An LDA Study of Shear rate profiles of Rushton turbine in mixing tanks

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Abstract

In this article, distributions of local shear rates for Rushton turbine impeller have been studied using laser Doppler Anemometry (LDA) for viscoelastic liquids. The normalized local tangential velocity and local shear rate profiles are independent of Rushton turbine impeller speeds and main variations of shear rate occur in the vicinity of impeller. This is due to the large variations in tangential velocity in this region. In the transition region, i. e. ~30 < Re < ~2000, tangential velocity component and local shear rate, are shown to be negligible at axial coordinate of $z = 0.0315$ m above impeller tip plane, i. e. $z = 0$.

Keywords: Anemometry (LDA) , *Local shear rate; Viscoelastic liquids; Mixing; Rushton turbine impeller.*

INTRODUCTION

Many transformation processes in the chemical and polymer processes involve mixing of complex fluid streams such as viscoelastic materials. The flow conditions in the mixers are known to govern the mixing process efficiency and product quality. These flow conditions are particularly sensitive to the non-Newtonian properties such as elasticity of the media at hand. Although it is now recognized that close clearance impellers are more effective for mixing rheologically complex fluids, however, the classical Rushton turbine remains the most common impeller in industrial and research equipment particularly in fermentation industry [1,2]. The latter impeller induces a strong radial discharge stream and a variation in the radial velocity component with impeller blade angle [3]. The effective shear or deformation rate is a very important design parameter. The classical approach to estimate shear rates in stirred tanks is the use of Metzner and Otto method [4]. According to this method, a given impeller rotational speed, *N*, produces an effective rate of deformation, $\dot{\gamma}_e$, in the mixing vessel which can be estimated by

$$\dot{\gamma}_e = k_s . N \tag{1}$$

Various numerical analyses have confirmed or extended the validity of this equation [5,6,7,8]. The significant method of Metzner and Otto for calculation of the effective deformation rate, i. e. Eq. (1), is limited to the laminar flow regime and is no longer valid in the transition region [9,10]. Ulbrecht and Carreau [11] pointed out that the use of the Metzner and Otto method could lead to very large errors for scale up in the transition region (Re >10). It is worth noting that, although most laboratory scale tests are carried out under laminar flow, scale up usually results in a change to a transitional or turbulent regime. A failure in the prediction of this transition can result in a misapplication of the Metzner and Otto method. Hocker et al. [12] and Bourne and Butler [13] proposed expressions relating shear rate in a transitional or turbulent flow to the power input. Wichterle et al. [14,15] found that for water, shear rates on the front of the blade were as high as 1200 times the impeller speed. The latter results are important in the design of shear sensitive mixing systems since the contribution of turbulence to shear is at least one order of magnitude greater than that of the velocity profile [7]. The majority of published investigations on shear rate with Rushton turbine are concerned with average shear rate of non-Newtonian fluids. Despite these studies, there is a lack of detailed data concerning the local shear rate of viscoelastic fluids in mixing processes with Rushton turbine. This work investigates the local shear rates of viscoelastic fluids in mixing tanks. Also, the effect of impeller speed is studied.

Experimental Method

Measurements were performed in a cylindrical tank of Plexiglas construction with an inside diameter D_T = 0.276 m and wall thickness of 0.003 m. The laser probe was mounted on the automated-controlled traversing mechanism allowing the user to conduct a complete scan of the mixing tank. The LDA system (Dantec Measurement Technology) was operated in the back scatter mode. The equipments and test fluids used in this work are given in the reference [16].

RESULTS AND DISCUSSION

The stress acting on a fluid element in a mixing tank can be related to the components of the rate of deformation tensor Δ which are written in terms of mean velocity components in Table 1.

Table 1. Components of the rate of deformation tensor in cylindrical coordinates.

$\Delta_{rt} = r\P\,(V_t / r)/\P r + \P\, V_r / r\P t$	$\Delta_{rr} = 2\P\, V_r / \P r$
$\Delta_{tz} = \P\, V_z / r\P\, t + \P\, V_t / \P\, z$	$\Delta_{tt} = 2(\P\, V_t / r\P t + V_r / r)$
$\Delta_{rz} = \P\, V_z / \P\, r + \P\, V_r / \P\, z$	$\Delta_{zz} = 2\P\, V_z / \P\, z$

In the impeller stream, all of the components of Δ are finite so that the inspection of an individual mean velocity gradient is cumbersome and does not provide an adequate picture of the deformation field. In addition, in a turbulent flow it is not possible to measure instantaneous deformation rates via LDA so that the mean deformation rate cannot be obtained [17]. Nevertheless, it is useful to consider gradient of mean velocity which represents the field deformation. On the other hand, the fluid motion caused by the rotating Rushton turbine impeller is approximated by an equivalent flow produced in a coaxial cylinder system with the inner cylinder rotating. The Rushton turbine impeller is replaced by the inner cylinder rotating with a constant angular velocity. For steady fully developed couette flow without end effects Δ_{rt} reads as [10]:

$$\Delta_{rt} = r \frac{\partial \, (V_t / r)}{\partial \, r} \tag{2}$$

To calculate the above component of the rate of strain tensor, eleven radial positions from the impeller tip to the vessel wall were chosen in order to measure the mean velocity components in mixing of PAA solutions. Local mean velocities at these points have been measured for different rotational speeds of Rushton turbine impeller and various concentrations of PAA solutions in the transition region, i. e. ~30 < Re < ~2000. Also, local mean velocities have been measured at two different heights, i. e., z = 0 and z = 0.0315 m for 900 ppm PAA solution. Fig. 1 shows an example of the local tangential velocities at different radial positions obtained through LDA measurements for 900 ppm PAA solution.

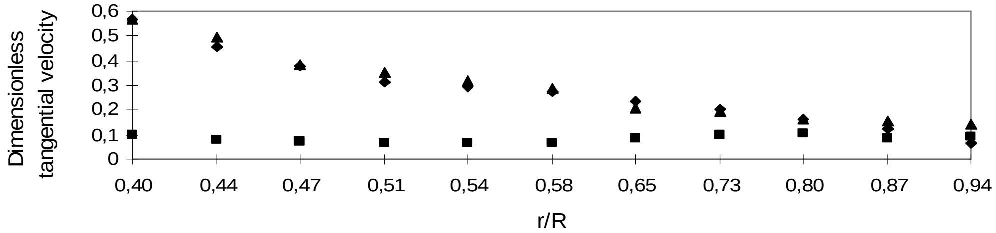

Fig. 1. Normalized (dimensionless) tangential velocity profiles of Rushton turbine impeller with different impeller speeds at axial locations for 900 ppm PAA solution.

These velocities are normalized through dividing by the blade tip speed and differentiated as in Eq. (2) to obtain the local shear rates. Dimensionless tangential velocity distributions, i. e. $\bar{V}_t / V_{tip}$ at a given axial position, z = 0, for different concentrations of PAA solution at various impeller speeds show that velocity profiles have the same exponential decay and are independent of impeller rotational speed (Fig. 1). The latter results have important design applications with respect to scale-up rules and are in agreement with literature [18,19]. It should be noted that this independence does not apply to pitched blade turbines due to different flow patterns [20]. The steep reduction in $\bar{v}_t / v_{tip}$ for the Rushton turbine impeller at different impeller speeds and solution concentrations occurs in the range of 0.4< *r/R* < 0.6 (Fig. 1). Contrary to the findings of Stoots and Calabrese [17], mean tangential velocities do not exceed the impeller tip speed. Figure 1 also shows that the values of $\bar{v}_t / v_{tip}$ at center line (z = 0) are much greater than the corresponding values at a height of z = 0.0315 m. It is showed that the mean values of tangential velocity component could be described by an exponential decay distribution at z = 0 [21]. However, as Fig. 2 reveals, the profile of $\bar{v}_t / v_{tip}$ has a nearly sinuous functionality in the horizontal plane of z = 0.0315 m. The following equation well correlates $\bar{v}_t / v_{tip}$ data at this height

$$\bar{v}_t / v_{tip} = 0.065 + 0.025 \, \mathrm{Sin} \, (2 \pi r / 0.47 R + 3.1) \quad (3)$$

Fig. 2 compares the results of Eq. (3) with experimental data of 900 ppm PAA solution for different impeller speeds at axial location of z = 0.0315 m. Mean deviation of Eq. (3) is about 21 percent.

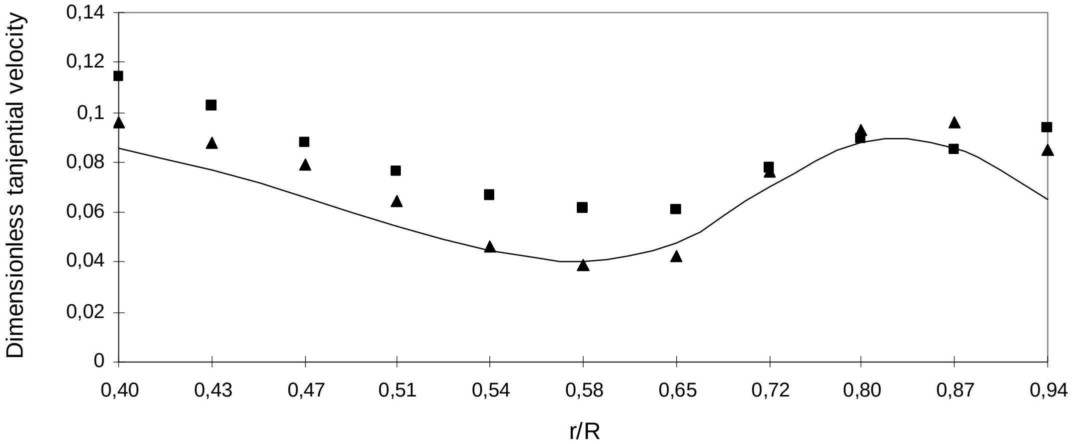

Fig. 2. A comparison of predicted tangential velocities, Eq. (3), with experimental data of 900 ppm PAA solution at a height of z = 0.0315 m and different speeds.

Equation (2) may be used to show the variations of the local shear rates for 900 ppm PAA solution at two heights, i. e. z = 0 and z = 0.0315 m, as a function of radial positions or impeller speeds. If $\dot{g}$ is the magnitude of Δ_{rt}, it may be made dimensionless by means of the impeller rotational speed to yield

$$\dot{g}^{*} = \dot{g} \; / \; N \tag{4}$$

Variations of dimensionless local shear rate, $\dot{g}^{*}$, are displayed in Fig. 3 for velocity profiles measured at two different heights. This figure shows that the regions of highest deformation are along the impeller tip. Typical values of $\dot{g}^{*}$ for 900 ppm PAA solution are 12 and 1 corresponding to horizontal planes of z = 0 and z = 0.0315 m. The elastic behavior of non-Newtonian fluids tends to decrease local shear rates with respect to inelastic Newtonian fluids. Stoot and Calabrese [17] found that for de-ionized water, an inelastic Newtonian liquid, dimensionless mean shear rate on the blade edge is $\dot{g}^{*}$ = 150 as a typical value. Also, Wichterle et al. [14] found that for water, shear rates on the front of the blade were as high as 1200 times the impeller speed. However, their electrochemical method allowed them to measure shear rates directly at the blade surface and not at a small distance away.

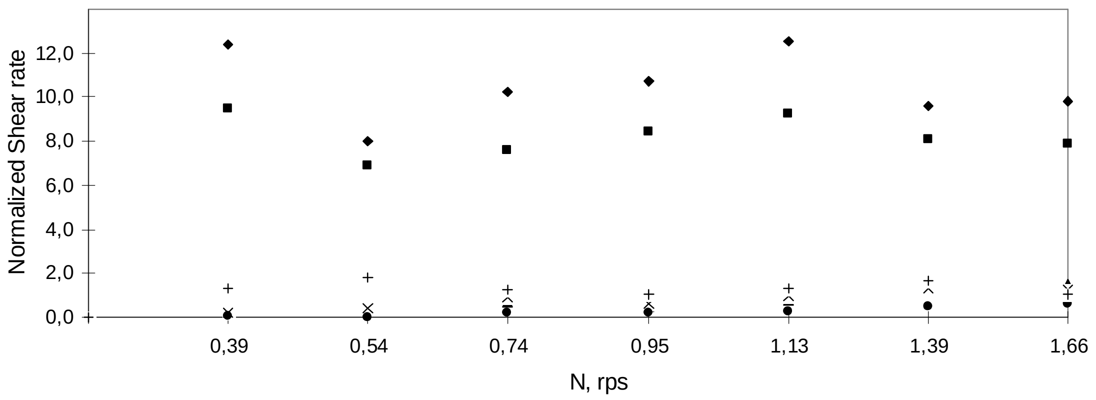

Fig. 3. Variations of normalized (dimensionless) shear rates versus Rushton turbine impeller speeds for 900 ppm PAA solution between center line (z = 0) and a hight of z = 0 .0315 m.

A comparison of $\dot{g}^{*}$ in these literatures with that of present work well explains the effect of elasticity on local shear rate for viscoelastic fluids in the transition region. On the other hand, elasticity reduces the effective shear rate in the transition region being in agreement with the findings of Cheng and Carreau, [10]. This may become clearer if one considers Metzner and Otto relationship, Eq. (1). The typical values between 1 and 12 for $\dot{g}^{*}$ in this work are smaller for viscoelastic liquids than those for inelastic Newtonian and non-Newtonian liquids. It is in agreement with the findings of Ducla et al. [22]

and Nienow and Elson [23]. Beyond the laminar regime, local shear rates seem to be strongly dependent on the rheological properties of the liquid or they are strongly dependent on the Reynolds number [10]. Variations of $\dot{g}^{*}$ as a function of radial position are shown in Fig. 4.

In this figure $\dot{g}^{*}$ profiles for 900 ppm PAA solution at various impeller speeds have nearly the same exponential decays and are independent of impeller speeds at different locations corresponding to z = 0 and z = 0.0315 m. Also, the steep reduction in $\dot{g}^{*}$ profiles for different impeller speeds corresponding to z = 0 have occurred in the range of 0.4 < r/R < 0.7. This result has important design implications with respect to scale-up rules in the design of shear sensitive mixing systems since the contribution of turbulence to shear is at least one order of magnitude greater than that of the velocity profile [7]. The effect of sinuous shape function of $\bar{v}_t / v_{tip}$ profiles caused to have negative values of $\dot{g}^{*}$ at z = 0.0315 m.

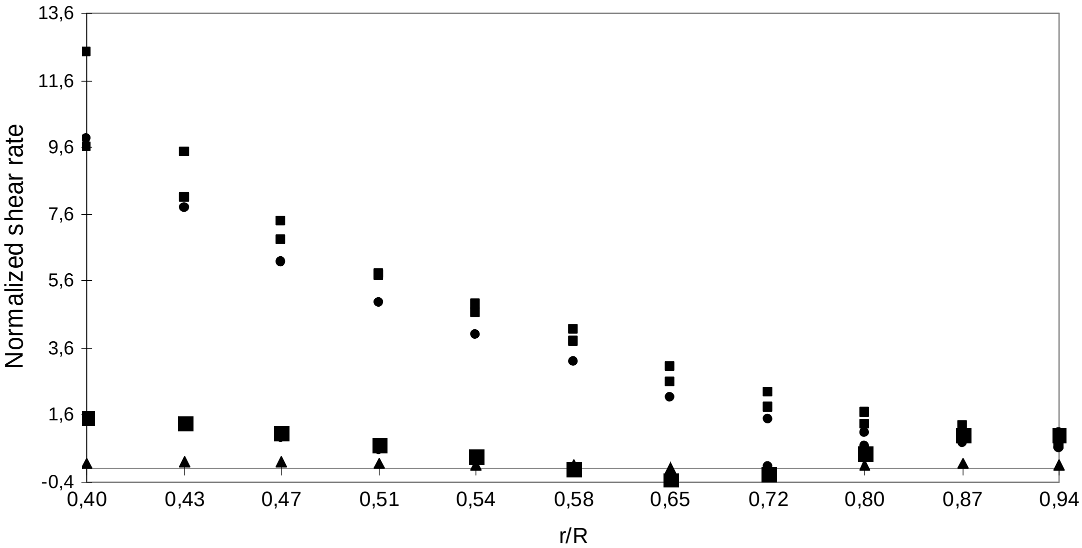

Fig. 4. Variations of normalized shear rates versus radius of agitated vessel with Rushton turbine impeller for 900 ppm PAA solution between center line (z = 0) and z = 0.0315 m.

Also, typical $\dot{g}^{*}$ values at z = 0.0315 m are about 1.5 that are similar to $\dot{g}^{*}$ values in the vicinity of vessel wall at z = 0. Therefore, as an approximation, the effective shear rate on center line may be used and shear rates at other axial locations are ignored because of small values of $\dot{g}^{*}$ in those regions.

CONCLUSIONS

Using the method of laser Doppler anemometry, the tangential velocity distribution in agitation of viscoelastic fluids with a typically Rushton turbine impeller is obtained. Dimensionless velocity profiles at different axial locations, z = 0 (center line) and z = 0.0315 m (out of center line), in the transition region, i. e. ~30 < Re < ~2000, are obtained. The following conclusions may be drawn from these measurements.

1. The effect of elasticity tends to decrease the local shear rate values in mixing of viscoelastic liquids in the transition region.

2. Normalized mean tangential velocity profiles and normalized local shear rates are independent of the Rushton turbine impeller speed and the values above the impeller disc, are smaller than the center line values.

NOTATION

Romans

D	impeller diameter, m
D_T	agitated vessel diameter, m
N	rotational speed, rev/s
r	radial coordinate, m
R	radius of agitated vessel, m
Re	Reynolds number, $r ND^2 / h_0$, dimensionless
Re_g	generalized Reynolds number, $r N^{2-n} D^2 k_s^{1-n} / k$
v_t	tangential velocity, m/s
v_{tip}	impeller blade tip speed = $p\ D\ N$, m / s
z	axial coordinate, m

Greek symbols

Δ	rate of deformation tensor, 1/s
$\dot{g}$	local shear rates,1/s
$\dot{g}^*$	dimensionless local shear rates,1/s
$\dot{g}_e$	effective shear rate,1/s

Subscripts

r, t, z	radial, tangential and axial components
tip	impeller tip
T	transpose of a second order tensor

Superscript

–	time or space value

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