

Coupling Between Heat and Momentum Transfer Mechanisms for Drag-Reducing Polymer and Surfactant Solutions

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Drag-reducing solutions exhibit simultaneous friction and heat transfer reductions, yet it has been widely believed that there is no direct coupling between the two. In this work, we have conducted a study to re-examine this issue, using measurements of friction and heat transfer over a wide range of flow conditions from onset to asymptotic, various pipe diameters, and several polymer and surfactant solutions. Contrary to some earlier suggestions, our tests show that no decoupling of the momentum and heat transfer mechanisms was seen at the onset of drag reduction, nor upon departure from the asymptotes, but rather that the friction and heat transfer reductions change simultaneously in those regions. For asymptotic surfactant and polymer solutions, the ratio of heat transfer and drag reductions was seen to be constant over a large range of Reynolds numbers, if modified definitions of the reduction parameters are used. In the nonasymptotic region, however, the ratio of heat transfer to drag reductions is higher and is a function of the reduction level, but is approximately the same for polymer and surfactant solutions. This variation is consistent with the concept of a direct coupling through a nonunity constant Pr_r , as also suggested by our local measurements of temperature and velocity profiles. We also saw that our diameter scaling technique for friction applies equally well to heat transfer. These findings allow us to predict directly the heat transfer from friction measurements or vice versa for these drag-reducing fluids, and also suggest that a strong coupling exists between the heat and momentum transfer mechanisms.

1 Introduction

It has been shown repeatedly that small amounts of polymers or surfactant additives lead to reduced turbulent friction and heat transfer coefficients compared to those of water. Early analyses implied that the drag reduction characteristics have a direct equivalent in the heat transfer reduction; for example, that the maximum drag reduction asymptote (MDRA) has an equivalent maximum heat transfer reduction asymptote (MHTRA). This could also mean that the Reynolds analogy suggesting that the turbulent Prandtl number (Pr_t) is equal to 1, is as much applicable for these fluids as it is for water (Poreh and Paz, 1968; Kale, 1977; Smith and Edwards, 1981). It was later suggested, however, by Cho and Hartnett (1982) and others, that this assumption is not proper because the percentage reductions corresponding to the MHTRA are always significantly larger than those for the MDRA. In addition, for nonasymptotic fluids, the percentage of heat transfer reduction (HTR) is normally higher than the percentage of drag reduction (DR) at the same Reynolds number (Re). (The definitions we use here for DR and HTR are

$$DR = \frac{(C_{F_{w,T}} - C_F)}{C_{F_{w,T}}} \times 100; \quad HTR = \frac{(Nu_{w,T} - Nu)}{Nu_{w,T}} \times 100$$

where "W, T" stands for turbulent flow of water at the same Reynolds number.)

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This difference in the reduction levels may indicate that a direct coupling between the heat and momentum transfers through a Pr_r of about 1, does not hold for this type of fluids. Indeed, various eddy diffusivity models were developed, most of them predicting a Pr_r much greater than one (e.g., Kale, 1977; Mizushima et al., 1975; Yoon and Ghajar, 1987). Roethig and Matthys (1988), for example, estimated values of Pr_r on the order of 10–15 for asymptotic conditions. Such a large difference between the eddy diffusivities is a striking concept, and it is indeed a very interesting issue worth looking at carefully because of the fundamental implications that it may have.

Other consequences of this apparently increased Pr_r is a difference between heat and momentum developing lengths and a difference between the velocity and temperature profiles. With respect to the entry lengths, Ng et al. (1980) observed that the thermal development region was at least three times longer than that for friction for the fluids they studied, and that many of the experimental setups used previously did not have the minimum length needed for the development of the temperature profile. Toh and Ghajar (1988) and Matthys (1991) also observed thermally developing flow even after 600 D , with little or no effect of the Reynolds number after appropriate nondimensionalization, whereas it was generally believed that the momentum entrance length was only about 100 diameters. Recently, however, we have revisited the problem of the relationship between HTR and DR within the developing region for surfactant solutions (Gasljevic and Matthys, 1997) and we have seen that—contrary to what was believed to be the case for most polymer solutions—the friction and heat transfer coefficients for cationic surfactants were still changing at the same rate 300 D downstream of the entrance, when nondimensionalized by the "fully developed" values measured at more than 650 D downstream. This finding could imply that the Pr_r

is not as large as that predicted by some earlier studies, at least for surfactant solutions. This notion is also supported by some of our recent studies on turbulent temperature profiles (to be presented elsewhere).

Besides the possibility of higher Pr_t , there was also a possibility of complete decoupling of the two exchange mechanisms in some limited regions. For instance, previous experimental evidence seemed to suggest that there are different onsets for drag and heat transfer reductions. To complicate the matter further, it was shown (Ng and Hartnett, 1979; Matthys, 1991) that in the process of degrading an asymptotic polymer solution, the HTR begins to decrease from its asymptotic level before the DR does, suggesting that in this region the DR and HTR are decoupled. We decided therefore to investigate this latter issue further, and to look in more detail at the relationship between DR and HTR close to the asymptotic regimes.

Finally, we have recently studied the diameter effect on friction, and we have developed a simple correlation based on bulk velocity that allows us to scale readily DR up or down with diameter. If a fixed relationship between DR and HTR does not exist, the HTR would likely not be well represented by the correlation applicable to the DR. On the other hand, if a fixed relationship does exist, the diameter effect on heat transfer should be the same as that for DR. This issue still had to be resolved prior to the present study.

To address the problem of relationship between the two transfer mechanisms, we rely in this work on global measurements of the friction coefficient and Nusselt number. Although local measurements of velocity and temperature profiles (which we will address elsewhere) are best suited for direct determination of the Pr_t , the global measurements can contribute greatly as well to the discussion, and particularly so in the region at and close to onset, where profile measurements become inaccurate because of the smaller velocity and temperature gradients. Global measurements are also the best tool for resolving the problem of possible decoupling during departure from the asymptotes by dilution or degradation. The aim of the present work was therefore to analyze the relationship between the DR and HTR by performing measurements of both, under wide experimental conditions and for various drag-reducing fluids.

2 Experimental Setup and Procedure

The experimental setup consists of four stainless steel tubes of 2, 5, 10, and 20-mm inner diameters. These tubes are fed from a pressurized tank by a distribution line. The pipes are 1000 diameters long each, except for the largest pipe which is 680 diameters long. This setup was previously used for studies of the diameter effect on friction (for details on this setup see Gasljevic (1990) and Aguilar (1995), and only additional instrumentation was needed for the heat transfer measurements.

The pipes were fitted with temperature sensors (miniature 100 Ω , 10 \times 2 mm RTDs), cemented on top of the outer wall at 860 and 960 diameters downstream of the entrance, and at 634 and 675 diameters for the 20-mm pipe. Another RTD (100 Ω) was placed

in the supply manifold of the pipes for bulk temperature measurements. This shielded probe was inserted perpendicular to the flow at the pipe entrance. The three RTDs for each pipe were connected to a precision multimeter (Keithley 199 DMM/Scanner). Errors in the measurements were reduced by noise rejection and averaging techniques. A near-uniform wall heat flux condition was provided by two 20 kW DC power supplies connected directly to each pipe by means of customized copper clamps providing very good electrical contact (in order to prevent contact heating). The heat transfer measurement technique is described in more detail in Gasljevic and Matthys (1997). For better comparison, we controlled the heating in such a way that for each experiment the bulk temperature was about the same at the location where both DR and HTR are measured. All these experiments were carried out in a once-through mode to avoid unintentional flow perturbations and fluid degradation, and the flow rate was measured continuously by discharging the fluid into instrumented calibrated tanks.

The equipment was calibrated for friction and heat transfer measurements by running tests with tap water. The results were successfully compared with some of the better correlations for Newtonian fluids for friction coefficients (Blasius, 1913; Filomenko, 1954; Petukov, 1970); and for heat transfer coefficients (Kays, 1966; Petukov, 1970; Sleicher and Rouse, 1975). The accuracy of the flow rate measurement is about one to two percent (Gasljevic, 1990). Altogether, the uncertainty of our experimental data for water is estimated to be about five percent for the friction measurements, and eight to ten percent for the Nusselt number over most of the velocities covered, and somewhat higher—between seven to eight percent for friction and 12 to 15 percent for heat—for low velocities. The expected uncertainty is lower for the drag-reducing solutions where the temperature differences between the wall and bulk temperatures are bigger and the uncertainty becomes proportionally smaller. The uncertainty in the calculation of the relative drag and heat transfer reductions is also about half of those for C_f and Nu because the errors in some of the parameters cancel out when the HTR and DR ratios are calculated.

We used three different drag-reducing fluids, one polymer and two surfactant solutions, each in a number of concentrations: Separan AP-273, a hydrolyzed high-molecular weight polymer by Dow chemicals; SPE 95285, a nonionic surfactant developed in collaboration with Dr. M. Hellsten at Akzo Nobel Chemicals; and Ethoquad TI3-27, a cationic surfactant by Akzo Nobel Chemicals. The water used as solvent was deionized or tap water, and in the case of the 50 ppm Separan solution small amounts of NaCl were added to the tap water in order to illustrate the effect of salts on the drag-reducing ability of the fluid. We have also examined data from other authors.

When working with drag-reducing fluids, it is often critical to measure and take properly into account the viscosity if we want to avoid large errors. We have therefore systematically measured the viscosity of the fluids either with Couette or high-shear capillary systems. For the polymer solutions with concentrations of 50 ppm or less, the viscosity was found to be very close to that of water at

Nomenclature

$C_f = 2\tau_w/\rho V^2$ = friction coefficient	$u^* = \sqrt{\tau_w/\rho}$ = shear velocity (m/s)	ρ = density (kg/m ³)
D = pipe diameter (mm)	V = bulk velocity (m/s)	τ_w = shear stress at the wall (N/m ²)
$h = q''/\Delta T_{w-b}$ = heat transfer coefficient (W/m ² K)	Greek Letters	Subscripts
k_f = fluids thermal conductivity (W/mK)	$\alpha = k/\rho C$ = thermal diffusivity (m ² /s)	H = relative to heat
$Nu = hD/k_f$ = Nusselt number	ϵ = eddy diffusivity (m ² /s)	L = relative to laminar flow
$Pr = \nu/\alpha$ = Prandtl number	ΔT_{w-b} = wall to bulk temperature difference (°C)	M = relative to momentum
$Pr_t = \epsilon_H/\epsilon_H$ = turbulent Prandtl number	ν = kinematic viscosity (m ² /s)	T = relative to turbulent flow
$Re = VD/\nu$ = Reynolds number		W = relative to the solvent (water)

shear rates comparable to those encountered in the pipe runs; for polymer concentrations of 100 ppm, the apparent wall viscosity was used to compute the Reynolds number and the corresponding DR and HTR values. For the 4000 ppm nonionic surfactant solution, the viscosity at room temperature was about twice as high as water, but at the temperature used in the tests (33–35°C), the viscosity was also found to be close to that of water. To most of the Ethoquad T13-27 solutions, we added 3 mM/l of copper hydroxide $\text{Cu}(\text{OH})_2$ in order to increase the stability of the fluid and to reduce the viscosity to the water level as well. When this approach was not followed, the apparent wall viscosity of the surfactant solution was used to compute the Reynolds number, DR and HTR values (as in Figs. 7 and 8). Except for the test with the 4000 ppm nonionic surfactant, all the other fluids were tested at room temperature (approx. 20°C.) Unless otherwise indicated, all fluids exhibited a molecular Prandtl number of about 6 during these tests.

3 Results and Discussion

3.1 Diameter Effect on Drag and Heat Transfer Reduction.

We have recently conducted a study of the diameter effect on polymeric drag-reducing fluids (Gasljevic et al., 1999). According to our results, the DR data measured in various pipe diameters for these fluids can be represented by a single curve if plotted as a function of the bulk velocity. It was then decided to investigate the diameter effect on the heat transfer, and to verify the validity of the same correlation for heat transfer reduction. For this purpose we performed simultaneous measurements of DR and HTR under various conditions. Figure 1 shows our results for a nonasymptotic 20-ppm polyacrylamide (Separan AP-273) solution measured in four pipes of 2, 5, 10, and 20-mm inner diameter. As can be seen in the upper graph, the HTR scales with bulk velocity just as well as DR does, which means that the ratio between HTR and DR does not depend on the pipe diameter in this representation. The ratio does, however, depend on the flow velocity, as seen in the lower graph, with a ratio tending to about 1.15 at high DR levels. In a previous article (Aguilar et al., 1998), the data scatter at low velocities was attributed to the difficulty in conducting these measurements in that region, but it was later observed that this scatter was more likely due to viscosity and buoyancy effects, as discussed below.

This independence of the HTR/DR ratio on the pipe diameter suggests that the diameter effect on heat transfer is the same as that on friction, essentially eliminating the diameter effect on heat

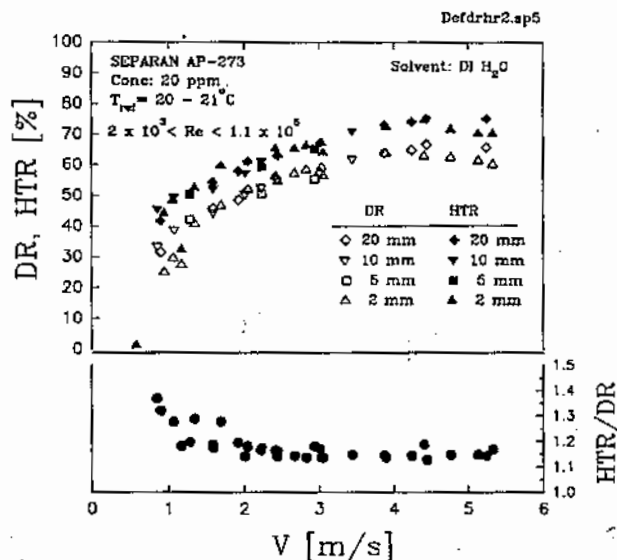


Fig. 1 Diameter and velocity effects on DR, HTR, and the HTR/DR ratio for a polymer solution

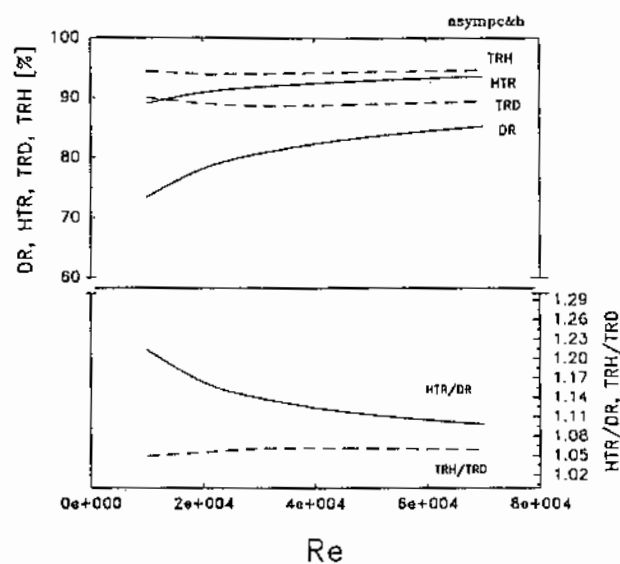


Fig. 2 Maximum drag reduction asymptote (MDRA) and maximum heat transfer asymptote (MHTRA) from Cho and Hartnett (1982) plotted as DR, TRD, HTR, and TRH versus Reynolds number. The ratios between the corresponding heat transfer and friction parameters are also shown in the lower graph.

transfer as a separate problem. In addition to its usefulness for predictions, this finding has theoretical implications in that it suggests that a strong coupling does exist between the heat and momentum transfer mechanisms. The dependence of the HTR/DR ratio on velocity indicates that this coupling may not be a simple relationship, however.

3.2 Maximum Drag and Heat Transfer Reductions (Asymptotic Regime).

Figure 2 shows the maximum drag and heat transfer asymptotes (MDRA and MHTRA) proposed by Cho and Hartnett (1982) for polymer solutions. The asymptotes are presented in two ways; on the one hand in terms of the usual DR and HTR (solid lines), and on the other hand, in terms of the parameters that we have recently referred to as "turbulence reduction-drag" (TRD) and "turbulence reduction-heat" (TRH) (the dashed lines). These latter quantities are defined as follows:

$$\text{TRD} = \frac{(C_{Fw,T} - C_F)}{(C_{Fw,T} - C_{Fw,L})} \times 100;$$

$$\text{TRH} = \frac{(\text{Nu}_{w,T} - \text{Nu})}{(\text{Nu}_{w,T} - \text{Nu}_{w,L})} \times 100$$

where the subscript T stands for turbulent flow, L for laminar flow, and w for the solvent (water).

(Regarding the second representation, similar parameters have been proposed in earlier studies as an alternative to the percentage reduction parameters (DR and HTR). The former are indeed physically more meaningful since they reflect the degree of turbulence reduction with respect to full laminarization rather than to an artificial zero-viscosity fluid (Astarita et al., 1969; Schmitt, 1988). They were disregarded early on, though, because they incorporate an additional parameter (the laminar friction coefficient) and because the difference between these and the DR and HTR parameters is in some cases small. We have recently shown (Gasljevic and Matthys, 1999), however, that although both representations are equally useful in providing information in some cases, in some others the TRH and TRD definitions may indeed be much better than DR and HTR.)

The ratio of the two reductions is calculated for both presentations and shown in the lower graph of Fig. 2. We can see that the ratio between HTR and DR is dependent on the Reynolds number, whereas TRH/TRD is about independent of the Reynolds number

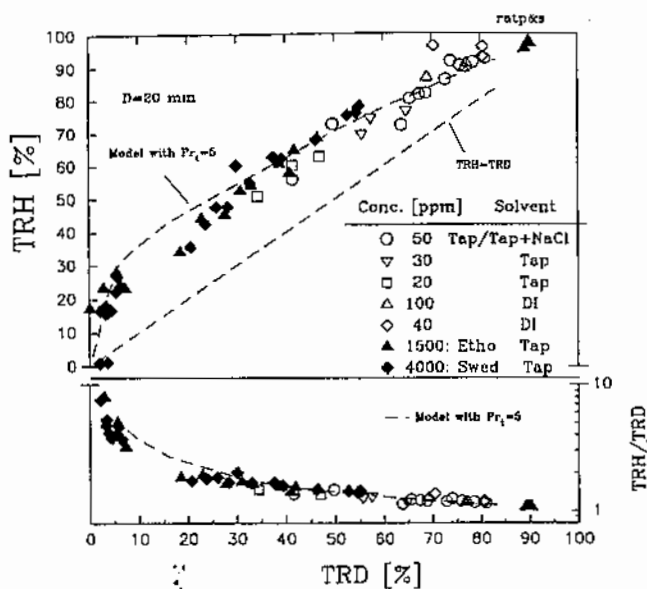


Fig. 5 TRH versus TRD for two surfactant solutions: Elhoquad T13-27 and SPE 95285 (solid symbols) and for the polymer solution data shown in Fig. 4 (hollow symbols). The upper dashed line shows the predicted TRH based on a three-layers temperature profile model assuming a constant $Pr_t = 5$. The TRH/TRD ratio is shown at the bottom for the experimental data (symbols) and the model predictions (dashed line) (pipe ID = 20 mm).

levels of TRD approaches the constant value measured for asymptotic conditions (about 1.06).

Figure 5 shows results for surfactant solutions, including data close to onset, together with our data for the polymer solutions shown in Fig. 4. The results for surfactants are close to those for polymer solutions. Both surfactant solutions used in these experiments had water-like viscosity (see Section 2), which we endeavored to eliminate the effect of strong viscosity dependence on the shear rate in the calculations of friction and heat transfer coefficients. In this case the fluids were found to show a Pr_t of approximately 5. We also see that TRH/TRD increases significantly at very low levels of drag reduction. (It should be noted, however, that the measurement uncertainty is larger in this region.) As we see, for both polymer and surfactants, a Pr_t of about 5 in the mathematical model gives predictions that fit well the experimental data. For the surfactants, it was possible to obtain measurements closer to the onset, which show a sharper increase in TRH than in TRD, as was indeed predicted by the model. Since the surfactants used for these tests had water-like viscosity, a practical advantage of knowing this ratio is that it can also be used to determine whether or not other more viscous solutions are in reality asymptotic. Viscosity affects TRD and TRH in opposite directions, which means that the fluid might have a high viscosity if the expected TRH/TRD ratio is not obtained in simultaneous drag and heat transfer tests.

Overall, these results suggest that although TRH/TRD seems to be a function of the level of drag-reducing effects (TRD), there is indeed a strong coupling between the heat transfer and friction reductions for these fluids through a constant, or approximately constant, nonunity Pr_t . In addition, it appears that both surfactant and polymer solutions exhibit very similar TRH/TRD ratios.

(A word of caution is appropriate here, however. All our results reported here, except for those shown in Figs. 7 and 8, correspond to fluids with a molecular Prandtl number of about 6 around ambient temperature. Some later tests conducted with fluids exhibiting significantly higher Pr (e.g., 40 to 60 for some surfactant solutions) showed a somewhat higher TRH/TRD ratio at low Re , however. We are presently investigating further this issue through direct measurements of the temperature profiles and the preliminary findings suggest that the viscous layer may be significantly

thickened for some fluids, which would indeed cause the molecular Prandtl number to affect the TRH/TRD ratio. These results will be published elsewhere.)

3.4 Onset of Heat Transfer and Friction Reduction Phenomena. A possible decoupling between heat transfer and friction has been thought to take place at the onset of drag and/or heat transfer reductions, each of which could conceivably occur at a different shear stress. Different onsets means that there would be some drag reduction without heat transfer reduction, or vice versa. This was apparently observed in some previous studies (Mizushima and Usui, 1977; Kwack et al., 1982). This concept is puzzling, however, if one thinks in terms of the physical flow/fluid interaction mechanisms behind turbulent viscoelastic drag reduction, and one might think it rather unlikely. Accordingly, we undertook investigations to reexamine this issue. In these experiments, the heat transfer and friction coefficients were measured in pipes of various diameters and with various flow velocities. The velocity was lowered systematically, so that the TRD for all pipes was reduced until Newtonian turbulent friction coefficients were detected (i.e., $DR = TRD = 0$ percent).

Some data for a surfactant solution are shown in Fig. 6, where we plot TRD (hollow symbols) and TRH (solid symbols) as a function of shear velocity, i.e., of shear stress. Data for both a 10-mm and a 20-mm pipes are shown. The TRD data are as measured, but the TRH data have been corrected by a constant Nusselt number multiplier coefficient (different for each pipe) to remove a small positive constant offset (ten percent or less, i.e., within the limits of uncertainty for that region) in TRH observed in the data before onset. This is not necessary for the purpose of estimating the onset of drag and heat transfer reductions, but it makes the figure much clearer and we have therefore decided to include it here for better illustration of the onset effect. (Practically speaking, this correction only shifts the curves vertically in this graph.) This offset may result from buoyancy effects (described elsewhere) or from instrumentation calibration errors, but its constancy before onset over a wide range of velocities clearly suggests that it is indeed purely a measurement offset rather than a true viscoelastic reduction effect, and is therefore not affecting our onset evaluation.

The data for both pipes are seen to be very similar, as expected

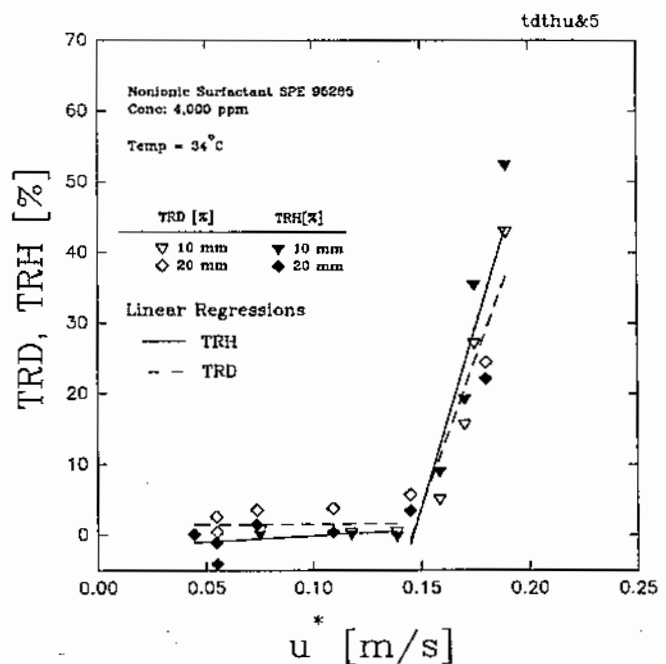


Fig. 6 TRH (corrected) and TRD: onset of drag and heat transfer reductions (solvent: tap water)

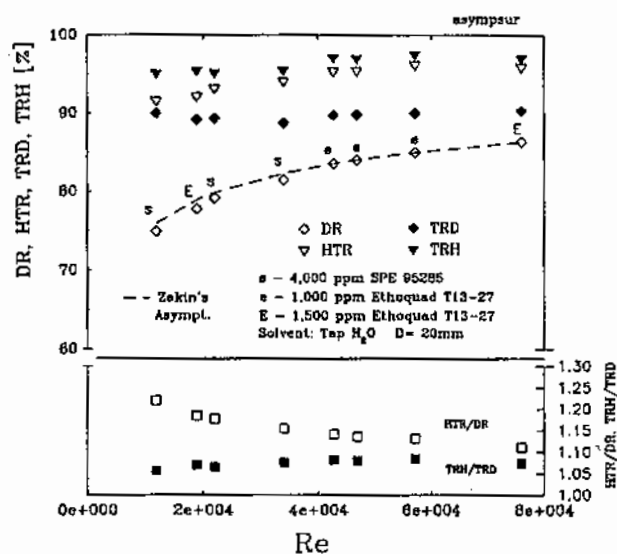


Fig. 3 Asymptotic values of drag and heat transfer plotted as DR, TRD, HTR, and TRH versus Reynolds number for various surfactant concentrations. The MDRA proposed by Zakin et al. (1996) is shown for comparison (dashed line). The ratios between the corresponding heat and friction parameters are also shown in the lower graph. All solutions showed water-like viscosity under the test conditions (solvent: tap water, pipe ID = 20 mm).

(since both TRD and TRH are as well), and is about 1.06. (If Virk's asymptote is used for friction instead of Cho and Hartnett's, a slightly higher value in the ratio is obtained, i.e., about 1.12.) The HTR/DR ratio decreases here from about 1.2 to 1.1 as the Reynolds number increases, in good agreement with Fig. 1.

Figure 3 (top) shows data for asymptotic friction and heat expressed both in terms of DR and HTR (hollow symbols) and in terms of TRD and TRH (solid symbols) for various asymptotic surfactant solutions. The HTR/DR and TRH/TRD ratios are also shown (bottom). As it has been frequently observed, higher levels of reductions are achieved with surfactant than with polymer solutions. It is also seen that the power-law asymptotic correlation proposed by Zakin et al. (1996) fits our data reasonably well. The TRH/TRD ratio is again practically independent on Re, showing a value of approximately 1.07, very close to that for the polymer solution asymptotes (1.06). This difference between the ratios obtained for the surfactant and polymer solutions may be considered to be well within the limits of experimental error.

3.3 Intermediate Drag and Heat Transfer Reductions (Nonasymptotic Regime). We have seen above that a constant ratio between the reductions in heat and drag holds for asymptotic drag reduction if our "turbulence reduction parameters" (TRH and TRD) are used. However, in the nonasymptotic regime, the HTR/DR ratio clearly depends on velocity (as does the HTR/DR ratio for any asymptotic reductions—although much less as seen in Fig. 2). We decided then to examine the generality of the ratio between TRH and TRD (or HTR and DR) for nonasymptotic fluids, including both polymers and surfactants. Figure 4 (top) shows results of simultaneous heat transfer and friction measurements for polymer solutions, presented as TRH versus TRD. The TRH/TRD ratio (which was independent of Reynolds number for asymptotic conditions) is also shown (bottom) as a function of TRD. This is a convenient representation because it allows us to see easily the relative variation of TRH with TRD, and it is also independent of the fluid drag-reducing ability.

Data from three sources are presented: Various polyacrylamide (Separan AP-273) solutions of different concentrations prepared in our laboratory; a 20 ppm Separan AP-273 solution used by Matthys (1991) at three different levels of degradation; and two polyethylene oxide solutions (Polyox) used by Yoon and Ghajar

(1987). The results of Matthys and of Yoon show a practically constant TRH/TRD, whereas our data show an increased ratio at low levels of TRD. The difference in results is likely not due to different solutions, because Matthys' and ours were the same type of polymer. In an earlier article (Aguilar et al., 1998), we plotted all these results together and considered TRH/TRD to be approximately constant with Re, although with a relatively large scatter at low reduction levels. However, after a detailed analysis, we decided to distinguish the two groups of results, and it is seen here that all our solutions show a stronger variation of the ratio compared to the measurements of Yoon and Ghajar or Matthys, which show more constant values. The reason for this discrepancy is not yet fully known, but it is likely that it originated in the variations of the experimental conditions, including differences in the quality of the solvents.

Our measurements of temperature profiles for fluids which are believed to be well represented by Virk's three-layers velocity profile model, such as these low concentration Separan solutions, indicate that the Pr, is about constant and equal to 5 or 6 across the region of the pipe radius where drag-reducing effects occur (the elastic layer, according to Virk's three-layers model). Based on this finding, we have made use of a simple mathematical model to calculate the TRH and TRD using Virk's three-layer velocity profile, a constant Pr, = 5, and the assumption of equal thickness for the momentum and thermal elastic layers. The results of these calculations are shown as the upper dashed line on Fig. 4 (top), indicating that TRH should increase faster than TRD with increasing level of reduction right after the onset. The values of TRH/TRD computed with this model are also plotted as a dashed line in the lower portion of Fig. 4 showing a reasonably good fit with our data. (The difference between the modeled and the measured values could be reduced or eliminated if the thickness of the thermal elastic layer is reduced relative to the thickness of the momentum elastic layer in the model, or if the Pr, is somewhat reduced in the region closer to the wall. For our purposes here, however, the point was not to improve the model (e.g., by tuning Pr,), but rather simply to show that the variation of TRH/TRD which we measured is reasonable.) As expected, TRH/TRD at high

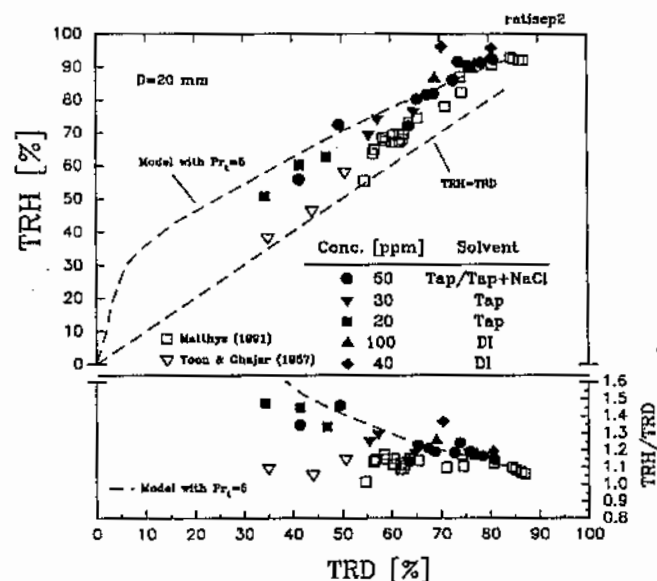


Fig. 4 TRH versus TRD for various polyacrylamide (Separan AP-273) concentrations (solid symbols). Data from Matthys (1991) for a 20 ppm AP-273 Separan solution at various degradation levels and data from Yoon and Ghajar (1987) for a 50 and 100 ppm Polyethylene oxide (Polyox) solutions are also shown (hollow symbols). The upper dashed line represents the TRH predicted by a three-layers temperature profile model assuming a constant Pr, = 5. The TRH/TRD ratio is shown in the lower graph for experimental data (symbols) and the model predictions (dashed line) (pipe ID = 20 mm).

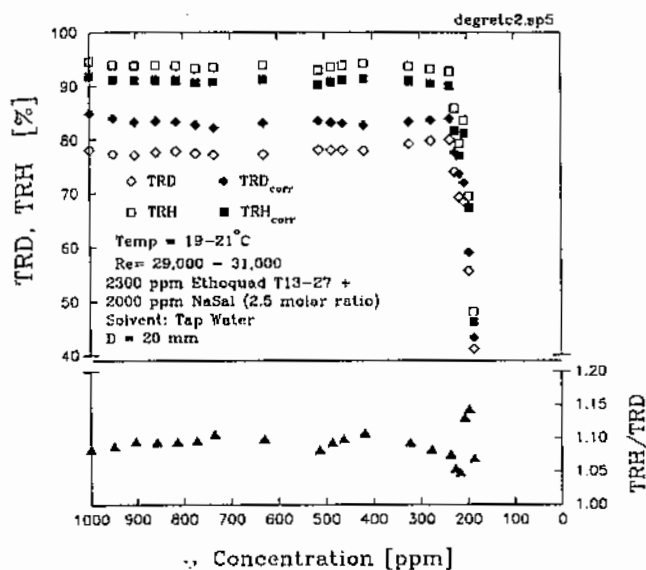


Fig. 7 Relationship between TRH and TRD in the asymptotic and non-asymptotic regions: effect of a decrease in concentration for a surfactant solution. (TRH_{corr} and TRD_{corr} are calculated by using the solution apparent viscosity at the wall, rather than the solvent viscosity as used for TRH and TRD) (pipe ID = 20 mm).

in this representation. To quantify better the onsets, we show calculated linear regressions through both pipe data, both before and after the sharp increase in TRH and TRD. Whereas such a procedure is approximate, we nevertheless clearly see through the extrapolated intersections of the regressions that the onsets for both friction and heat transfer reductions take place at about the same shear stress (corresponding to about $u^* = 0.15$ m/s in this case) i.e., simultaneously. This is in sharp contrast to the concept that heat transfer and friction might depart from Newtonian behavior under different flow conditions, as some have suggested. It is also interesting to see that the data confirm that the onsets take place at the same shear stress for both pipe diameters.

3.5 Departure From Asymptotic Behavior. Another apparent contradiction with the idea of coupling through constant Pr, is an observation reported by some authors (Ng and Hartnett, 1979; Matthys, 1991) that HTR departs from its asymptotic value sooner than DR during the process of degradation. If this is indeed the case, then the momentum and heat transfer mechanisms would not be coupled in this region. It appears that relatively small uncertainties in viscosity estimations might account for the apparent initial decrease in the friction and the apparent rapid increase in heat transfer after the start of degradation shown in Ng and Hartnett (1979). Once compensated for, this viscosity effect would indeed lead to data consistent with simultaneous departure of heat transfer and friction coefficients from their asymptotic values. This viscosity effect would not explain the data in Matthys (1991), but it is possible that the latter may have been affected by buoyancy effects as described above. In an attempt to clarify these issues, we conducted dedicated experiments with the same polymer solution (Separan AP-273) and with a surfactant solution (Ethoquad T13-27). In both cases we started out with a fluid showing asymptotic TRD and TRH, but the procedure by which we departed gradually from the asymptotic conditions was different. Figure 7 shows the experimental data for the surfactant solution, which was gradually diluted until a clear decrease of TRD and TRH occurred. This sudden change results from the critical shear stress for micellar breakup becoming smaller at that reduced concentration than the actual shear stress in the pipe. Samples of each concentration were taken in order to measure the viscosity in a capillary pipe viscometer at the same apparent shear stress as the flow in the pipe. The corresponding molecular Prandtl number ranged from about 15 at

high concentration to about 6 at low concentration (and similar numbers for the polymer solution discussed in Fig. 8 at no and high degradation, respectively.) The TRD and TRH values with no correction for viscosity are shown in Fig. 7 as the hollow symbols (assuming a constant viscosity equal to that of the solvent), whereas the solid ones are calculated with the actual solution viscosity. It should be noted that the viscosity corrections affect heat transfer and friction in opposite directions. The effect is not large here, because we have used a fluid with a viscosity close to that of water, which is advantageous if we want to reduce the possible errors due to the complex issue of appropriate choice of viscosity. Throughout all levels of dilution we see a constant ratio of approximately 1.07 again (with larger scatter after the sudden drop because of calculation uncertainties there). It is also apparent that both heat transfer and friction drop off suddenly at the same concentration, suggesting again that they are coupled in the near-asymptotic region and that departure from asymptotic conditions takes place simultaneously for drag and heat transfer.

Figure 8 shows the data for the polymer solution experiment. A relatively high concentration of Separan AP-273 (100 ppm) was used to provide enough resistance to mechanical degradation, resulting in a noticeable increase of the fluid viscosity. In this case the fluid was gradually degraded by recirculation in a loop including a near-closed valve generating high shear stresses. Simultaneous TRD and TRH measurements in the loop were conducted at various times. As with the surfactant solution, samples of fluid were taken at every stage and their viscosity was measured with a capillary viscometer at approximately the same apparent shear stress as in the pipe. Again, the TRD and TRH values with and without correction for viscosity are shown. We see that the departure from asymptotic conditions occurs at the same time for friction and heat transfer, and that further decreases appear to occur in parallel. The TRH/TRD ratio is indeed again remarkably constant throughout the whole range of degradation levels and again remains at a value very close to 1.07. These data again reinforce the notion that a strong coupling exists between heat and friction under asymptotic and near-asymptotic conditions. These results for both polymer and surfactant solutions all do indeed appear to be contradicting the notion suggested in some earlier studies that heat transfer reduction may depart earlier from its asymptote than the friction.

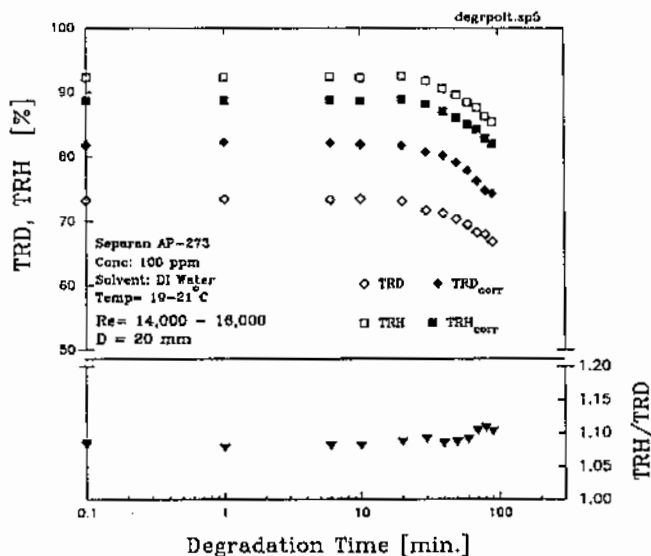


Fig. 8 Relationship between TRH and TRD in the asymptotic and non-asymptotic regions: effect of mechanical degradation for a polymer solution. (TRH_{corr} and TRD_{corr} are calculated by using the solution apparent viscosity at the wall, rather than the solvent viscosity as used for TRH and TRD) (pipe ID = 20 mm).

4 Summary and Conclusions

In this work we investigated the coupling between drag and heat transfer reductions for polymer and surfactant solutions through the use of global flow parameters (friction and heat transfer coefficients).

In the asymptotic regime an approximately constant value of the TRH/TRD ratio is found if modified definitions of the level of reductions are used. The ratio of these modified reduction definitions, which we referred as turbulence reduction-heat (TRH) and turbulence reduction-drag (TRD) was found to be about 1.06 for polymer and surfactant solutions.

In the nonasymptotic regime, however, TRH/TRD is a function of the level of drag reduction. At high levels of TRD the ratio is equal to its value measured for asymptotic regime, whereas it increases with decreasing TRD. The reason for this behavior is likely that TRH increases much faster than TRD with increasing velocity after the onset.

A simple mathematical model based on a three-layers velocity profile model, on our measurements of temperature profiles for the same fluids (showing a Pr, of about 5 or 6 within the elastic layer), and on the assumption of the same thickness for both thermal and momentum elastic layers, would predict the same type of behavior. Altogether, a strong coupling between the heat and momentum exchange mechanisms is indeed suggested, although certainly not as simple as the Newtonian Reynolds analogy of a unity turbulent Prandtl number.

Decoupling of the two exchange mechanisms was also suggested by some authors in the region close to the onset and in the vicinity of asymptotes. Our tests with both surfactant and polymer solutions in both regions showed the opposite, i.e., a strong coupling of the two exchange mechanisms: In simultaneous measurements of heat transfer and friction, at increasing flow velocity, drag and heat transfer reductions appeared to begin to take place at the same onset shear stress. In tests in a circulation loop with asymptotic fluids, the first signs of departure from the asymptotes due to either mechanical degradation or dilution appeared at the same time for drag and heat transfer.

On the theoretical side these results are very interesting in that they suggest a much stronger coupling between heat and momentum transfer than was generally believed recently, but yet not the full physical coupling ($Pr, \approx 1$) seen for Newtonian fluids.

On the practical side, these findings are also very useful. As the ratio TRH/TRD appeared to be a unique function of TRD even for very different fluids such as polymer and surfactant solutions, one can readily predict the heat reduction based on measurements of drag reduction, or vice versa. This may also be particularly useful for surfactant solutions which exhibit a strong dependence of the viscosity on shear rate. For example, if simultaneous measurements of friction and heat transfer reductions are made, one could easily check if the viscosity used in evaluating both friction and heat transfer coefficients is appropriate by testing for the expected ratio of reductions. This is particularly convenient for the asymptotic regime, for which the ratio is a constant.

Our study of the diameter effect on heat transfer for drag-reducing fluids showed that the scaling procedure proposed for friction holds just as well for heat transfer; i.e., that the ratio between heat transfer and drag reduction does not depend on pipe diameter.

Finally, the observation that the same ratio holds for both the surfactant and polymer solutions does support the notion that the drag reduction phenomenon involves similar physical mechanisms for both type of solutions.

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