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The Ultimate Asymptotes and Possible Causes of Friction Drag and Heat Transfer Reduction Phenomena

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Abstract

The phenomena behind the fascinating friction drag and heat transfer reduction, associated with turbulent flows of so-called "drag-reducing fluids" (certain dilute polymer solutions, but also many others including gas suspensions), are not well understood. Major obstacles are a very complex structure and properties of these fluids (polymer solutions), and the turbulence itself is not yet fully comprehended. It is believed that elastic fluid properties are strongly related to these phenomena, up to an extreme to evaluate the fluid elasticity on the basis of the corresponding drag reduction in turbulent channel flow. Due to absence of drag reduction, the polyacrylic-acid resin (Carbopol) aqueous solutions (with cross-linked macromolecular structure) were mistakenly believed to be non/weakly elastic. On the other hand, the drag reduction is very strong in so called "linear (non-linked) macromolecular" solutions, like polyethylene-oxide or polyacrylamide. The non-linked, originally randomly oriented macromolecules, easily realign in flow direction (as opposed to the cross-linked polymers) making the flowing fluid structure (and its properties) anisotropic. The turbulence is considerably suppressed in normal-to-main-flow direction, substantially reducing momentum and energy transfer, even in minute polymer concentrations, for which the solution does not have any measurable elasticity. This fact suggests that turbulence suppression (i.e. flow laminarization) is a determining factor for the reduction phenomena, not the fluid elasticity. Accordingly, the drag and heat transfer reduction phenomena are analyzed with regard to new references: the extended laminar flow results (100% laminarization), which represent the lowest physically-possible friction and heat transfer in duct flow, the ultimate reduction asymptotes.

Introduction

Ever since Toms' discovery (1949) [1] that the friction drag of some solutions under turbulent flow conditions is considerably smaller than the expected values, many researchers have been excited about the peculiar and often unexpected flow and heat transfer behavior of these drag-reducing and often-called viscoelastic fluids. It is now well-known that the pressure drop and heat transfer associated with the turbulent duct flow of certain fluids, see Table 1, are considerably lower than the corresponding values of Newtonian fluids. Excellent articles on the subject are presented by Dodge and Metzner [2], Metzner [3], Lumley [4], Virk [5], Hoyt [6,7], Cho and Hartnett [8], and Hartnett [9]. Hence, it is not the intention of this work to review existing literature, but to present the most peculiar behaviors and applications, see Tables 2 and 3, while the interested readers are referred to the indicated articles, some of which [3,6,7,8] cite extensive references on the subject. Although these "miraculous" phenomena have been extensively investigated in recent decades, the underlying mechanism producing the drag and heat transfer reduction is not yet fully understood. Not surprisingly, Bird and Curtiss [10] titled their paper "Fascinating Polymeric Liquids," and even the New York Times wrote about these unusual and important phenomena in an article " Slippery Water Mystery Seems Finally Solved" [11]. Actually the "mystery" remains in clouds of hypotheses, far from resolution, primarily for two reasons:

1) classical isotropic fluid mechanics approach does not work well for the very complex flow-induced anisotropic fluid structure (even if the corresponding motionless fluid is isotropic); i.e., the constitutive equations are inadequate, and

2) the turbulence itself is not yet well understood even for "common" Newtonian fluids.

The so called "drag reducing" fluids are simultaneously even stronger "heat-transfer reducing" fluids. The most effective drag and heat transfer reducing fluids are aqueous solutions of non-linked high-molecular-weight polymers such as polyethylene oxide and polyacrylamide. They are listed, together with other drag-reducing additives, in Table 1. Their characteristic channel-flow and heat-transfer behavior are summarized in Table 2.

A number of useful applications using drag-reducing fluids are listed in Table 3. Many fluids in the chemical, pharmaceutical, biomedical and food processing industries are of a rather complex structure and may be drag- reducing and/or visco-elastic. Hence, it is very important to advance understanding of the phenomena associated with the drag-reduction, in order to further utilize their peculiar behavior.

In light of the large reductions in friction and heat transfer compared to the corresponding turbulent Newtonian flows, it is not surprising that the early reports of these phenomena caused a considerable stir in the scientific community. At first, it appears that the friction drag reduction phenomenon is miraculous, energy- savior, as if something is obtained from nothing, almost a "perpetuum mobile." However, the friction-drag and heat-transfer reduction phenomena will be enlightened from a somewhat different point of view, from the so- called ultimate asymptotes or natural/logical/physical references.

Theories of Reduction Phenomena: Drag Reduction versus Fluid Visco-Elasticity

The existing theories and present author's hypothesis about possible mechanisms of turbulent drag-reduction are presented here:

1). Shear Thinning: Originally it was speculated that the near-wall-layer, by virtue of shear-thinning may have extremely lower friction coefficient than pure solvent. Later this theory was discounted since it was proved that the shear-thinning friction is somewhat lower, but not nearly that of drag reduction friction.

2). Visco-Elasticity and Normal-Stresses: This may well be the most unfortunate theory. Drag-reducing polymer solutions are viscoelastic and show the normal-stress differences, but for concentrations extremely high by drag-reduction standards. Very dilute solutions do not exhibit any measurable

Table 1: Drag reducing additives and their properties

Type of Additive	*Characteristic Properties*
1. High-Polymers -polyethylene oxide (the best) -polyisobutylene (oil-soluble) -polyacrylamide -carboxymethylcellulose	The most important features are: macromolecules - high molecular weight (10^6 or higher), linear structure, with maximum extensivity (up to hundreds of thousands of extended-length-to-width ratio of a macromolecule), excellent solubility. Also some other polyelectrolites are known as drag-reducing agents.
2. Soap and Surfactant aggregates	Low-molecular-weight alkali-metal and ammonium soap molecules form aggregates or "micelles" in long-chains. Non-ionic commercial surfactants are very good drag-reducers.
3. Fibers -asbestos -nylon -wood pulp	Asbestos fibers are extremely long (hair-like). Nylon fibers are shorter (length-to-diameter ratio about 50). Wood pulp suspensions in water reduce turbulent friction. Drag reduction is less in fiber-gas suspensions.
4. Solid/Liquid Particles -thoria -sand and dust particles -droplets in gases	Turbid rivers flow faster than when clear. Pneumatic systems have higher flow rates when dust laden than with clean air only. Suspension of thoria in water show drag reduction. Even droplets in gasses reduce friction.
5. Other Natural Sources	Natural gums (like guar), algas and bacteria usually produce copious, high-molecular-weight polysaccharide.

PRINCIPAL PROPERTIES OF DRAG-REDUCING ADDITIVES

- ***Extended length and/or sufficient mass (inertia) to interfere and suppress turbulent fluctuations, particularly transverse ones.***
- ***Rigidity and/or elasticity to suppress and absorb turbulent fluctuations***

Table 2: Known friction and heat-transfer behaviour of drag-reducing fluids

	Characteristic Phenomena
1. Friction Factor	Considerable friction drag reduction even for minute concentration (0.5 ppm of polyethylene oxide in water) gives friction reduction of 40%, which, with increase of polymer concentration, reaches the limiting asymptotic value up to 80%, i.e. the solution friction drag is only 20% of the pure solvent (usually with higher polymer concentrations).
2. Heat Transfer	Even stronger heat-transfer reduction than friction drag reduction; over 90% of corresponding Newtonian values for the limiting asymptotic case. Rarely, this phenomenon is useful, like in crude-oil pipelines (smaller losses, i.e. lower viscosity at higher temperature). In contrast, heat transfer is increased in boiling and in laminar flow through non-circular ducts.
3. Entrance Lengths	Much longer than the corresponding Newtonian values. Order of 100 and 500 hydraulic diameters for hydrodynamic and thermal entrance lengths respectively.
4. Transition to Turbulence	Smoother transition from laminar to turbulent flow, as opposed to jump-like and abrupt transition of Newtonian fluids. Also higher transitional Reynolds number values (much higher than 2000, often 5000 or higher). In some cases the "onset" of drag-reduction is encountered.
5. Mean Velocity Profiles	Flatter velocity profiles (in central region) than the solvent alone. That is quite the opposite from the influence of pipe roughness on the profile.
6. Turbulence structure	Fluctuating v' velocity component is reduced, while axial component u' is less effected; though some results are conflicting. Spacing between large-scale slow-streaks is more than doubled, and time between the "bursts" (fluid lumps), ejected from the wall region, is increased tenfold.
7. Other	Other important effects include: Cavitation is of a different character and is often greatly reduced. Extensional flows through porous media (an application in Enhanced-Oil-Recovery) and jet flows have different characteristics than in pure solvent. Several other behaviors of more-concentrated polymer solutions, like die-swell, Weissenberg rod-climbing effect, tubeless siphon, inverse secondary flow etc., are markedly different from Newtonian flows.

elasticity, nor change of viscosity from pure solvent, still they are very strong drag reducers. Also, viscoelastic, cross-linked polyacrylic acid (Carbopol) solutions do not show any drag-reduction, except for shear-thinning effect. It may well be that viscoelasticity does not play any major role in drag reduction, but is merely an accompanying property of some drag-reduction fluids. It is known that both, viscoelastic and non-elastic fluids may produce drag-reduction.

3). **Molecular "Stretching"**: Greatly extended linear macromolecules in shear direction interfere with turbulence, providing a stiffening effect, thus reducing friction drag. Other postulates that molecular entanglements is responsible for interfering with, and enlarging the sublayer eddies. Some have argued that macromolecules elastic properties and continuous deformation, like a yo-yo effect are responsible for damping small turbulent eddies, storing-and-recovering, otherwise dissipated turbulent energy. However, for extremely dilute solutions it seems unlikely that such a hypothesis could be valid.

4). **Decreased Turbulence Production**: Some researchers suggest that polymer additives interfere with the production of turbulence, and that the reduction phenomena are not due to turbulence dissipation but are driven by reduced generation of turbulence. Since the two have to be in balance, their role may be easily mistaken.

Table 3: Applications with drag-reducing fluids

Application	*Description*
1. Pipelines	The first application of drag-reducers was use of guar in oil-well "fracturing," presently a routine practice. Use of oil-soluble polymers in Trans-Alaska-Pipeline-System is the most impressive success of drag reducing phenomenon. Typical systems achieve drag reductions of 30-50% at polymer concentrations of 10 ppm (0.001%). Coal and other slurries, and large central-heating hot-water installations are potential candidates as well as many other pipeline systems.
2. Storm-sewer Augmentation	By adding polymers the storm-sewer flow capacity may be increased about 30%. If it is done only during the peak-demands, like during storms and floods, it may be very cost-effective, thus eliminating large capital expenditure.
3. Fire Fighting	Water flow rates and jet distances may be increased, or smaller hose-lines may be used. Polymers have been used by fire-fighters in Hamburg (Germany), New-York City and Paris. However, this promising application does not seem to have gained wide acceptance, probably the efficiency is a secondary issue in this business.
4. Ocean/River Ship Flows	Friction-drag reduction may be obtained by ejecting concentrated polymer solutions near the ship nose, or through a porous wall, or from an ablating coating. Substantial drag-reduction was measured in a water tunnel with ejection of a 500 ppm Polyox solution. Major reduction in polymer cost is necessary for commercial ship application to be feasible.
5. Scientific Studies	The friction and heat-transfer reduction phenomena may assist in the studies of molecular properties and, as ironic as it may be (since it changes turbulence structure), in better understanding of turbulence, a very complex flow phenomenon. Several other scientific challenges are emerging.
6. Other	Soluble coatings for rapid-sinking of oceanographic instruments and other objects, polymer addition to entire city water supply if in high demand due to emergency, like a major fire, irrigation systems augmentation, are attractive and possible applications.

5). Decreased Turbulence Dissipation: It is the belief of the present author that the turbulence energy dissipation via finest eddies are greatly reduced (suppressed) by additives interference, to an extent equal to the drag-reduction, while larger eddies and large-scale flow instability are present (still turbulent flow), but with different and more favorable structure.

6). Vortex Stretching: It is postulated that resistance to vortex stretching reduces the mixing and energy losses. It is further shown that dilute polymer solutions may have thousands of times higher extensional viscosity than the steady-state viscosity, which may have a strong influence on drag-reduction mechanism, believed to play a major role in a region just outside the laminar sublayer ($5 < y^+ < 50$).

7). Non-isotropic Properties and Turbulence: This is another idea of the present author and is elaborated on in the text. Since viscosity is shear-rate dependent and the shear-rate is directional, the solution structure becomes anisotropic, hence viscosity (including dynamic and higher order stress coefficients) has to be anisotropic: For shear thinning fluids, it is lower in the flow direction and higher in cross-flow directions, thus suppressing considerably the cross-flow fluctuating velocity components.

8). Laminarization of Turbulent Flow: Turbulence is the "wasteful" dissipation of fluid energy via the finest turbulent eddies, thus it directly increases friction drag. Therefore, drag reduction is direct measure of partial flow laminarization. By definition, turbulence is random fluctuations and energy dissipation, otherwise flow instability will have some orderly secondary (and unsteady) flow patterns.

The first Shear Thinning drag-reduction theory was already discounted, the second one, based on fluid Visco- Elasticity and Normal-Stresses is the most contradictory and questionable, while the remaining ones are inter- related and centered around more-or-less the same thing: changed (or better yet, reduced) turbulence activity/structure of the flow. Therefore, some comments and analysis in that direction will be in order, and are elaborated in the following sections.

The following are some characteristic, among many unanswered, questions:

* Does viscoelasticity have any direct relation with turbulent drag-reduction?

* Influence of wall may or may not be crucial since polymers may profoundly modify jets and free turbulence?

* Internal and external boundary layers may have different influence on drag reduction and an attempt to unify the phenomena may be deceptive?

* Why is "onset" of drag reduction present with some, but not all drag-reduction fluids?

* Why do additives produce the maximum friction and heat-transfer reduction asymptotes but can not fully laminarize flow (Ultimate Drag Reduction)?

* Why is the asymptotic heat-transfer reduction stronger and occurs for higher polymer concentration than friction drag?

And many other questions!

An Essential Fluid Model: Flow-Induced Non-Isotropic Properties

A high-molecular-weight polymer dissolved in water (or other solvent) builds up a long, macromolecular chain structure, similar to fiber-like composite substance, sort of flexible (and partially elastic) "molecular web," which reinforces the original solvent structure [12]. This is reflected in a general increase in the fluid-solution viscosity at all shear rates, particularly at the lower shear rates, see Fig.1. The important difference between a solid fiber-composite and a polymer-solution is that the fibers are molded (fixed) in the matrix, while the macromolecules may move within the solvent during a flow. The latter will change the original solution structure and make the viscosity (resistance to flow) shear-rate dependent, i.e. the solution is called the non-Newtonian fluid.

The fluid viscosity is measured in the so-called isometric flow, where only one component of the shear-stress tensor is non-zero, like one-dimensional flow through circular pipe, between cone-and-plate or concentric cylinders. Under shearing stresses the flexible macromolecular chains, originally randomly shaped and oriented in a motionless fluid, realign along the shearing layers, see Fig.1. With the shear-rate increase, the macromolecular chains become better aligned and untangled in the flow

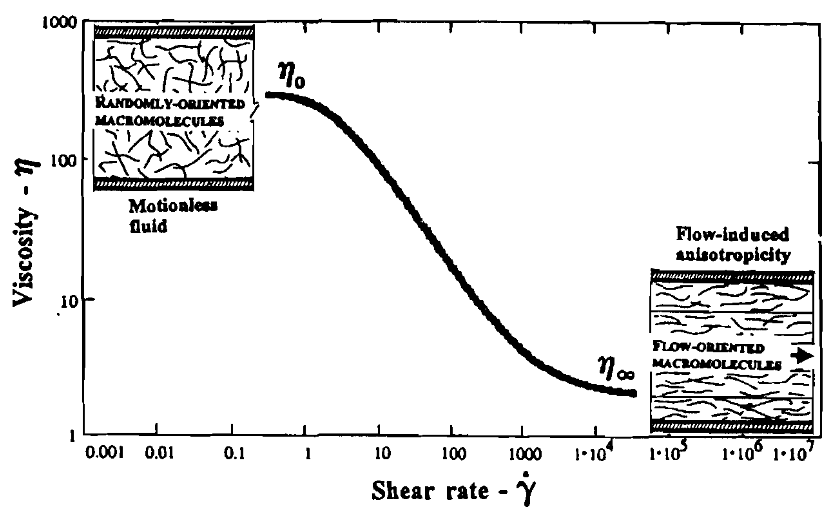

Fig. 1: Shear-rate dependent viscosity and flow-induced anisotropic structure of an aqueous polymer solution

direction, and the original resistance to flow (zero-shear-rate viscosity, η_o), due to random shape and orientation of the chains, is considerably reduced, reaching a minimum (infinite-shear-rate viscosity, η_∞) at some limiting shear-rate after which further alignment and/or entanglement of the macromolecules are not possible, see Fig.1. Therefore, $\eta_o > \eta_\infty > \eta_s$, the latter being the viscosity of the original solvent; these differences are negligible for a very dilute solution ($\eta_o \approx \eta_\infty \approx \eta_s \approx$ constant). The viscosity - shear rate function (relationship) is successfully expressed by the Powell-Eyring model:

$$\eta^* = \frac{\eta - \eta_\infty}{\eta_o - \eta_\infty} = \frac{\sinh^{-1}\dot{\gamma}^*}{\dot{\gamma}^*} = \eta^*(\dot{\gamma}^*) \tag{1}$$

where dimensionless viscosity η^* and dimensionless shear rate $\dot{\gamma}^*$ are defined in Eq.1. In dimensionless form $\eta^* = \eta^*(\dot{\gamma}^*)$, the Powell-Eyring equation is a universal one for any fluid, after the dimensional equation is scaled with the time constant (t), and the zero and infinite shear rate viscosities (η_o, η_∞), which are characteristic constants of a particular fluid. For example, using Eq.1, from the measured steady shear rate viscosity as function of the shear rate (see Figure 1) the constants t, η_o, η_∞ are determined to be 6.1sec, 300cPs, 3cPs for a 0.1% polyacrylamide aqueous solutions respectively [13] (note: 1centi-Poise [cPs] = 1mPasec). For a narrow shear-rate range (often in general due to simplicity) the viscosity may be expressed by the so-called power-law model: $\eta = \eta(\dot{\gamma}) = K\dot{\gamma}^{\,n-1}$ with two constants, K and n only.

According to this author, the major fallacy is made when the isometric-flow results are generalized (extrapolated) to multi-dimensional flow situation. Namely, the measured directional shear-rate $\dot{\gamma}_{ij}$ is generalized (substituted) by a shear-rate invariant-magnitude $\dot{\gamma}$, of the shear-rate tensor $\{\dot{\gamma}_{ij} = \partial u_i/\partial x_j + \partial u_j/\partial x_i,\ i \neq j\}$ through the second invariant of the tensor, i.e.:

$$\dot{\gamma} = \sqrt{\frac{1}{2}(\dot{\gamma}_{i,j} : \dot{\gamma}_{i,j})} \tag{2}$$

This implies that the fluid viscosity is directionally independent, i.e. isotropic, and is valid for isotropic fluids only. However, from the observed polymer-solution structure while under shearing (see Fig.1), it is obvious that polymer chains will be realigned in a preferable flow (iso-shear-rate) direction, making the fluid structure and resistance to flow (read viscosity) directionally dependant, i.e. anisotropic. It should be obvious, at least for such kind of polymer solutions (probably for many others), that resistance to cross-flow (with macromolecules aligned in axial main-flow direction) should be much higher than the resistance to axial flow (at least as η_o). The fluid is "shear-thinned" in one direction only, producing flow-induced anisotropic structure and anisotropic viscosity. At least for such fluids, it would be simpler, more realistic, and more accurate (less extrapolation of isometric flow) if the shear rate magnitude $\dot{\gamma}$ in Eq.2, used in the viscosity function of Eq.1, is expressed as magnitude of the corresponding component of shear-rate, i.e. for the shear-stress $\tau_{i,j}$, the shear rate magnitude $\dot{\gamma} = |\dot{\gamma}_{i,j}|$. This way, the viscosity will be directionally dependent (anisotropic), i.e. a function of the corresponding shear-rate component:

$$\eta_{i,j} = \eta(|\dot{\gamma}_{i,j}|) \tag{3}$$

Indeed, the conventional extrapolation of isometric (one-dimensional) viscosity measurements to multi-dimensional flow situation, using an invariant shear-rate magnitude, made the viscosity shear-rate dependent and non-uniform. However, the obvious flow-induced anisotropicity is overlooked. It is not unfair to state that measured properties in an isometric flow are safely applicable to one-directional flow only, beyond which proper justification is necessary. Furthermore, for motionless solution (shear-rate is zero for all directions) the so-called zero-shear-rate viscosity will be isotropic which complies with the random orientation of macromolecules. After all, if the fluid structure is isotropic the fluid properties have to be isotropic, and vice versa for an anisotropic fluid structure. The flow-induced anisotropic fluid structure, consequences of which are anisotropic viscosity, dynamic viscosity, and other (higher order) viscosity and stress coefficients may play a major role in changing the turbulence structure and the reduction of friction drag and heat transfer.

The Ultimate Asymptotes: "Extended" Laminar Flow and Heat Transfer

A logical question arises: "For a given real/viscous fluid, channel size, and flow-rate, is there the most efficient flow and, if so, what should it be like?" The answer is rather simple: Such flow has to be "purpose- or goal-oriented." Velocities of all fluid particles have to be in the exclusive, main flow direction, without any components in the other futile directions, orthogonal to the main flow or backwards, like turbulent fluctuating components. The former contributes to the over-all flow rate, the goal of the flow, while the latter do not produce any useful flow rate, but rather dissipate energy only, apparently unnecessarily. The most efficient channel flow of any real (viscous) fluid would be the corresponding laminar flow at any Reynolds number value. For such a flow, the friction drag would be the minimum possible, just to overcome the molecular viscous friction. Therefore, the maximum-possible turbulent drag-reduction could be achieved if all turbulent fluctuating velocity components are suppressed, or never allowed to develop, if the flow is somehow maintained laminar, regardless of the Reynolds number value. This will establish the "ultimate" friction-drag asymptote. Incidentally, such flow is possible (though difficult) to achieve if utmost care is taken to avoid any flow-disturbances which will otherwise generate flow-instability and turbulence for higher Reynolds numbers [14]. Consequently, if drag- reduction is observed to be so large, resulting in a friction drag smaller than in the corresponding laminar flow, that would warrant some experimental or some other fundamental error(s), including use of inappropriate value of fluid viscosity.

Likewise, the heat transfer under the condition of extended laminar flow (at any Reynolds number) will be laminar, i.e. the absolute physical minimum of heat transfer for a given flow rate. This establishes the "ultimate" heat transfer asymptote for any turbulent heat-transfer reduction process. The terms "extended" laminar flow and corresponding "ultimate" friction-drag and heat-transfer asymptotes refer here to the pertinent laminar friction factor f_L, and heat-transfer j_L -factor respectively, regardless of the magnitude of the Reynolds number: as if the flow is laminar no matter what! These ultimate

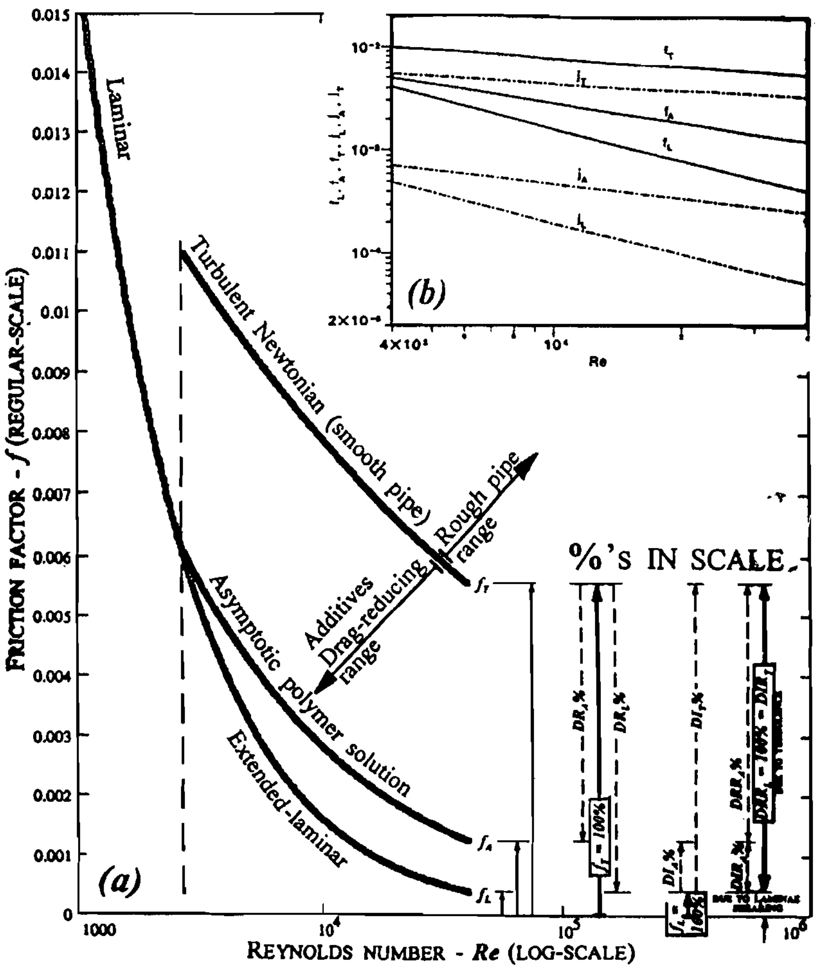

Fig.2: a) Friction factors of three characteristic flows (in semi-log scale) and presentation of drag reduction, increase and ratio terms (see tables 4 & 5)

b) Friction factors - f and heat transfer j - factors for laminar (L), asymptotic (A) and turbulent (T) flows (see tables 4 & 5) asymptotes (subscript L) are presented in Fig.2, together with other characteristic results for Newtonian ("common" turbulent, subscript T) and asymptotic drag-reducing turbulent flows (subscript A).

An "Upside-Down Analysis" with Reference to Ultimate Asymptotes

The so-called "drag-reducing" fluids, like certain polymer solutions, show considerable friction-drag and even stronger heat-transfer reduction as compared to common (Newtonian) fluids. The friction-drag reduction increases with an increase of polymer concentration up to a certain asymptotic limit, first observed by Virk [5]. Similarly, there is an asymptotic limit (at higher polymer concentration than for friction-drag asymptote) for heat-transfer reduction [8]. Once these maximum friction-drag or heat-transfer asymptotes have been reached, further increase in polymer concentration does not influence the friction or heat transfer coefficients. It is believed that these maximum asymptotes are functions only of the Reynolds number and are independent of pipe size and polymer type. The maximum asymptotic Fanning friction factor ($f = \tau_w/(\frac{1}{2}\rho\, U^2)$ and the Colburn heat-transfer factor ($j = Nu/(\mathrm{Re}\, Pr^{1/3})$ may be approximately expressed, for the Reynolds number range of interest, by the familiar and simple equations [15]:

$$f = a\mathrm{Re}^{b} \quad \text{and} \quad j = c\,\mathrm{Re}^{d} \tag{4}$$

where the constants a,b,c,d are given in Table 4, together with corresponding constants for ("extended") laminar and turbulent flow for Newtonian fluids (the Blasius equation). If the conventional Reynolds number is replaced with more generalized, the Metzner or Kozicki Reynolds number, the Eq.4 will be valid for non-Newtonian fluids and/or non-circular ducts respectively [16].

Originally [7], the drag reduction (DR) was defined as pressure drop difference between the solvent (s) and polymer solution (p) with regard to that of the solvent, DR = 100% $(\Delta p_s - \Delta p_p)/\Delta p_s$, for a given pipe length. However, it is more general to express the drag reduction through the corresponding dimensionless friction factors, and similarly, the heat-transfer reduction (HR) through dimensionless heat-transfer factors, i.e.:

$$DR = \frac{f_T - f}{f_T} \quad \text{and} \quad HR = \frac{j_T - j}{j_T} \tag{5}$$

where, non-subscripted factors refer to "drag-reducing" fluid, while subscript "T" refers to the corresponding reference, turbulent Newtonian value, without friction-drag or heat-transfer reduction. There is one difference between the original pressure-drop drag-reduction and the friction-factor drag-reduction. The original drag reduction, defined through pressure drops, is based on a constant flow rate (more practical), while the drag reduction, defined through friction factors, is based on a constant Reynolds number (more fundamental). With the increase of polymer concentration and solution viscosity while keeping the flow rate constant, the dimensional pressure drop may start increasing after some polymer concentration level, which is not the case with the dimensionless friction factor at a constant Reynolds number (requires an increase in flow rate). For the very dilute solutions (with viscosity equal to that of solvent) the drag reductions defined through the pressure drops or friction factors are the same.

It was pointed out in the previous section that it is fundamentally beneficial to analyze friction-drag and heat transfer phenomena with regard to the corresponding ultimate asymptotic values, i.e. the corresponding "extended" laminar values as the new reference. Since the turbulent friction and heat-transfer factors of drag reducing fluids are higher than the corresponding extended-laminar

Table 4: Friction factor and heat transfer J - factor equations for different flows

EQUATIONS	$f = a\,Re^b$		$j = c(Pr)\,Re^d$				
FLOW ↓ / COEFF.→	*a*	*b*	*c(Pr)* ↓	*c* *Pr=1*	*c* *10*	*c* *100*	*d*
Laminar (L)	16.00	-1.00	$4.364 \cdot Pr^{1/3}$	4.364	2.03	0.94	-1.00
Asymptotic-Virk/UIC (A)	0.59	-0.58	0.03	0.030	0.03	0.03	-0.45
Turbulent-Blasius/Newtonian (T)	0.079	-0.25	$0.023 \cdot Pr^{0.0667}$	0.023	0.027	0.031	-0.20

values, the new terms are defined: drag increase (DI) and heat-transfer increase (HI). i.e.:

$$DI=\frac{f-f_L}{f_L} \quad \text{and} \quad HI=\frac{j-j_L}{j_L} \tag{6}$$

where, non-subscripted factors refer to "drag-reducing" fluid, while subscript "L" factor refers to the corresponding reference, extended-laminar value, the most efficient flow possible for a real (viscous) fluid, refer to the previous section.

The characteristic asymptotic friction and heat transfer factors for "drag-reducing" fluids, together with the two reference results (extended-laminar and Newtonian-turbulent flows) are calculated, using Eq.4 and Table 4, and presented in Table 5 and Fig.2. Also, the conventional drag and heat-transfer reduction terms of Eq.5 and newly defined drag and heat-transfer increase terms of Eq.6 are defined more specifically and calculated for the three characteristic flows in Table 5, and presented graphically in Fig.3.

Table 5 and Fig.3a reveal that the friction-factor reduction associated with the asymptotic limit of a "drag- reducing" fluid as compared with a turbulent Newtonian flow, ranges from approximately 52% at Re = 4000 to 77% at Re = 40,000, while the corresponding drag-reductions for the hypothetical (but possible) extended-laminar flow are about 60% and 93% respectively. It is indicative to express the asymptotic (or any actual) drag- reduction as the ratio of the "ultimate drag reduction" of the extended laminar flow. This ratio, designated here as Drag Reduction Ratio (DRR), see Table 5 and Fig.3a, represents the fundamental drag reduction effectiveness of any drag-reducing additive, i.e. solution. Similarly, the Heat-transfer Reduction Ratio (HRR) is defined as the ratio of an actual heat-transfer reduction to that of extended laminar heat-transfer reduction, the latter being the maximum physical possibility, i.e.:

$$DRR=\frac{DR}{DR_L}=\frac{f_T-f}{f_T-f_L} \quad \text{and} \quad HRR=\frac{HR}{HR_L}=\frac{j_T-j}{j_T-j_L} \tag{7}$$

where the nomenclature is explained in Eqs.5&6 and Tables 4&5. The calculated results are presented in bold in Table 5 and on Fig.3. It is interesting to note that the heat-transfer reductions of the asymptotic, ultimate extended-laminar, and their ratios are all larger than their drag-reduction counterparts. The reduction ratios, see Table 5 and Fig.3a, are in the 80's and 90's percentiles for the asymptotic friction and heat transfer reduction respectively.

Since we are analyzing friction-drag and heat-transfer reduction, it makes sense to analyze them with regard to the most effective flow possible, the extended-laminar flow for which the reductions are ultimate, i.e. 100%. With regard to this new reference, the friction and heat-transfer factors of drag-reducing fluids are now larger (including the maximum asymptotic values) than the corresponding extended-laminar results. The "wonder miracle" of drag-reduction is unveiled now in different, more realistic form: The turbulent flow of these "miraculous" fluids are actually flow-inefficient ("unnecessarily" energy dissipative), but not nearly as inefficient (dissipative, wasteful) as the common Newtonian fluids. The measure of flow inefficiency or wasteful turbulent- dissipation of energy is

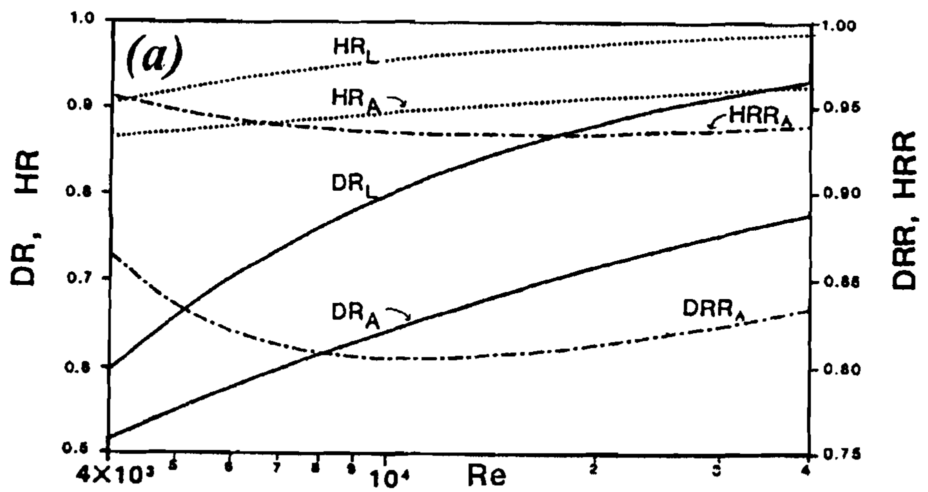

Fig. 3a: Drag reduction and ratio (DR, DRR) and heat transfer reduction and ratio (HR, HRR) for characteristic flows of tables 4 and 5

Table 5: Definitions of drag and heat transfer reduction and increase and their characteristic values

Name	Definition	Description
Friction Drag Reduction - ASYMPTOTIC (A) - LAMINAR (L) - RATIO	$DR = (f_T - f)/f_T$ $DR_A = (f_T - f_A)/f_T$ $DR_L = (f_T - f_L)/f_T$ $DRR = DR/DR_L$	DEFINED AS REDUCTION FROM REFERENCE TURBULENT QUANTITY WITH RESPECT TO THE LATTER. MAXIMUM POSSIBLE REDUCTION IF FOR EXTENDED LAMINAR FLOW AND THE RATIO REPRESENTS REDUCTION WITH RESPECT TO IT. IT IS MEASURE OF FLOW LAMINARIZATION.
Heat Transfer Reduction - ASYMPTOTIC (A) - LAMINAR (L) - RATIO	$HR = (j_T - j)/j_T$ $HR_A = (j_T - j_A)/j_T$ $HR_L = (j_T - j_L)/j_T$ $HRR = HR/HR_L$	THE SAME AS ABOVE.
Friction Drag Increase - ASYMPTOTIC (A) - TURBULENT (T) - RATIO	$DI = (f - f_L)/f_L$ $DI_A = (f_A - f_L)/f_L$ $DI_T = (f_T - f_L)/f_L$ $DIR = DI/DI_T$	DEFINED AS INCREASE FROM REFERENCE EXTENDED LAMINAR QUANTITY WITH RESPECT TO THE LATTER. MAXIMUM INCREASE IS FOR THE NON-REDUCING, NEWTONIAN TURBULENT FLOW AND THE RATIO REPRESENTS INCREASE WITH RESPECT TO IT. IT IS MEASURE OF FLOW TURBULIZATION.
Heat Transfer Increase - ASYMPTOTIC (A) - TURBULENT (T) - RATIO	$HI = (j - j_L)/j_L$ $HI_A = (j_A - j_L)/j_L$ $HI_T = (j_T - j_L)/j_L$ $HIR = HI/HI_T$	THE SAME AS ABOVE. *NOTE: Definitions of the **laminar** (L), asymptotic (A), and **turbulent** (T) flows are given in TABLE 4*

	FRICTION FACTOR			HEAT TRANSFER J-FACTOR *(Pr=10)*		
Re	$f_L \times 10^3$	$f_A \times 10^3$	$f_T \times 10^3$	$j_L \times 10^3$	$j_A \times 10^3$	$j_T \times 10^3$
4,000	4.00	4.80	9.93	0.51	0.72	5.11
15,000	1.07	2.23	7.14	0.14	0.40	3.92
40,000	0.40	1.26	5.59	0.05	0.25	3.22

	Drag Reduction			*Heat Transfer Reduction*		
Re	DR_A	DR_L	DRR_A	HR_A	HR_L	HRR_A
4,000	0.516	0.597	**0.864**	0.859	0.901	**0.954**
15,000	0.687	0.851	**0.808**	0.899	0.966	**0.931**
40,000	0.774	0.928	**0.833**	0.921	0.984	**0.936**

	Drag Increase			*Heat Transfer Increase*		
Re	DI_A	DI_T	DIR_A	HI_A	HI_T	HIR_A
4,000	0.201	1.483	**0.136**	0.418	9.08	**0.046**
15,000	1.093	5.692	**0.192**	1.934	28.02	**0.069**
40,000	2.159	12.97	**0.167**	4.032	62.61	**0.064**

expressed by the newly defined friction Drag Increase (DI) and Heat-transfer Increase (HI) in Eq.6, and their respective Drag Increase Ratio (DIR) and Heat-transfer Increase Ratio (HIR), see Table 5 and Fig.3b, are:

$$DIR = \frac{DI}{DI_T} = \frac{f - f_L}{f_T - F_L} \text{ and } HIR = \frac{HI}{HI_T} = \frac{j - j_L}{j_T - j_L} \quad (8)$$

In light of the new reference, the extended-laminar flow, the characteristic results are presented in the lower part of Table 5 and on Fig.3b. The physical meaning of the Table 5 last-row numbers is: For an asymptotic drag- reducing flow at 40,000 Reynolds number (Re), the drag increase is 2.159 or about an additional 216% with reference to the corresponding (same Re number) laminar flow. Still, this considerable friction-drag increase is much less wasteful than the common Newtonian flow's friction-drag being an additional 12.97 times larger, or about 1300% more than the reference laminar flow at the same Re number. These give us the drag-increase-ratio of 0.167, meaning that the inefficiency of the asymptotic drag-reducing flow is only 16.7% of the inefficiency of Newtonian turbulent flow at the same Reynolds number. The heat transfer increases for the asymptotic and turbulent Newtonian flows are, in absolute measures of the reference laminar heat transfer, higher for an

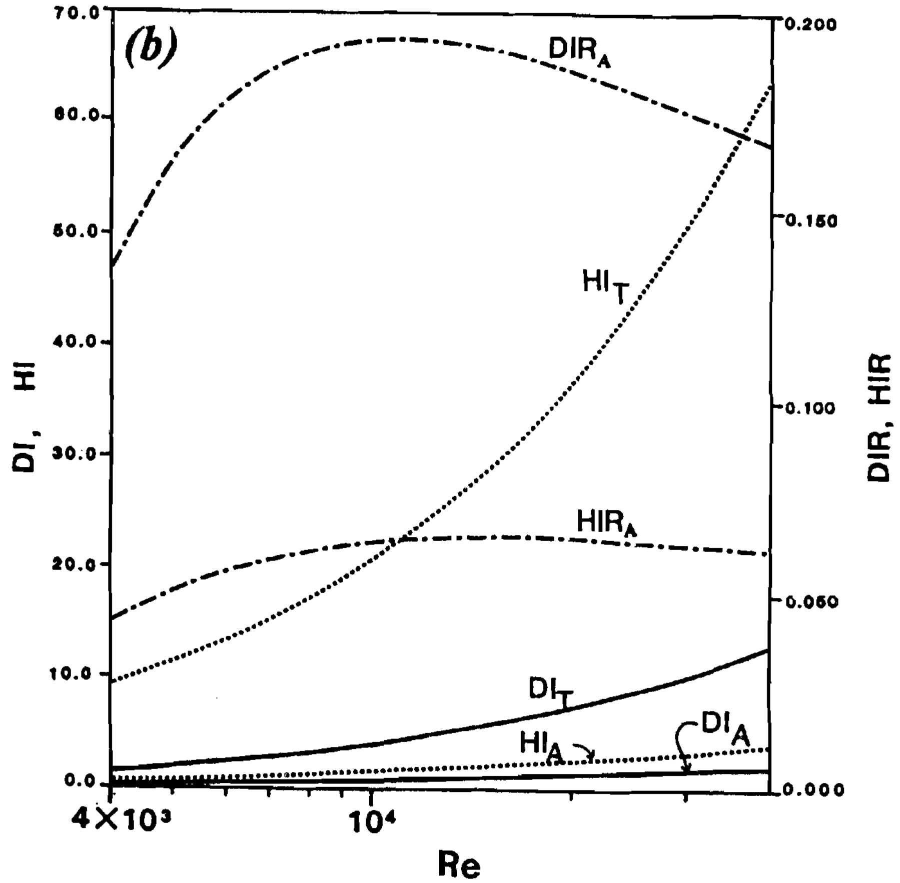

Fig. 3b: Drag increase and ratio (DI, DIR) and heat transfer increase and ratio (HI, HIR) for characteristic flows of tables 4 and 5

additional 4.032 and 65.37 times respectively. However, the heat-transfer increase ratio is 0.062 only, i.e. the asymptotic heat-transfer increase, in addition to the laminar heat-transfer, is only about 6% of the usual heat- transfer increase associated with the common Newtonian turbulent flow, considerably smaller than its drag reduction counterpart (16.7%). This analysis, quite opposite ("upside-down") from conventional drag and heat-transfer reduction analysis, gives additional insight into the drag and heat-transfer reduction phenomena.

Discussion and Conclusion: It Has To Be Laminarization

The fact that the asymptotic friction and heat-transfer factors are much closer to the corresponding extended- laminar results than to the corresponding turbulent Newtonian results, suggests that the addition of polymer (or other additives) decreases the turbulent energy-dissipation, thereby laminarizing the turbulent flow. This is also consistent with the observed high values of the transitional Reynolds number and of the hydrodynamic and thermal entrance lengths. In addition to the above, this author likes to emphasize the importance of flow-induced anisotropic fluid structure and properties. A number of speculations on several up-to-now unanswered questions, will be set forth along with some supporting facts:

1) It is unlikely that fluid viscoelasticity plays a major role in turbulent drag reduction phenomena if at all. Aqueous solutions of polyacrylic acid (Carbopol) are viscoelastic but do not show drag reduction (Carbopol anomaly, but is it?). It is known that non-elastic fluids (including very dilute polymer solutions and some gas suspensions) show considerable drag reduction. It may well be that the two phenomena, drag reduction and viscoelasticity, are independent but accompanying properties of certain fluids.

2) The wall influence is important, but not a determining factor of drag reduction. Drag reduction is associated with certain fluids, not

certain walls or boundaries. Turbulence suppression is present in boundary layer flows as well as in jet and other free turbulence flow situations.

3). The drag reduction associated with internal and external boundary layers may be fundamentally different. In external boundary layer flows the boundary influence and the laminar sublayer are probably predominant. However, in the internal boundary layer flows, like in channel flows, the turbulence structure (dissipation) within the enclosed interior determines the over-all flow by shaping the sublayer accordingly. The turbulent friction factor is determined by integration of the universal velocity profile over the cross-section, while the contribution of laminar sublayer may be neglected. In the opinion of this author, the laminar sublayer in internal duct flow is the consequence of internal flow activity, not the other way around. The sublayer simply adjusts to balance the internal stresses, mainly due to over-all turbulence in a duct. Attempts to unify the internal and external boundary layer flows may be impossible and therefore deceptive. The similarity between the two universal velocity profiles may be merely due to the coarseness of the log-log- scaling.

4) In some flow situations the so-called 'onset' of drag reduction is present. In such flows the drag reduction does not start with transition to turbulence, but rather is postponed and occurs at some larger Reynolds number than the transitional. Though, this phenomenon is not fully resolved, the present author agrees with the existing thoughts that some critical shear-stress is needed to realign or untangle the additive "threads" or macromolecules in the main-flow direction.

5). Why do the friction and heat-transfer reduction show certain asymptotic limits, without achieving the ultimate possible (100%) reduction, i.e why cannot the additives totally suppress flow instability and turbulence and transfer a high Reynolds number flow in laminar regime (extended laminar flow)? One possible answer would be: depending on the additive "thread" properties, they interfere only with the smallest turbulent eddies (the most responsible for energy dissipation - friction drag) while larger scale instabilities and turbulence remain. The former explains considerable friction drag reduction achieved, while the latter rationalizes the turbulence presence and difficulties in achieving total laminarization. The natural existence of turbulent drag reduction gives us an aspiration to look for additional (possibly artificial) and more efficient additives which, one day, may transfer some existing turbulent flows into ones without turbulence, the extended-laminar flows.

6) Why is the asymptotic heat-transfer reduction stronger than the asymptotic friction-drag reduction? One possible explanation may be a non-homogeneous turbulence, due to the flow-induced anisotropicity of fluid structure and properties. Since the drag reduction depends on the main-flow fluctuating velocity component u' and the cross-flow components v' and w', while the heat-transfer reduction depends on the cross-flow velocity components only, and since the v' and w' components are more suppressed by the flow-induced anisotropic fluid structure than the u', that would result in the stronger heat-transfer reduction than the friction-drag reduction. Another reason may be found by examining the newly defined drag and heat transfer increases for turbulent flow, see DI_T and HI_T values in Table 5. It is interesting that the increase of heat transfer due to turbulence in Newtonian fluids is much higher (5 times or more) than corresponding friction drag increase, giving more "room" for heat-transfer reduction as compared to friction-drag reduction, even for the same level of flow "laminarization."

In the conclusion, the present author would like to emphasize three points:

a) If there weren't wasteful turbulent energy-dissipation, there couldn't be any friction-drag reduction. There is not and there could not be room for drag reduction in laminar flow. The new insight is achieved with the above "upside-down-analysis". After all, the "miraculous" drag reducing fluids/flows are not "energy- savers"...they are just not as bad as Newtonian turbulent flows.

b) No matter what mechanism is used to describe drag and heat-transfer reduction phenomena, it has to come down to less turbulent-energy dissipation. We need to ask ourselves "what is turbulence after all?" It is this author's understanding that turbulence is that dissipative flow mechanism which "breaks and damps" large scale flow instabilities, considerably increasing the friction drag of laminar flow. Therefore, whether the drag reduction is called molecular or vortex "stretching," or decreased turbulence production or suppression, in its essence it has to be turbulent flow laminarization. Large scale instability does exist in the drag-reducing flows, but the most important part of turbulence, the smallest eddies are considerably eliminated by the additives, and the proof is the substantially reduced friction drag. Therefore, the answer has to be: the reduction phenomena are in essence a turbulent flow laminarization!

c) This author tends to believe that the determining factor of drag reduction phenomena and turbulent flow laminarization is a "thread" like additive structure in solvent which produces flow-induced anisotropic structure, consequence of which are anisotropic fluid properties, including but not limited to steady and dynamic viscosities. This is rather obvious for higher concentrations of linear polymer solutions. Since turbulence is the outcome of flow instability, even properties' gradients (and/or the higher order coefficients) may play an important role beyond their absolute values.

This paper deals with the very complex fluids and even more complex flow phenomena. Many more authentic questions may be raised and only some answers are speculated on the basis of limiting facts. However, this author also believes that nature usually works much simpler than what we presume. Flow induced anisotropic fluid structure and properties cause a tangible laminarization of turbulent flow. Many diverse flow situations only add to the confusion to these rather complex phenomena. It is certain that many challenges in this interesting and useful area will keep researchers very busy well through the next century and beyond.

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Nomenclature

a,b,c,d	=	constants/coefficients of Eq.4 and Table4
DI	=	drag increase, Eq.6 and Table 5
DIR	=	drag increase ratio, Eq.8 and Table 5
DR	=	drag reduction, Eq.5 and Table 5
DRR	=	drag reduction ratio, Eq.7 and Table 5
f	=	Fanning friction factor, $f = \tau_w / \frac{1}{2} \rho U^2$
HI	=	heat-transfer increase, Eq.6 and Table 5
HIR	=	heat-transfer increase ratio, Eq.8 and Table 5
HR	=	heat-transfer reduction, Eq.5 and Table 5
HRR	=	heat-transfer reduction ratio, Eq.7 and Table 5
j	=	Colburn heat-transfer factor, $Nu/(RePr^{1/3})$
K	=	power-law fluid consistency index, $\tau_w = K\dot{\gamma}^n$
n	=	power-law fluid power-law index, $\tau_w = K\dot{\gamma}^n$
Nu	=	Nusselt number
Pr	=	Prandtl number
Re	=	Reynolds number
t	=	time constant in Powell-Eyring fluid model, Eq.1
$U,\bar{u}$	=	time-averaged velocity in main-flow direction
u'	=	fluctuating turbulent velocity component in main-flow direction x
v'	=	fluctuating turbulent velocity component in cross-flow direction y
w'	=	fluctuating turbulent velocity component in cross-flow direction z

Greek symbols

$\dot{\gamma}$	=	shear rate magnitude
$\dot{\gamma}_{i,j}$	=	shear-rate tensor
$\dot{\gamma}^*$	=	dimensionless shear rate, Eq.1
Δp_p	=	pressure drop for a given pipe length for solvent flow
Δp_s	=	pressure drop for a given pipe length for polymer-solution flow
η	=	apparent viscosity
$\eta_{i,j}$	=	anisotropic viscosity, Eq.3
η_o	=	zero-shear-rate viscosity (at very small shear rates)
η_∞	=	infinite-shear-rate viscosity (at very large shear rates)
η^*	=	dimensionless viscosity, Eq.1
ρ	=	fluid density
$\tau_{i,j}$	=	shear stress tensor
τ_w	=	shear stress at wall

Subscripts

A = asymptotic drag or heat-transfer reduction
L = laminar or extended-laminar (ultimate asymptote)
T = turbulent Newtonian (without drag or heat- transfer reduction)

References

1. B. A. Toms, "Some observations on the flow of linear polymer solutions through straight tubes at large Reynolds numbers," Proc. 1st Int. Cong. Rheol., **II**, 135, North Holland Publ.Co., Amsterdam, (1949).
2. D.W. Dodge and A.B. Metzner, "Turbulent flow of non-Newtonian systems," AIChE J. **5**, 189, (1959).
3. A. B. Metzner, Heat transfer in non-Newtonian fluids, Adv. Heat Transfer, **2**, .357, 1965.
4. J.L. Lumley, "Drag reduction by additives," Annual Review of Fluid Mechanics, **1** (W.R. Sears, editor), 367, Annual Reviews, Inc., Palo Alto, CA, (1969).
5. P. S. Virk, H. S. Mickley, and K. A. Smith, The ultimate asymptote and mean flow structure in Tom's phenomenon. Trans.ASME J.Appl.Mech., **37**, 488 (1970).
6. J.W. Hoyt, "The effect of additives on fluid friction (A Freeman Scholar Lecture)," Transac. ASME, J. Basic Eng., No.6, 258 (1972).
7. J.W. Hoyt, "Drag reduction," in Encyclopedia of Polymer Science and Engineering, Second Edition, John Wiley & Sons, Inc., **5**, 129 (1986).
8. Y. I. Cho and J. P. Hartnett, Non-Newtonian fluids in circular pipe flow. Adv. Heat Transfer, **15**, 59 (1982).
9. J.P. Hartnett. "Viscoelastic fluids: A new challenge in heat transfer," The 1989 Max Jacob Memorial Award Lecture, J.Heat Transfer, **114**, 296 (1992).
10. R. B. Bird and C. F. Curtiss, Fascinating polymeric liquids. Physics Today, 36-43, (1984).
11. J. Gleik, 'Slippery Water' Mystery seems finally solved. The New York Times, January 12, 1988.
12. R. B. Bird, R. C. Armstrong, and O. Hassager, Dynamics of Polymeric Liquids, 2nd Ed., Wiley, New York, (1987).
13. M. Kostic, Heat transfer and hydrodynamics of water and viscoelastic fluid flow in a rectangular duct. Ph.D. Thesis, University of Illinois, Chicago, (1984).
14. H. Schlichting, Boundary-Layer Theory, Seventh Edition, McGraw-Hill Book Co. (1979).
15. M. Kostic and J.P. Hartnett, "Pressure drop and heat transfer in viscoelastic duct flow - A new look." Fundamentals of Convection in Non-Newtonian Fluids-HTD 79 (J.S.N. Chen, T.M. Ekmann, and G.P. Peterson, eds.). ASME, New York, 1-15, (1987).
16. J. P. Hartnett and M. Kostic, "Heat transfer to Newtonian and non-Newtonian fluids in rectangular ducts," Adv. Heat Transfer, **19**, 247-356 (1989).