Asymptotes of maximum friction and heat transfer reductions for drag-reducing surfactant solutions

Guillermo Aguilar [*,1], Kazimir Gasljevic, Eric F. Matthys

Department of Mechanical and Environmental Engineering, University of California, Santa Barbara, Santa Barbara, CA 93106, USA

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Abstract

A new maximum drag reduction asymptote (MDRA) for surfactant solutions is presented. Various concentrations including cationic and non-ionic surfactant solutions were used to experimentally determine this asymptote. It is shown that if solvent viscosity is used to compute Reynolds and Prandtl numbers for viscous solutions, it leads to underestimations of the friction coefficient. To avoid uncertainties in the selection of the fluids viscosity, most solutions used were intentionally conditioned so their shear viscosity was water-like in the ranges covered. Using the same solutions, a maximum heat transfer reduction asymptote (MHTRA) was also determined – a correlation that did not exist for surfactants until now. Finally, by using slightly modified definitions to quantify the heat transfer and drag reductions (TRH and TRD), it is possible to express the ratio between the MHTRA and MDRA with a constant value of 1.06, independent of Reynolds number. This relationship can be used as an auxiliary criterion to determine whether or not a solution is asymptotic when there is an uncertainty about the shear viscosity. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Asymptotes; Drag reduction; Heat transfer reduction; Surfactants

1. Introduction

It is well known that the maximum or asymptotic drag and heat transfer reductions are well established for polymer solutions, and also, that high concentrations of certain surfactant solutions provide higher levels of drag and heat transfer reductions than polymer solution asymptotes predict. However, the asymptotic limits for surfactant solutions are not yet confirmed. The first reason for this is because surfactants emerged as drag-reducing agents later than polymers, and therefore, the amount of experimental work done with the former in order to support an empirical asymptotic limit, is lesser than that done with the latter. The second reason, and perhaps more important, is that most friction and heat transfer coefficient measurements are typically evaluated as a function of solvent-based rather than solution-based Reynolds number. This is a justified practice regarding practical application of drag-reducing solutions, because it shows directly the overall effect of the additive in relation to the solvent (usually water), and it is also acceptable for most dilute polymer solutions, where increase in the solvent shear viscosity is typically small (particularly considering the high shear stresses present in turbulent flows, where the drag-reducing effects are observed). However, typical surfactant solutions that are able to provide high asymptotic levels of drag reduction, may exhibit up to 20 times higher wall shear viscosity than water at low flow velocities (or low shear stresses). This increase in viscosity represents a problematic issue because there is always an uncertainty of which is the appropriate viscosity to use to compute Reynolds and Prandtl numbers. In general, the use of the apparent viscosity at the wall, i.e., the viscosity corresponding to the same wall shear stress measured in a laminar flow capillary viscometer, has been a good choice for the description of various aspects of drag reduction for

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[*] Corresponding author. Tel.: +1-949-824-3754; fax: +1-949-824-6969.

E-mail address: gaguilar@bli.uci.edu (G. Aguilar).

[1] Present address: Department of Chemical and Biochemical Engineering and Materials Science, University of California, Irvine, CA 92697, USA.

Nomenclature

$C_F = 2\tau_w/\rho V^2$ — friction coefficient

$C_{F,WL} = 16/Re$ — friction coefficient for laminar Newtonian flow

$C_{F,WT} = [1.58 \times \ln(Re) - 3.28]^{-2}$ — friction coefficient for turbulent Newtonian flow (Filomenko)

D — pipe diameter (mm)

$DR = [1 - C_F/C_{F,WT}]100$ — drag reduction level (%)

$HTR = [1 - Nu/Nu_{WT}]100$ — heat transfer reduction level (%)

$j_H = StPr^{1/3}$ — Colbourn factor

k_f — thermal heat conductivity (W/m K)

$Nu = q''D/\Delta T_{w-b}k_f$ — Nusselt number based on D

$Nu_{WL} = 4.36$ — Nusselt number for laminar Newtonian flow

$Nu_{WT} = 0.012(Re^{0.87} - 280)Pr^{0.4}$ — Nusselt number for turbulent Newtonian flow (Gnielinski)

$Pr = v/\alpha$ — Prandtl number

q'' — heat flux at the wall (W/m²)

$Re = VD/v$ — Reynolds number based on D

$St = Nu/(RePr)$ — Stanton number

ΔT_{w-b} — inner wall–bulk temperature difference (K)

Greek symbols

α — thermal diffusivity (m²/s)

v — kinematic viscosity (m²/s)

ρ — fluid density (kg/m³)

τ_w — wall shear stress (N/m²)

Subscripts

a — refers to apparent at the wall

w — refers to water

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polymers, as reported by Kostic [1]. However, even using this apparent viscosity, may not be completely satisfactory. On one hand, viscosity changes with distance from the wall as a function of shear stress, and in highly drag-reducing flows viscous effects may be important even in the regions further away from the wall, as pointed out by Bewersdorff and Ohlendorf [2]. On the other hand, standard measurements of shear viscosity of surfactant solutions may, in some cases, be a function of the viscometer geometry, as pointed out by Hu et al. [3].

The most well known maximum drag reduction asymptote is that proposed by Virk et al. [4], which, in terms of the Prandtl–Karman coordinates, is given as:

$$C_F^{-1/2} = 19.0 \log\left(ReC_F^{1/2}\right) - 32.4. \tag{1}$$

A fairly good power law approximation to this implicit equation is given by:

$$C_F = 0.58 Re^{-0.58}. \tag{2}$$

This asymptotic correlation has been confirmed by a great amount of experimental data with regard to dilute polymer solutions, and it has shown to be independent of pipe diameter, concentration, molecular weight, coil size, etc. Although some experimentalists have claimed some deviations from this asymptote for polymer solutions, the differences are small.

Two other asymptotic correlations are:

$$C_F = 0.20 Re_a^{-0.48} \tag{3}$$

proposed by Cho and Hartnett [5], valid in the range of $6000 < Re_a < 60,000$, and

$$C_F = 0.624 Re_a^{-0.585} \tag{4}$$

proposed by Matthys [6], valid in the range of $6000 < Re_a < 90,000$, where Re_a represents the apparent Reynolds number.

For heat transfer, Cho et al. [7] proposed empirical correlations for estimation of the heat transfer coefficients of asymptotic polymer solutions measured within the developing region, as well as under fully developed conditions. These correlations were expressed in terms of Colbourn factor (j_H), and they are valid for Re_a between 6000 and 60,000:

$$j_H = 0.03 Re_a^{-0.45} \quad \text{for } x/D > 450, \tag{5}$$

$$j_H = 0.13(x/D)^{-0.24} Re_a^{-0.45} \quad \text{for } x/D < 450.$$

More recent studies by Matthys [6] suggested a slightly different correlation of heat transfer coefficients for fully developed conditions, valid in the range of Re_a between 6000 and 90,000:

$$j_H = 0.0596 Re_a^{-0.523}. \tag{6}$$

As mentioned before, there is almost an unanimous consensus that the MDRA for surfactants should be higher than the MDRA for polymers, despite some claims made by Bewersdorff & Ohlendorf [2] among others, in which they reported asymptotic velocity profiles similar to those of polymers, and thus similar asymptotic friction coefficients.

In a recent publication, Zakin et al. [8] proposed a new MDRA for surfactants. This MDRA is approximately valid in the range between $4000 < Re < 130,000$ and is based on the solution shear viscosity:

$$C_F = 0.315 Re^{-0.55}. \tag{7}$$

Regarding the maximum heat transfer reduction asymptote (MHTRA), surfactant solutions show the same qualitative behavior in terms of their heat transfer coefficients as polymer solutions. However, as for asymptotic friction coefficients, asymptotic heat transfer coefficients for surfactants also appear to be somewhat lower than those for polymers (higher heat transfer reduction), although no correlation has yet been proposed.

In a recent publication, a study about the relationship between drag reduction (DR) and heat transfer reduction (HTR) was conducted for a variety of polymer and surfactant solutions [9]. Part of that experimental study was focused on the relationship between HTR and DR at asymptotic levels. In that work, the classical percent drag and heat transfer reductions (%DR and %HTR) were represented in a slightly modified fashion, and referred as turbulence reduction-heat (TRH) and turbulence reduction-drag (TRD) [10], defined as follows:

$$TRD = \frac{(C_{F,WT} - C_F)}{(C_{F,WT} - C_{F,WL})} 100;$$
$$TRH = \frac{(Nu_{WT} - Nu)}{(Nu_{WT} - Nu_{WL})} 100, \tag{8}$$

where the subscript T stands for turbulent flow, L for laminar flow, and W for solvent (water). By using these definitions it was shown that an approximately constant value of the ratio between TRH and TRD (TRH/TRD) was about 1.06, applicable to both polymer and surfactant asymptotic solutions. This finding gave place not only to the simplest way of representing one asymptote in terms of the other, but, as it will be shown, it could also be used as a test to determine whether a solution is asymptotic or not, whenever its shear viscosity is uncertain.

In this work the following objectives are pursued: (i) show the importance that the solution shear viscosity has in the appropriate determination of MDRA (particularly for surfactants), (ii) propose a new corrected MDRA; (iii) propose a new MHTRA for surfactants; and (iv) show the advantage of using TRH and TRD to represent the asymptotic friction and heat transfer coefficients, as well as its potential use as a tool to determine asymptotic solutions.

2. Experimental setup

The experimental setup consists of four stainless steel tubes of 2, 5, 10 and 20 mm inner diameters. To avoid unintentional fluid degradation, these tubes are fed from a pressurized tank by large diameter distribution lines (38 to 50 mm I.D). The pipes are 1000 diameters long each, except for the largest pipe which is 680 diameters long due to space limitations. This setup was previously used for studies of the diameter effect on friction and the relationship between drag and heat transfer reduction (for details on this setup see [9,11,12]). In this work it suffices to say that altogether, the uncertainty of the experimental data for water is estimated to be about 5%, and 8–10%, for friction coefficient (C_F) and Nusselt number (Nu) measurements, respectively, for velocities above 3 m/s; and somewhat higher – between 7% and 8% for C_F and 12–15% for Nu, for velocities below 3 m/s. The expected uncertainty is lower for drag-reducing solutions where the differences between the wall and bulk temperature are larger, and thus, the uncertainty becomes proportionally smaller. The uncertainties in the calculation of the relative drag and heat transfer reductions is about half of that for C_F and Nu because the errors in some of the parameters cancel out when the HTR and DR ratio (or TRH and TRD ratio) is calculated. Error bars appearing on some figures illustrate standard deviations of experimental measurements.

2.1. Fluid preparation

Two different surfactant solutions were used for this study: a cationic surfactant, tris (2-hydroxy-ethyl) tallowalkyl ammonium acetate (tallowalkyl-N-$(C_2H_4)OH)_3$ Ac, usually referred by its trademark: Ethoquad T13-27; and a non-ionic surfactant, SPE 95285, developed in collaboration with Dr. M. Hellsten; both by Akzo Nobel Chemicals.

During years of experimenting with this cationic surfactant (Ethoquad T13-27), it was noticed that the fluid drag-reducing properties were changing with time. Chemical agents (particularly copper hydroxide–$Cu(OH)_2$, originated from copper or brass parts of circulation loops), caused noticeable changes in the drag-reducing ability of the fluid. It was noticed that the presence of this component improved the resistance to degradation (i.e., increased the critical shear stress at which the fluid loses its DR ability), and thus allowed higher DR level with increasing Reynolds number. For the purpose of these tests, the effects of this compound on the surfactant solution (what was referred as "contaminated" solution) offered apparent advantages. In first place, after a certain exposure to the environment in the circulation loop, this contaminated surfactant solution reached a chemically stable condition. When a fresh solution was prepared and recirculated for a while, its drag-reducing ability changed very quickly at the beginning, making any kind of long lasting tests meaningless since these tests could not be made in all tubes at the same moment. On the other hand, a high concentration of Ethoquad solution

containing small amounts of this contaminant (Cu(OH)$_2$), seemed to reach and remain at stable conditions – both in terms of viscosity and drag-reducing ability, over a period of a few days. This period of time was enough to complete all the tests needed with a given fluid. Another advantage was that this contaminated fluid remained less temperature sensitive around room temperature, a condition that allowed performance of more accurate heat transfer tests. Finally, and most importantly for these tests, shear viscosity of this fluid was decreased to practically the same as water, and yet showed high (seemingly asymptotic) levels of DR in all pipes. The contaminated Ethoquad T13-27 surfactant solutions used in these tests were prepared by adding 1.5, 3.0 and 3.75 mM of Cu(OH)$_2$ to the 1000, 1500 and 2300 ppm surfactant concentrations, respectively. This compound was prepared by mixing cupric chloride—CuCl$_2$, with sodium hydroxide – NaOH (both from Sigma-Aldrich, St. Louis, MO). The amount of Cu(OH)$_2$ used was the minimum needed to bring the fluid shear viscosity to a water-like level. In all cases, sodium salycylate (NaSal) was also added as counterion in a 2.5 Surf/NaSal ratio, which corresponds roughly to 870, 1300 and 2000 ppm of NaSal, respectively. This ratio is optimal to enhance the drag-reducing ability of this particular surfactant. Obviously, due to the empirical nature of the MDRA and MHTRA, it was not enough to use only fluids with water-like viscosity to prove the generality of new or corrected asymptotic correlations. Therefore, a solution of the same kind but with higher viscosity than water was prepared as well. This solution was a ''fresh'' Ethoquad T13/27 surfactant with concentration of 2300 ppm plus 2000 ppm of NaSal. To avoid a significant variation of the fluid drag-reducing ability for the experiments conducted with the fresh surfactant solution, all experiments were carried out 24 h after the solution was prepared, and finalized within a few hours.

The non-ionic surfactant (SPE 95285) was developed to operate effectively around a span of temperatures between 5°C and 25°C, although it still showed drag-reduction ability up to 40°C (at concentrations of about 4000 ppm). Besides the difference in its ionic nature, this surfactant had very different properties than those of Ethoquad. For instance, for a given concentration, the phase separation (solubility problem) appeared towards higher temperatures, while transition from cylindrical to globular micelles appeared towards lower temperatures; as opposed to what happens with Ethoquad solutions. For the purpose of asymptotic drag reduction measurements, a 4000 ppm surfactant solution proved to be well suited, since it appear to be very stable with time, and, when used at temperatures around 25–27°C, it showed water viscosity, while apparently maintaining asymptotic levels of drag reduction.

2.2. Viscosity measurements

The shear viscosity of all surfactant solutions was systematically measured. For that purpose the following devices were used: (1) a cone and plate Brookfield viscometer, which covered a range of shear rates from 90 to 450 (s^{-1}); (2) a custom built capillary viscometer developed in our laboratory [13], with I.D. ranging from 0.178 to 2 mm. This viscometer allowed the fluid to be driven either by gravity (for low shear rate measurements) or by pressurized vessels. The capillary tube was inserted concentrically into a larger diameter PVC pipe, and water at a controlled temperature was pumped in between to provide an isothermal bath around the pipe during the viscosity test. To provide a pre-shear stage (typically for surfactants), an additional smaller diameter tube was inserted prior to the entry section of the capillary tube; (3) for extremely low shear rate measurements, the actual test tubes (2, 5, and occasionally 10 and 20 mm), which are normally used for turbulent drag-reducing flow experiments [14] were used. Besides measuring viscosity with these conventional methods, two auxiliary criteria were used to test the adequacy of the viscosity evaluation, namely, laminar to turbulent transition and, TRH/TRD ratio, as will be discussed below.

3. Results

Fig. 1 shows shear viscosity measurements of the four Ethoquad solutions used for this study. As can be seen, the shear viscosity of the three contaminated solutions (solid symbols) show practically water-like values over the whole range of shear rates covered (20–30,000 s^{-1}). Fig. 1 also shows the shear viscosity of the fresh Ethoquad solution (hollow symbols) measured on the capillary viscometer. As it is appreciable, the viscosity is more than 10 times higher than water at low shear rates, and even at shear rates of about 10,000 s^{-1}, the viscosity is about twice as high as water. The decrease in the fluid's viscosity is attributed to the adsorption of the surfactant and counterion on insoluble hydroxidc particles, which effectively reduces their concentration and affects its ratio, as concluded by Hu and Matthys [15].

The shear viscosity measurements for the 4000 ppm SPE 95285 surfactant solution are shown as a function of temperature in Fig. 2. These viscosity measurements were carried out in the Brookfield cone & plate viscometer for three different shear rates; namely, 90, 225 and 450 s^{-1}. Note that the shear viscosity around 15°C is about twice as high as that of water. Also note that for the measurements at the minimum temperature ($\approx$8°C) the viscosity is already larger than for water, presumably indicating the existence of micellar structures. However, the increase seen between 8°C to about 15°C is pre-
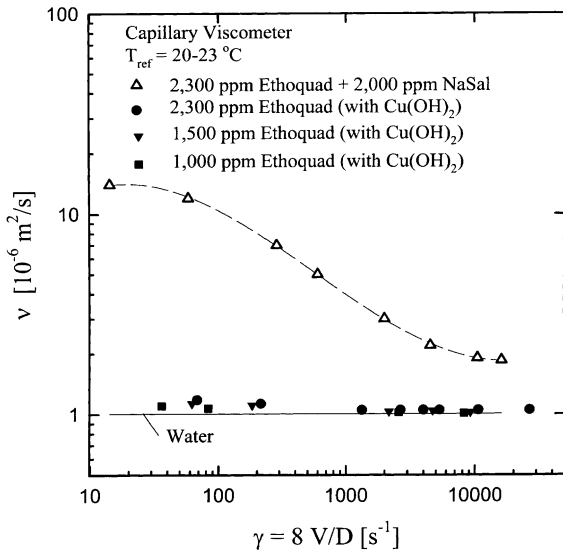
Fig. 1. Kinematic viscosity as a function of the wall shear rate for various Ethoquad T13/27 solutions. Hollow triangles: 2300 ppm plus 2000 ppm NaSal; circles: 2300 ppm plus 2000 ppm NaSal plus 3.75 mM/l of $Cu(OH)_2$; solid triangles: 1500 ppm plus 1300 ppm NaSal plus 3.00 mM/l of $Cu(OH)_2$; squares: a 1000 ppm plus 870 ppm NaSal plus 1.50 mM/l of $Cu(OH)_2$. Measurements carried out with a capillary viscometer. Temp = 20–23°C.
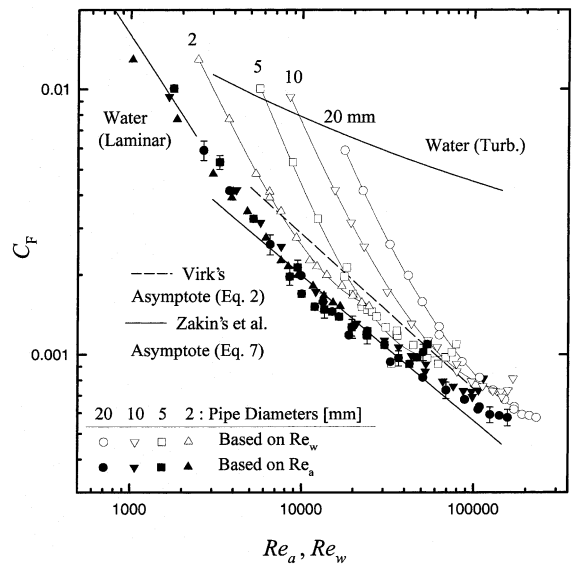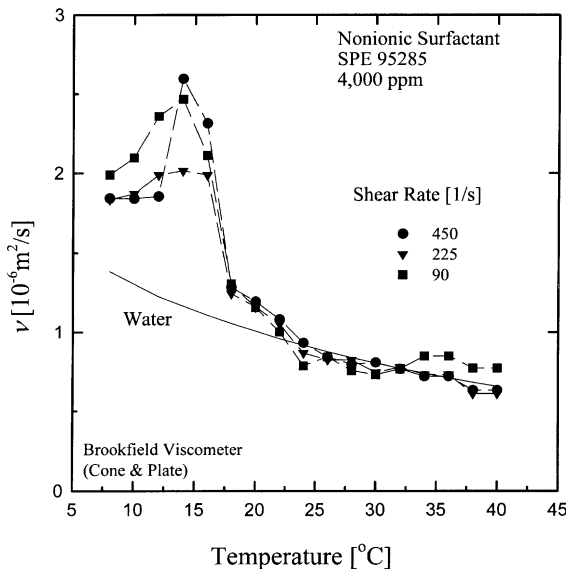

Fig. 2. Kinematic viscosity as a function of temperature for a 4000 ppm solution of a biodegradable non-ionic surfactant (SPE 95285 by Akzo) measured at three different shear rates (90, 225 and 450 s^{-1}). Measurements taken on a cone and plate viscometer (Brookfield).

Fig. 3. Friction coefficients for four different pipe diameters (20, 10, 5 and 2 mm) as a function of solvent Reynolds number (hollow symbols), and as a function of the apparent Reynolds number (solid symbols) for a fresh solution of Ethoquad T13/27, 2300 ppm, plus 2000 ppm of NaSal as counterion.

sumably attributed to the formation of the shear-induced structure (SIS), followed by the destruction of it as temperature increases.

Fig. 3 shows drag reduction measurements of the fresh surfactant solution in pipes of different diameters. The open symbols represent friction coefficient measurements plotted as function of solvent Reynolds number (Re_w). On the other hand, solid symbols represent the same measurements plotted as function of apparent Reynolds number (Re_a). The solution viscosity corresponding to each test is estimated from the corresponding wall shear stress (i.e., the apparent viscosity at the wall). In particular, these results illustrate the need for using a more appropriate viscosity in the analysis of diameter effect for surfactants [16]. The fact that C_F measurements of all four pipes collapse into basically one curve showing a smooth transition from the laminar regime to the MDRA (typical transition for many surfactant solutions), gives an additional certainty that the shear viscosity has been appropriately considered for the computation of Re.

Fig. 4 shows drag reduction measurements as a function of fluid temperature, carried in a 15 mm ID pipe for the same fluid described in Fig. 2. The DR is computed using the solution viscosity (i.e., based on the Re_a, which varied between 10,000 and 12,000). As seen, the maximum DR extends within the temperature range of 15°C to about 25°C. Therefore, by maintaining the fluid temperature between 25°C and 27°C, it was possible
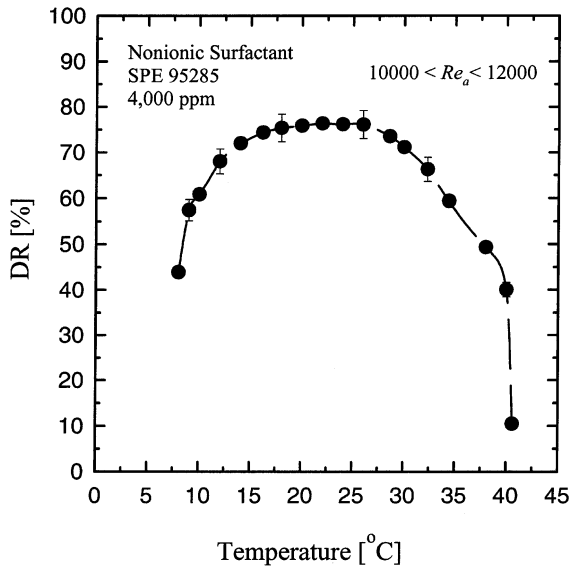
Fig. 4. Drag reduction as a function of temperature for a 4000 ppm biodegradable non-ionic surfactant (SPE 95285 by Akzo). All measurements were conducted on a 15 mm ID closed loop at a Re_a varying between 10,000 and 12,000.

to keep this solution with water-like viscosity, and yet maximum drag reduction ability of this fluid.

The results of the drag reduction tests for both kinds of surfactants are presented in Figs. 5 and 6 in different coordinates. The coordinates used in Fig. 6 may be more appropriate for the accurate representation of the asymptote, as it was the case for Virk's asymptote for polymers [17]. Besides our results, Zakin et al. [8] MDRA power law is presented in both figures. In Fig. 6, the lower bound envelope of all experimental data they used is also shown. Although their power law MDRA does not seem much off from our data in the C_F vs Re representation (Fig. 5), in Fig. 6, it is noticeable that the lower bound envelope underpredicts drag reduction practically in the whole range of Reynolds numbers, while the MDRA power law fits the data somewhat closer (although still being on the side of underpredicting drag reduction).

The implicit definition of the asymptote defined by our data can be given as:

$$\frac{1}{\sqrt{C_F}} = 23.9 \log(Re\sqrt{C_F}) - 40, \tag{9}$$

approximated by the power law:

$$C_F = 0.18 Re^{-0.50}, \tag{10}$$

valid over the range of $6000 < Re < 80{,}000$ and $4.0 < Pr < 6.5$. This correlation is slightly different from the power law proposed by Zakin et al. (Eq. (7)).
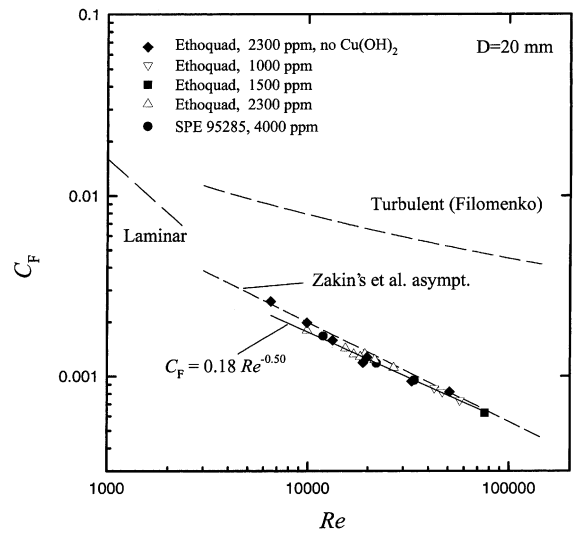

Fig. 5. Friction asymptote for the fresh cationic surfactant solution (Ethoquad T13/27): (A) 2300 ppm, plus 2000 ppm NaSal; the three contaminated cationic surfactant solutions (Ethoquad T13/27): (B) 1000 ppm, plus 870 ppm NaSal, plus 1.5 mM/l Cu(OH)$_2$; (C) 1500 ppm, plus 1300 ppm NaSal, plus 3.0 mM/l Cu(OH)$_2$; (D) 2300 ppm, plus 2000 ppm NaSal, plus 3.75 mM/l Cu(OH)$_2$, and a non-ionic surfactant SPE 95285: (E) 4000 ppm. Both kind of surfactants showed viscosity equal to water viscosity at the experimental conditions. (Pipe I.D. = 20 mm.)
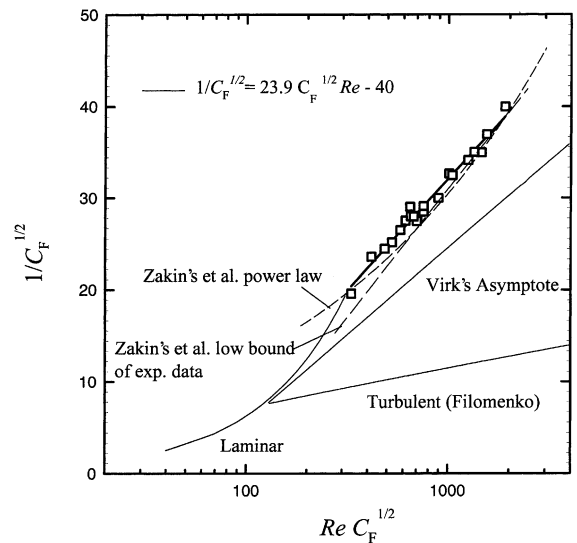

Fig. 6. Friction data for the same measurements shown in Fig. 5, but presented in the Prandtl–Karman coordinates. (Pipe I.D. = 20 mm.)

Fig. 7 presents the results of heat transfer measurements for the same water-like viscosity fluids presented in Figs. 5 and 6. As can be seen, the heat transfer
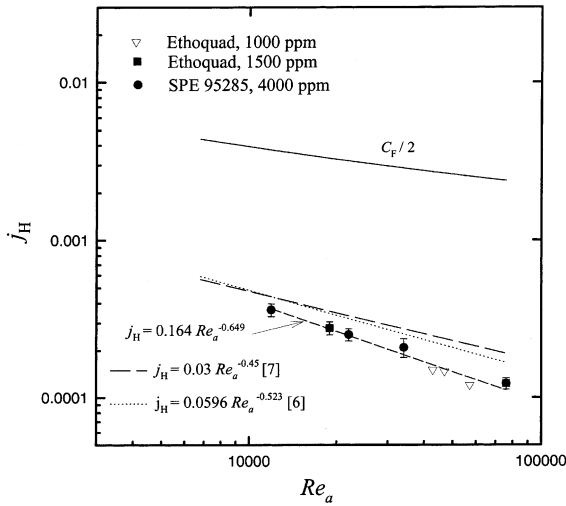
Fig. 7. Heat transfer data for the cationic surfactant solution (Ethoquad T13/27): (A) 1000 ppm, plus 870 ppm NaSal, plus 1.5 mM/l Cu(OH)$_2$; (B) 1500 ppm, plus 1300 ppm NaSal, plus 3.0 mM/l Cu(OH)$_2$; and the non-ionic surfactant SPE 95285: (C) 4000 ppm. Same experimental conditions as in Fig. 6. (Pipe I.D. = 20 mm.)
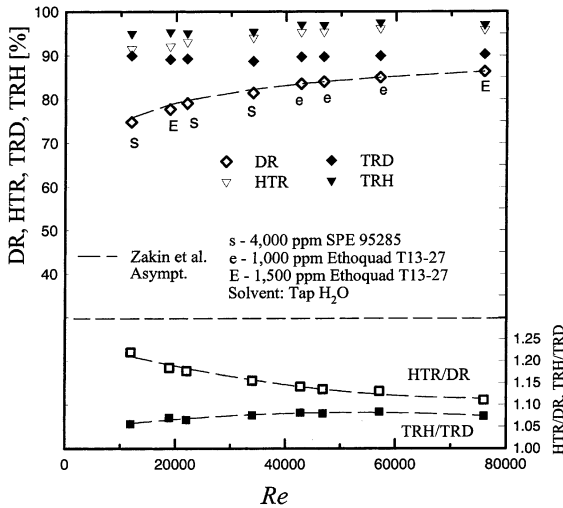

Fig. 8. Friction and heat transfer asymptotes for the same surfactant solutions as in Fig. 7 plotted in terms of drag and heat transfer reductions, as well as the modified definition of reductions (TRD and TRH). The ratio of corresponding heat transfer and drag reduction is shown in the bottom part of the figure. (Pipe I.D. = 20 mm.)

coefficients measured for surfactant solutions are lower than those measured for asymptotic polymer solutions as proposed by Cho and Hartnett [5] and Matthys [6] (plotted for reference). The asymptotic heat transfer correlation for these surfactants can be well represented by the following power law:

$$j_H = 0.164 Re^{-0.649} \tag{11}$$

valid over the range of $12,000 < Re < 80,000$ and $4.0 < Pr < 6.5$.

Finally, Fig. 8 shows both friction and heat transfer asymptotes for surfactant solutions presented in Fig. 7. The results are shown in terms of the usual drag and heat transfer reductions (DR and HTR), as well as in terms of the modified definition of reductions (TRD and TRH). As can be seen from the top portion of Fig. 8, both asymptotes expressed in terms of HTR and DR are function of Reynolds number, while in terms of TRH and TRD the asymptotes may be presented as almost constant values, independent of Reynolds number; TRH = 96%, and TRD = 90%. The ratio of the two reductions is calculated for both presentations and shown at bottom of Fig. 8. Clearly, HTR/DR is dependent on the Reynolds number, while TRH/TRD is practically independent of it (since both TRD and TRH are as well), being about 1.06.

4. Discussion

As discussed above, the use of solution viscosity for the determination of drag and heat transfer reductions has not been the practice in general, partly due to the legacy of early works with dilute polymer solutions (where shear viscosity was practically water-like), and also due, in part, to the convenience of using solvent viscosity for practical applications, where the DR is only relevant if referred to water. As shown in Fig. 3, when the apparent wall viscosity is used instead of the solvent viscosity, the friction coefficients measured on several diameter pipes, may collapse in one single curve, presumably corresponding to an asymptotic limit. At this point it may be stated that an additional certainty of the appropriateness of the viscosity is more apparent because the measured friction coefficients in the laminar region nicely fit the theoretical curve (laminar), and at the same time, the data in the turbulent region collapse to the same curve for all four pipes. This curve presumably indicates that the real asymptote is achieved, and that it is uniquely defined in terms of the friction coefficient (C_F) and the apparent Reynolds number (Re_a). On the other hand, the MDRA for surfactants proposed by Zakin et al. [8] seems to overpredict the values of C_F. The reason for this is that in all the data they collected, as well as their own, the solvent viscosity was used to compute the Reynolds numbers.

Note that for the case of the non-ionic surfactant solution, the criterion of asymptotic conditions needed for this study, could have been met by conducting the tests at about 15°C as well; however, as discussed above, that would have added an additional complication of determining the fluid viscosity as a function of the wall

shear stress (or wall shear rate), which we wanted to avoid as much as possible. The fact that all surfactant solutions used for this study, namely, the contaminated surfactant solutions, the fresh solution, and the non-ionic solution collapsed on the same curve when the apparent viscosity is used instead of the solvent viscosity, gives additional credibility to the new MDRA proposed in this study. For the same reason, the new MHTRA proposed in this study is likely a good representation of the asymptotic limit for surfactant solutions.

Regarding the use of the TRH and TRD parameters, it should be mentioned that similar parameters have been proposed in early studies as an alternative definition for the percentage reduction of drag, as they are physically more meaningful [10] since they reflect the degree of turbulence reduction with respect to full laminarization rather than to an artificial zero viscosity fluid. However, these have been disregarded early on because they incorporate an additional parameter (the laminar friction coefficient) and because the difference between these and DR and HTR is in many cases small. It has been recently shown [10], however, that although both reduction definitions are equally useful in providing information in some cases, in some others, the TRH and TRD definitions may indeed be much better suited than DR and HTR, and this study may be a good example.

The value of the TRH/TRD ratio obtained in this study (1.06), is the same value obtained for non-asymptotic polymer and surfactant solutions having equal or higher viscosity than water [9]. Note that any error in viscosity evaluation would affect the calculated TRH and TRD levels in opposite directions, i.e., increasing TRH and reducing TRD, or vice versa, and thus, that would increase the sensitivity of TRH/TRD ratio as a viscosity test tool. Besides simplicity, the definition of asymptotes in terms of constant values of TRD and TRH is very useful because of the constant ratio between them, i.e., TRH/TRD. This concept can be particularly useful for fluids with uncertain viscosity, since this ratio can be used as a test to assess whether or not a polymer or surfactant solution is asymptotic.

5. Conclusions

An improved MDRA for surfactants was proposed. This correlation showed a slightly higher DR than the one previously proposed by Zakin et al. [8], but it is presumably a better one since the viscosity of all fluids used is more accurately evaluated. For the solution with viscosity higher than water, two auxiliary criteria were used to assess the proper choice of its shear viscosity: laminar to turbulent transition, and TRH/TRD ratio. The former is depicted as a smooth transition from the laminar to the asymptotic curve, when the Re_a is used instead of the Re_w; the latter being recently established as universal for non-asymptotic and asymptotic fluids [9]. This improved correlation is given in terms of an implicit form (Eq. (9)) and in an approximate power law (Eq. (10)), both valid within the ranges of $4.0 < Pr < 6.5$ and $6000 < Re < 80,000$, and applicable to cationic surfactant solutions (fresh and contaminated) and a non-ionic solution.

Based on the measurements of the same solutions used for the MDRA measurements, a new MHTRA for surfactant solutions was proposed, a correlation that did not exist until now. This new MHTRA is given in terms of a power law approximation (Eq. (11)) and is also valid within the same range of Prandtl numbers, and within the range of $12,000 < Re < 80,000$.

Finally, the constant TRH/TRD ratio experimentally determined can be particularly useful as a tool to assess whether or not a polymer or surfactant solution is asymptotic.

References

[1] M. Kostic, Different non-Newtonian Reynolds and Prandtl number: their usage and relationship, Developments in Non-Newtonian Flows, FED-206/AMD-191 (1994) 163–169.

[2] H.W. Bewersdorff, D. Ohlendorf, The behavior of drag-reducing cationic surfactant solutions, Colloid Polym. Sci. 266 (1988) 941.

[3] Y.T. Hu, P. Boltenhagen, E.F. Matthys, D.J. Pine, Shear thickening in low-concentration solutions of wormlike micelles. II. Slip, fracture, and stability of the shear-induced phase, J. Rheology 42 (1998) 1209–1226.

[4] P.S. Virk, H.S. Mickley, K.A. Schmitt, The ultimate asymptote and mean flow structure in Toms' phenomenon, ASME J. Appl. Mech. 37 (1970) 488–493.

[5] Y.I. Cho, J.P. Hartnett, Non-Newtonian fluids in circular pipe flows, Advances in Heat Transfer, Academic Press, New York, vol. 15, 1982, pp. 60–141.

[6] E.F. Matthys, Heat transfer, drag reduction, and fluid characterization for turbulent flow of polymer solutions; recent results and research needs, J. Non-Newtonian Fluid Mech. 38 (1991) 313–342.

[7] Y.I. Cho, K.S. Ng, J.P. Hartnett, Viscoelastic fluids in turbulent pipe flow: a new heat transfer correlation, Lett. Heat Mass Transfer 7 (1980) 347–351.

[8] J.L. Zakin, J. Myska, Z. Chara, New limiting drag reduction and velocity profile asymptotes for nonpolymeric additives systems, AIChE J. 42 (1996) 3544–3546.

[9] G. Aguilar, K. Gasljevic, E.F. Matthys, Coupling between heat and momentum transfer mechanisms for drag reducing polymer and surfactant solutions, J. Heat Transfer 121 (1999) 796–802.

[10] K. Gasljevic, E.F. Matthys, Improved quantification of the drag reduction phenomenon through turbulence reduction parameters, J. Non-Newtonian Fluid Mech. 84 (1999) 123–130.

[11] K. Gasljevic, Design and construction of an experimental installation for the investigation of heat transfer and drag reductions in turbulent flow of viscoelastic fluids, M.Sc. Thesis, University of California, Santa Barbara, Santa Barbara, 1990.

[12] G. Aguilar, An experimental study of drag and heat transfer reductions in turbulent pipe flows for polymer and surfactant solutions, Ph.D. Dissertation, University of California, Santa Barbara, Santa Barbara, 1999.

[13] K. Gasljevic, An experimental investigation of drag-reduction by surfactant solutions and of its implementation in hydronic systems, Ph.D. Dissertation, University of California, Santa Barbara, Santa Barbara, 1995.

[14] K. Gasljevic, G. Aguilar, E.F. Matthys, An improved diameter scaling correlation for turbulent flow of drag-reducing polymer solutions, J. Non-Newtonian Fluid Mech. 84 (1999) 131–148.

[15] Y. Hu, E. Matthys, Effect of metal ions and compounds on the rheological properties of a drag-reducing cationic surfactant solution exhibiting shear-induced structure formation, J. Colloid Interface Sci. 186 (1997) 352–359.

[16] K. Gasljevic, G. Aguilar, E.F. Matthys, On two distinct types of drag-reducing fluids, diameter scaling, and turbulent profiles , J. Non-Newtonian Fluid Mech., in press.

[17] P.S. Virk, Drag reduction fundamentals, AIChE J. 21 (1975) 625–656.