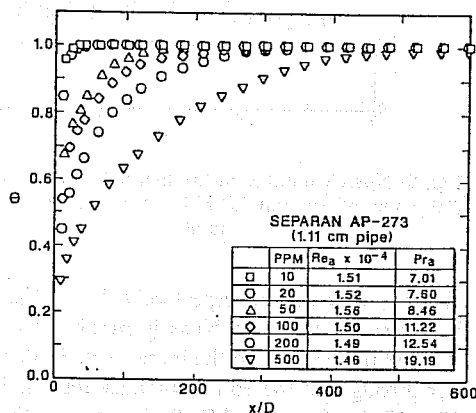


FIG. 3. Dimensionless temperature vs  $x/D$  in the thermal entrance region for various concentrations of Separan AP-273 solutions.

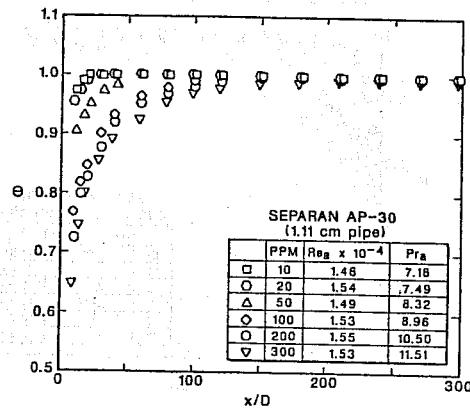


FIG. 4. Dimensionless temperature vs  $x/D$  in the thermal entrance region for various concentrations of Separan AP-30 solutions.

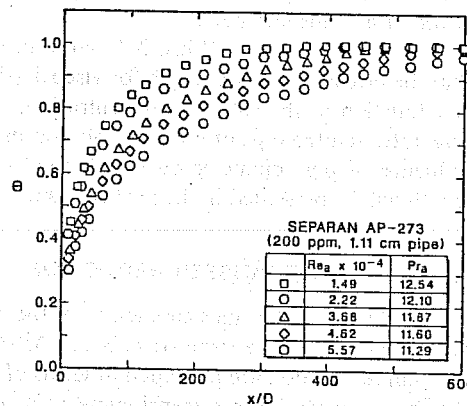


FIG. 5. Dimensionless temperature vs  $x/D$  in the thermal entrance region for 200 p.p.m. of Separan AP-273 at a wide range of Reynolds numbers.

Comparison of Figs. 3 and 4 at a fixed concentration and Reynolds number reveals that the type of polymer used also has an influence on the thermal entrance length. In this case, the thermal entrance length for Separan AP-273 is much longer (approximately by a factor of 2) than that for Separan AP-30 at comparable concentrations and Reynolds numbers. This is because Separan AP-273 with its much higher average molecular weight ( $6 \times 10^6$ ) compared to Separan AP-30 ( $4 \times 10^6$ ) is more elastic. Therefore, it requires a longer thermal entry length to approach the fully developed condition.

The effect of Reynolds number (or flow rate) on the thermal entrance length for a fixed value of polymer concentration is depicted in Figs. 5 and 6 for Separan AP-273 (200 p.p.m.) and Separan AP-30 (300 p.p.m.), respectively. From these figures it can be concluded that the thermal entry length increases with the increase in Reynolds number or flow rate. For example, for the highest Reynolds number reported in Fig. 5 for Separan AP-273, the temperature profile is still developing after 600 pipe diameters. This result is consistent with the findings of Matthys [3] that the

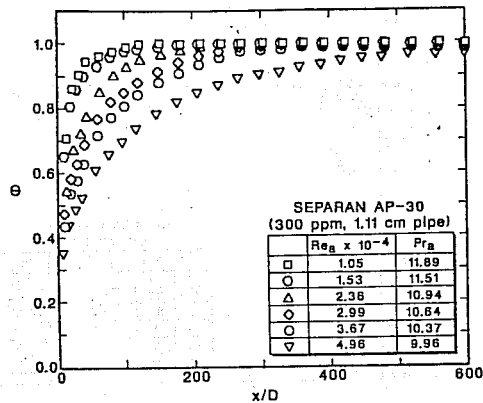


FIG. 6. Dimensionless temperature vs  $x/D$  in the thermal entrance region for 300 p.p.m. of Separan AP-30 at a wide range of Reynolds numbers.

thermal entry length may exceed 600 pipe diameters at high Reynolds numbers.

The presented results (Figs. 3–6) confirm the fact that the thermal entrance length for viscoelastic fluids is a function of the solution concentration, solution flow rate, and the type of polymer solution used. The influence of pipe diameter on the thermal entrance length will be presented in the next section.

#### HEAT TRANSFER REDUCTION

The heat transfer measurements in the thermal entrance region for Separan AP-273 and AP-30 in the 1.11 cm test section are presented in terms of Nusselt number ( $Nu$ ) and the dimensionless axial distance ( $x/D$ ) in Figs. 7–10. The effect of polymer concentration on the heat transfer for an approximately fixed value of Reynolds number ( $Re_n \approx 15000$ ) is shown in Figs. 7 and 8 for Separan AP-273 and AP-30, respectively. These figures clearly demonstrate that an increase in the polymer concentration generally results in a decrease in the dimensionless heat transfer coefficient ( $Nu$ ) up to a certain asymptotic limit (Fig. 7). For the studies shown on Fig. 7, this asymptotic limit for Separan AP-273 was reached at a concentration of 200 p.p.m. Once this asymptotic heat transfer has been reached, further increases in polymer concentration do not influence the heat transfer. The asymptotic limit of 200 p.p.m. for Separan AP-273 is in agreement with the results of Matthys [3].

Comparison of Figs. 7 and 8 at a fixed concentration and Reynolds number reveals that the type of polymer used also influences heat transfer in the thermal entrance region. In this case, Separan AP-30 requires concentrations higher than 200 p.p.m. (Fig. 8) to reach the heat transfer asymptotic limit. As discussed earlier, this is attributed to the less elastic nature of Separan AP-30 as compared to Separan AP-273.

The effect of Reynolds number (or flow rate) on the heat transfer in the thermal entrance region for a fixed value of polymer concentration is shown in Figs. 9 and 10 for Separan AP-273 (200 p.p.m.) and Separan

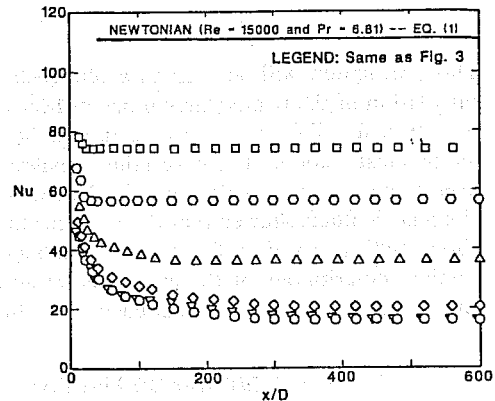


FIG. 7. Nusselt number in the thermal entrance region for various concentrations of Separan AP-273 solutions.

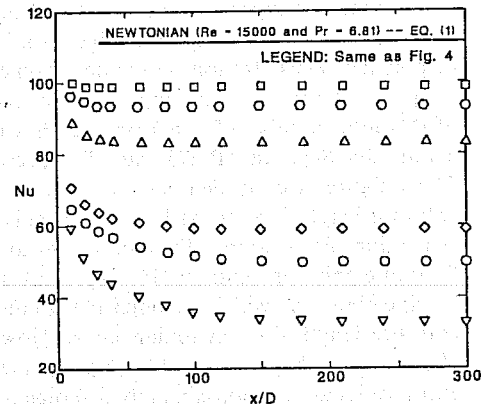


FIG. 8. Nusselt number in the thermal entrance region for various concentrations of Separan AP-30 solutions.

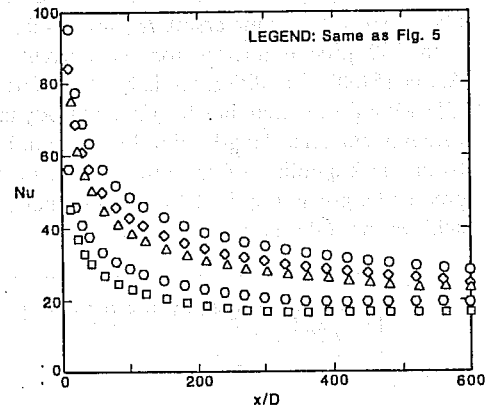


FIG. 9. Nusselt number in the thermal entrance region for 200 p.p.m. of Separan AP-273 at a wide range of Reynolds numbers.

AP-30 (300 p.p.m.), respectively. From Fig. 9 it can be observed that the Nusselt number for Separan AP-273 increases with the increase in Reynolds number throughout the entire entrance region. However, Fig. 10 for Separan AP-30 shows that the Nusselt number initially increases with the increase in Reynolds number but then starts decreasing. The entrance

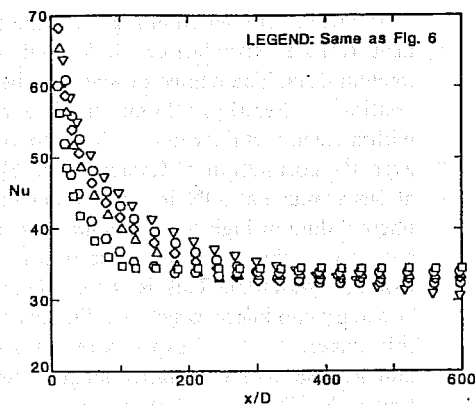


FIG. 10. Nusselt number in the thermal entrance region for 300 p.p.m. of Separan AP-30 at a wide range of Reynolds numbers.

length over which this decrease in the Nusselt number takes place increases with the increase in Reynolds number. For example, Nusselt number starts decreasing for  $Re_a = 10\,500$  at  $x/D = 150$  and for  $Re_a = 49\,600$  at  $x/D = 330$ . One possible explanation for this peculiar behavior is because Nusselt number is high in the region close to the start of heating (or tube thermal entrance) and since the thermal entrance length for Separan AP-30 is rather short at low Reynolds numbers (Figs. 4 and 6), the Nusselt number approaches its asymptotic value within a short axial distance. However, at high Reynolds numbers, the Nusselt number decreases continuously until it reaches its long thermal entrance length (Fig. 6).

It is customary in the literature to compare the heat transfer behavior of a viscoelastic fluid ( $Nu_p$ ) with the corresponding values for the turbulent flow of a Newtonian fluid ( $Nu_n$ ). Thus we speak of heat transfer reduction ( $HTR$ ) which is defined as

$$HTR = (Nu_n - Nu_p)/Nu_n \quad (2)$$

Some of the results presented in Figs. 7–10 are summarized in Tables 2 and 3 in terms of percent heat transfer reduction ( $\%HTR$ ). The results of Table 2

Table 2. Percentage heat transfer reduction for different polymer type and solution concentration

Polymer type	p.p.m.	$\%HTR$ c. fully developed†
Separan AP-273	10	15
	20	45
	50	70
	100	80
	200	85
	500	84
Separan AP-30	10	10
	20	19
	50	26
	100	48
	200	57
	300	70

† Compared at  $Re_a \approx 15\,000$ .

Table 3. Percentage heat transfer reduction for 200 p.p.m. of Separan AP-273 and 300 p.p.m. of Separan AP-30 at a wide range of Reynolds numbers

Reynolds number	$\%HTR$ c. $x/D = 100$	$\%HTR$ c. fully developed
200 p.p.m. of Separan AP-273 solution		
14 900	79.5	85.1
22 200	81.7	87.5
36 800	84.5	90.5
46 200	85.3	91.1
55 700	85.8	91.6
300 p.p.m. of Separan AP-30 solution		
10 500	57.8	58.3
15 300	67.8	70.2
23 600	75.8	79.8
29 900	79.3	83.7
36 700	82.0	86.5
49 600	85.3	90.0

indicate that for both polymer solutions, the  $\%HTR$  increases with the increase in concentration. However, the  $\%HTR$  for Separan AP-273 at comparable Reynolds numbers, concentrations, and axial locations is more pronounced than those for Separan AP-30. Table 3 summarizes the  $\%HTR$  for each polymer solution at a relatively high concentration as a function of Reynolds number at two different axial locations. As expected  $\%HTR$  increases with an increase in Reynolds number for both polymer solutions. It is interesting to note that 300 p.p.m. of Separan AP-30 solution produced approximately the same  $\%HTR$  as that of 200 p.p.m. of Separan AP-273 at high Reynolds numbers at both  $x/D$  locations. However, the  $\%HTR$  for Separan AP-30 at  $Re_a = 15\,300$  and  $x/D = 100$  is about 12% lower than that of Separan AP-273 at comparable conditions.

The effect of pipe diameter on the thermal entrance length and heat transfer reduction is presented in Fig. 11. It can be seen from this figure that the slope of the heat transfer curve for Separan AP-273 solution in the 1.11 cm pipe is steeper than that in the 1.88 cm pipe. This indicates that the thermal entrance length is longer in the smaller pipe than that in the larger one. Figure 11 also reveals that the reduction of heat transfer in the smaller pipe is much higher than that in the larger one. For example, there is a 61% (c.  $x/D = 300$ ) reduction in heat transfer for Separan AP-30 in the 1.11 cm test section while there is only 41% (c.  $x/D = 300$ ) reduction in the 1.88 cm test section when compared to the corresponding Newtonian value. A possible explanation for this effect may be the fact that polymer molecules are considered to influence the boundary layer close to the pipe wall. This influence should be seen in the smaller pipe before the larger one since the boundary layer would form a larger portion of the total flow in the small pipe. The polymer solution in the small pipe being more effective in heat transfer is consistent with the foregoing finding that a more effective polymer solution requires a

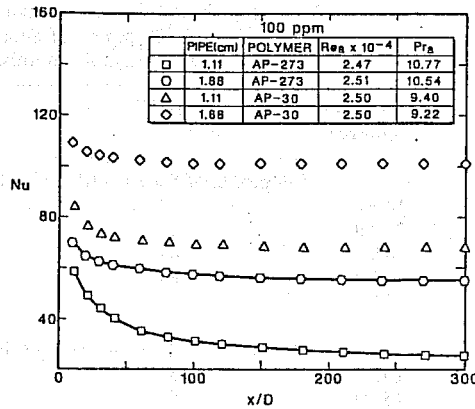


FIG. 11. Nusselt number in the thermal entrance region for 100 p.p.m. of Separan AP-273 and AP-30 solutions in two different pipe diameters.

longer thermal entrance length than a less effective polymer solution.

The presented results (Figs. 7–11 and Tables 2 and 3) confirm the fact that heat transfer in the thermal entrance region for viscoelastic fluids is a function of the solution concentration, solution flow rate, the type of polymer solution used, and the pipe diameter.

#### HEAT TRANSFER CORRELATION

The available heat transfer correlations in the thermal entrance region for the asymptotic limit are given in Table 1. These correlations satisfactorily correlated the experimental data from which they were developed. However, their validity has not been established with respect to one another using an independent set of experimental data. Figure 12 shows the comparison between the available correlations and our experimental data for 200 p.p.m. (asymptotic limit, see Fig. 7) of Separan AP-273. The actual experimental data used for these comparisons are shown in Fig. 9. It should be remarked that the range of Reynolds number and the axial distance covered by the experimental data used is compatible with the reported ranges of these parameters for the available heat transfer correlations.

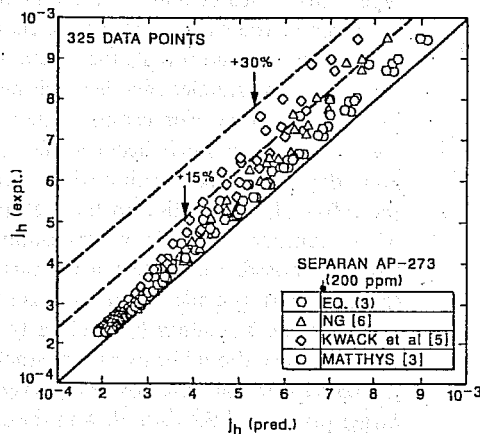


FIG. 12. Comparison of the predicted Colburn  $j$ -factors using the available and proposed correlations for heat transfer with experimental data.

The results presented in Fig. 12 indicate that all the heat transfer correlations underpredict the experimental data. The degree of underprediction for correlations of Matthys [3] and Ng [6] is generally well within the uncertainty range of the experiments. However, the correlation of Kwack *et al.* [5] shows deviations as much as 30% in comparison with the experimental data at high Reynolds numbers and near the entrance to the heat transfer section (high values of Colburn  $j$ -factor). This is mainly because of their boundary conditions which are different from those in this paper. In their experimental system, thermal and hydrodynamic entrance lengths develop simultaneously. Therefore, heat transfer is much greater at high Reynolds numbers and in the region near the entrance, and becomes the same at high  $x/D$ . It is interesting to note that the predictions for the correlations improve considerably at high  $x/D$  values (close to the fully developed region, low values of Colburn  $j$ -factor). This confirms the fact that the heat transfer asymptotic limit for fully developed viscoelastic turbulent pipe flows is general, independent of the experimental apparatus, procedures employed, the type of polymer used, and the size of pipe diameter [11].

A heat transfer correlation similar to the ones presented in Table 1 was also developed using our extensive set of experimental data (Fig. 9). The developed correlation is

$$j_h = 0.15(x/D)^{-0.29} Re_a^{-0.43} \quad (3)$$

The comparison between equation (3) and the experimental data is also shown in Fig. 12. In general, as expected, this correlation predicts our experimental data better than the other three correlations (within 8%).

#### CONCLUSIONS

Based on the extensive experimental data provided in this study, it was confirmed that the thermal entrance length and the rate of heat transfer reduction for viscoelastic fluids in turbulent pipe flows is not only a function of the solution concentration and flow rate, but also depends on the polymer type and the pipe diameter (Figs. 3–11). With an increase in the solution concentration or flow rate, or a decrease in the pipe diameter, the thermal entrance length increases (Nusselt number decreases). The influence of the polymer type on the thermal entry results is judged based on the effectiveness of a solution. The polymer solution with the higher molecular weight (Separan AP-273) proved to be more effective. This solution required a longer thermal entrance length and produced higher rates of heat transfer reduction in comparison with Separan AP-30 solution (Tables 2 and 3). The minimum heat transfer asymptote for Separan AP-273 was found to be at 200 p.p.m. (Fig. 7). However, a higher concentration (more than 300 p.p.m.) is needed for Separan AP-30 to achieve the

same results (Fig. 8). An empirical correlation for the minimum heat transfer asymptote was developed which predicts the experimental data with a maximum deviation of 8% (Fig. 12).

*Acknowledgement*—This work was partially sponsored by the University Center for Energy Research (UCER) at Oklahoma State University.

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#### TRANSFERT THERMIQUE DANS LA REGION D'ENTREE POUR DES ECOULEMENTS TURBULENTS DE FLUIDES VISCOELASTIQUES DANS DES TUBES

**Résumé**—On présente des résultats expérimentaux relatifs à l'effet de la concentration, du type de polymère, du débit de la solution et du diamètre du tube sur la réduction du transfert thermique et sur la longueur d'entrée thermique. Les expériences ont porté sur des solutions de Separan AP-273 et AP-30, avec des concentrations allant de 10 à 500 p.p.m., s'écoulant de façon turbulente dans des tubes ayant 1,11 et 1,88 cm de diamètre intérieur, avec flux thermique pariétal uniforme. Une formule empirique pour le transfert thermique minimal asymptotique est donnée pour représenter les résultats avec une déviation maximale de 8%.

#### WÄRMEÜBERGANG IM THERMISCHEN ANLAUFGEBIET VISKOELASTISCHER FLUIDE BEI TURBULENTER ROHRSTRÖMUNG

**Zusammenfassung**—Es werden Versuchsergebnisse vorgestellt, die den Einfluß von Polymerisat-Konzentration, Polymerisat-Art, Lösungsmitteldurchsatz und Rohrdurchmesser auf die Länge des thermischen Anlaufgebiets und die Verringerung des Wärmeübergangs zeigen. Die Experimente wurden mit Separan-Lösungen AP-273 und AP-30 im Konzentrationsbereich von 10 bis 500 p.p.m. durchgeführt, wobei Meßstrecken mit 1,11 und 1,88 cm Innendurchmesser turbulent bei konstanter Wand-Wärmestromdichte durchströmt wurden. Es wird eine empirische Beziehung für den Verlauf des Wärmeübergangs-Minimums eingeführt, mit der die vorliegenden Versuchsergebnisse bei einer maximalen Abweichung von 8% wiedergegeben werden können.

#### ТЕПЛООБМЕН В НАЧАЛЬНОМ УЧАСТКЕ ТУРБУЛЕНТНОГО ТЕЧЕНИЯ ВЯЗКОУПРУГИХ ЖИДКОСТЕЙ В ТРУБЕ

**Аннотация**—Представлены результаты экспериментального исследования влияния концентрации полимера, его типа, параметра расхода раствора и диаметра трубы на длину начального теплового участка и снижение теплообмена. Изучалось турбулентное течение растворов полимера Сепаран AP-27 и AP-30 с концентрацией в диапазоне от 10 до 500 PPM в рабочем участке, имеющем внутренний диаметр 1,11-1,88 см, при постоянном тепловом потоке на стенке. Предложена эмпирическая зависимость для асимптотики теплопереноса, с помощью которой соотносительные экспериментальные данные рассчитываются с максимальным отклонением в 8%.