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Power consumption and mixing time in rheologically complex fluids by a two-bladed impeller[†]

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Abstract

This study investigates the power consumption and mixing time of a two-bladed stirrer during the mixing of viscoelastic fluids in the laminar region of flow. For the rheological part, we use a polymer with low-concentration aqueous solutions that present viscoelastic behavior. The rheological study performed on polyacrylamide solutions shows the viscoelastic behavior of the generalized "Kelvin–Voigt" model. The power consumption for the viscoelastic fluids is greater than that needed to mix Newtonian fluids at the same Reynolds number. The mixing time is found to depend strongly on the viscoelasticity of the solutions.

Keywords: Experimental study; Power consumption; Mixing time; Stirred vessel; Two-bladed impeller; Viscoelastic fluid

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1. Introduction

In many industrial fluid-mixing operations, liquid raw materials, products, and intermediates are rheologically complex. Numerous examples can be found in the polymer-based industries (manufacturing and processing of synthetic rubbers, plastics, fibers, resins, plaints, coatings, and adhesives), food-processing industries, bio-chemical operations, and the manufacturing of detergents. The most frequently occurring anomalies are shear-dependent viscosity and viscoelasticity.

Viscosity is considered as the most important rheological function, and a common practice is to classify fluids into two categories for which different technologies are used for mixing. These categories are low-viscosity fluids, which imply turbulent flows, and high-viscosity fluids, which are limited to laminar flows in practice and are the focus of this study.

Rheological behavior is generally complex, and viscoelastic properties are often exhibited. Given that viscoelastic fluids are increasingly employed in industries, a thorough understanding should be gained about hydrodynamics in mixing systems when viscoelasticity is involved. For two-bladed impellers, a few works are available in the literature. Hiraoka et al. [1] and Bertrand and Couderc [2] performed a 2D numerical study on pseudoplastic fluids. For the same fluid, Bertrand et al. [3] studied the performance of a large paddle impeller through experiments. Youcefi [4] investigated the flow fields, power consumption, and mixing time induced by a large two-bladed impeller for Newtonian and non-Newtonian fluids through experiments. These studies have shown that flow is essentially tangential for a low impeller speed. A marked increase in power consumption was noted when viscoelasticity increased beyond a Reynolds number threshold, even when influence on mixing time was weak.

2. Basic concept

The relationship among the power consumption of an agitator, the physical properties of liquid, the speed of the agitator, and its characteristic dimensions is expressed by relating the power and Reynolds number using the following general functional equation:

$$Np = \frac{p}{\rho N^3 D^5} = f\left(\frac{\rho N D^2}{\eta}\right) = f(\text{Re}). \qquad (1)$$

For Newtonian fluids, the power consumption can be expressed as follows:

$$\text{Np. Re} = \text{A}, \qquad (2)$$

where A is a geometrical constant. Assuming that this relation is valid for non-Newtonian fluids as well, the power for non-Newtonian fluids can be calculated by replacing the Reynolds number in Eq. (2) with an apparent Reynolds number based on η_a [5]. Thus, the Reynolds number for a non-Newtonian

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fluid in a stirred tank is defined as follows:

$$\mathrm{Re}_a = \frac{\rho N D^2}{\eta \mathrm{a}}, \tag{3}$$

where ρ is the fluid density, N is the rate of rotation in a stirred tank, D is the impeller diameter, and ηa is the apparent viscosity of the non-Newtonian fluid.

The average shear rate in the vessel is assumed to be given by the Metzner–Otto approach as follows:

$$\dot{\gamma}_{\mathrm{a}} = \mathrm{K.N}, \tag{4}$$

where K is a constant for a given impeller/tank combination. If the power law model for the fluid rheology is also assumed, then

$$\mathrm{Re}_a = \frac{\rho N^{2-n} D^2}{m K^{n-1}}, \tag{5}$$

where m is the power law parameter, and n is the power law index.

3. Materials and methods

The experimental apparatus employed in this study is schematically shown in Fig. 2. The vessel is a cylindrical flat-bottomed plexiglass non-baffled tank. The impeller was built of polished stainless steel and mounted on a cylinder with 300 mm internal diameter and 0.50 m height. The height of the liquid in this tank is equal to the vessel diameter. The diameter of the two-bladed impeller is half of the vessel diameter. The impeller consists of two blades fixed on a shaft with diameter d/T = 0.046. The impeller shaft is concentric with the axis of the vessel. The geometrical ratio, that is, the height of the liquid/height of the impeller, was kept constant at 1.0.

The agitator is driven by a variable speed electric motor Leroy–Somer MVS-25 type of 0.185 kW coupled to the agitator through a speed reducer to give minimum and maximum agitator speeds. The rotational speed of the motor shaft and the torque were measured by a non-contact strain gauge torque meter HBM-T30FN in the range of 0 Nm to 50 Nm. The rheological properties of all liquids were measured by a Carri-Med controlled stress rheometer CS100 with cone and plate geometry, as schematically shown in Fig. 1. A cone with a gap angle of 2° and a radius of 4 cm was used to conduct the experiments.

Mixing time was measured by applying the decoration method using the reaction between the iodine and sodium thiosulfate solutions. Notably, 40% of sodium thiosulfate was employed. The change in color from rust to colorless was visually monitored.

$$I_2 + 2Na_2 + S_2O_3 \rightarrow Na_2S_4O_6 + 2NaI \tag{6}$$

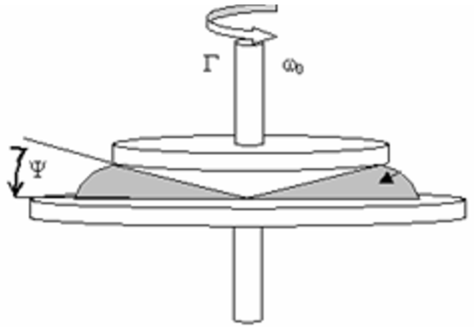

Fig. 1. Cone–plate rheometer.

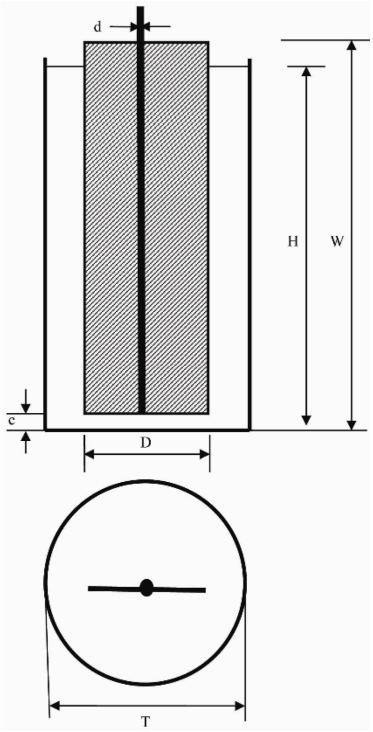

Fig. 2. Experimental apparatus.

The time of mixing was obtained through the direct measurement of the solution upon discoloration. The first fluid was accordingly colored with iodine solution. A rusty color was acquired. When a suitable amount of sodium thiosulfate solution with an excess of 40% over the amount of stoichiometric was added, an instantaneous chemical reaction occurred, which caused fluid discoloration. A value of 40% is recommended by the literature. The mixing time is considered to be reached when no visible trace appears, as visually detected.

For a vessel with 30 l of fluid, 10 ml of dye solution (iodine) is sufficient to ensure a good rusty color. For discoloration, 13 or 14 ml of bleaching solution (sodium thiosulfate) should be added. The change in color was progressively observed in different instances after the injection of the tracer. These additive volumes are negligible relative to the volume of the vessel.

Table 1. Impeller characteristics.

D (mm)	D/T (-)	H/T (-)	d/T (-)	c/T (-)
150	0.5	1.5	0.046	0.066

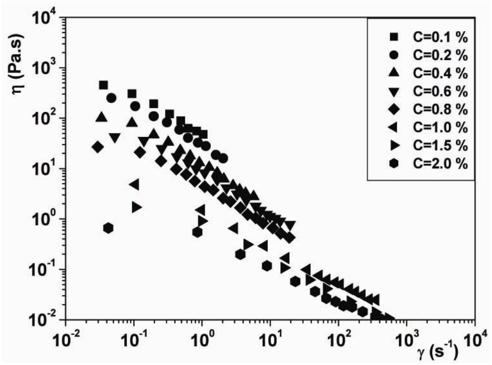

Fig. 3. Viscosity curves of PAA/water solutions.

4. Result analysis

4.1 Rheology

The rheological behavior of viscoelastic fluids is characterized as simple shear flow and is represented by the "Herschel–Buckley" law, that is, $\tau = \tau_0 + m(\dot{\gamma})^n$, in the shear rate range of 0.1 to 10. The range of values obtained is 0.225 to 0.415 for n and 0.37 to 38 for m. The study of the viscoelastic properties of polyacrylamide (PAA) solutions is performed using the creep and the oscillation technique. The rheological study performed on PAA solution shows the viscoelastic behavior characteristic of the generalized Kelvin–Voigt model, in which the creep function is given by

$$f(t) = J_0 + \sum J_i\,[1 - \mathrm{expo}(-t/\theta_i)] + t/\eta_0 . \tag{7}$$

Fig. 3 shows the measured flow curves of PAA solutions with different concentrations, which generally show a distinct pseudoplastic behavior. The increasing slopes of the curves at very low shear rates indicate the entry of the flow lines into the so-called Newtonian initial viscosity, which can be attained only for some solutions.

4.2 Power measurement

Regarding the variation of the geometrical parameters on the energy consumption, H/T parameter has been studied, whereas other geometrical parameters, such as D/T, have already been studied in the literature by other researchers for the same agitation system. This study is limited only to the parameter H/T for two different values, that is, H/T = 1.0 and H/T = 1.5. Many studies have examined the effect of geometrical parameters, such as D/H and D/T, whereas a few studies have been interested to the effect of the parameter H/T. For this reason, this study focuses on this parameter. Only two values of the parameter H/T are chosen, that is, H/T (1.0 and 1.5).

The power consumption P is determined by torque measurement on the shaft. The torque C is measured using a non-contact strain gauge torque meter of type HBM-T30FN for torque up to 50 Nm. The power required for mixing is calculated as follows:

$$P = 2\pi N(C - C_0), \tag{8}$$

where C_0 is the unloaded torque. The power consumption is a function of the system geometry, rheological properties of the fluid, and kinematic variables, namely, the rotation speed N. Results are presented by plotting the dimensionless power number Np as a function of the Reynolds number, which is defined as follows:

$$Np = \frac{p}{\rho N^3 D^5} . \tag{9}$$

The torque is achieved using a non-contact sensor with a stretching gauge, brand HBM, and T30FN type with measurements ranging from 0 Nm to 50 Nm regardless of the measured value. The uncertainty is associated with the value of the torque and 0.5 Nm. The values illustrated in Figs. 4 and 5 are averages obtained from several tests. We have not illustrated the differences to avoid crowded figures and make them unreadable. The estimated uncertainly is 2% on torque measurements and less than 8.5% on the power number.

For the viscoelastic fluids, the power consumption is greater than that needed to mix Newtonian fluids at the same Reynolds number. This increase observed for Reynolds is higher than 1.0; below this value, no effect on the power consumption because of elasticity is observed. The variation of the power number with Reynolds number for viscoelastic fluids to different concentrations is shown in Fig. 4.

In Fig. 4, the influence of the polymer concentration is studied on the basis of two concentrations (C = 0.4% and C = 1%). Curves Np = f (Re') for the two concentrations have the same shape but translated a relative to each other because of the effect of elasticity, which is greater for higher concentrations.

A study is conducted on PAA solution with concentration C = 1%. For H/T = 1.0 and 1.5, the relation Np = f (Re') is more important for H/T = 1.5. This result is shown in Fig. 5, which shows that they are similar in shape but slightly offset.

In the laminar zone, the power number Np depends only on the geometry of the system being studied and the Reynolds number of the agitator. For viscoelastic fluids, the evolution of curves is a result of a high power number for Reynolds numbers greater than the critical value (Re = 5) compared with inelastic non-Newtonian fluids. This deflection of the behavior of Newtonian or inelastic non-Newtonian is related to the elasticity of fluids. Extra-normal constraints are likely to be present, which could explain the relative increase in the power number observed on curves 4 and 5 starting from Re' > 5. The increase but it decreases slightly in the on the elastic forces and normal components that tend to oppose against the rota-

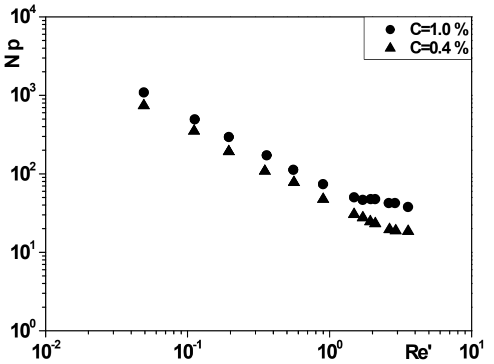

Fig. 4. Power number as a function of Reynolds for viscoelastic fluids at various concentrations (H/T = 1.5).

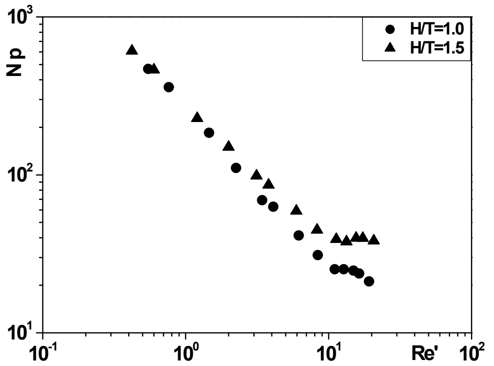

Fig. 5. Power number as a function of Reynolds for viscoelastic fluids at various ratios H/T (C = 1%).

tion of the agitator, hence influencing positively on the torque.

4.3 Mixing time

The dependency of the mixing time on other quantities may be expressed in a similar way by introducing the following dimensionless group $N.t_m$:

$$N \cdot t_m = f\left(\frac{\rho N D^2}{\eta}\right) = f(\mathrm{Re}'). \tag{10}$$

The experimental results of mixing time as a function of Reynolds number are shown in Fig. 6. These results are presented in dimensionless form. From these data (Fig. 4), the dimensionless mixing time does not depend on the Reynolds number up to Re' = 10, but it is sensitive to the variation of the concentration of PAA solutions. The analysis of the experimental data of mixing times can be conducted by comparison with the results in the literature, which has reported that the dimensionless mixing time, N.tm, is independent of the Reynolds number in the laminar region and that N.tm decreases with the increases in the transition region [1-15].

For the geometry studied in this work, the dimensionless mixing time strongly depends on the viscoelasticity. These results show that the dimensionless mixing time is roughly constant for the Reynolds numbers used in this study (0.4 < Re < 12). The independence of the result N.tm toward the Reynolds number indicates the absence of dead zones in the stirred tank. For solutions of PAA with concentrations ranging between 0.5% and 2%, the dimensionless mixing time N.tm is constant for low Reynolds numbers (Re < 10), but it decreases slightly in the transitional regime. For Re > 3, the product N.tm is constant. The evolution of velocity field observed for lower Reynolds numbers (15 < Re < 30) can explain that product N.tm (dimensionless mixing time) varies with the variation of the Reynolds number. For lower values, the evolutions of the velocity field have an insignificant effect on the mixing time.

Table 2. Comparison of mixing time.

Tank	Impeller	N.tm	Ref.
Cylindrical flat-bottomed	Helical screw	600	[1]
Cylindrical flat-bottomed	Helical screw	640	[15]
Cylindrical flat-bottomed	Two-blade	400-650	[10]

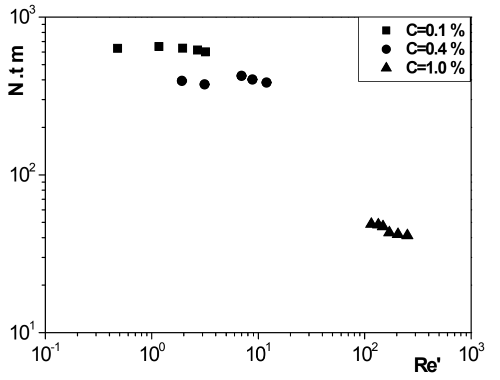

Fig. 6. Dimensionless mixing time for viscoelastic fluids.

The dimensionless mixing time for the studied geometry strongly depends on the viscoelasticity. These results demonstrate that the dimensionless mixing time is substantially constant in the considered Reynolds number (0.4 < Re' < 12). Ntm independence with respect to Reynolds number indicates the absence of dead zones in the stirred vessel.

Fig. 7 shows N.tm mixing time depending on the Reynolds number and for two different injection points, thiosulfate and iodine. This result shows that the injection does not affect the results. This problem has been widely discussed by other authors, including Nagata et al. [6] and Chavan et al. [7].

5. Conclusions

The mixing performance of a two-bladed stirrer is studied by measuring power consumption and mixing time. Experimental results in the laminar region (Re < 10) are as follows:

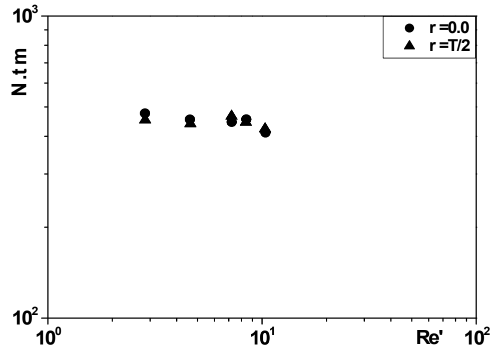

Fig. 7. Dimensionless mixing time for viscoelastic fluids at different injection points.

(a) Power consumption for elastic fluids is greater than that needed to mix Newtonian fluids at the same Reynolds number. Elasticity effects are negligible for $Re < 1.0$, but elasticity significantly increases power consumption for $Re > 1.0$.

(b) Dimensionless mixing times are essentially constant for a given solution. The elasticity increases the time required for mixing. The point of injection of the thiosulfate solution has no effect on the measured mixing time.

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Nomenclature

A : Constant
C : Torque, concentration
C_0 : Unloaded torque
c : Impeller off-bottomed clearance
D : Impeller diameter
d : Shaft diameter
J : Compliance elastic
H : Height of the two-bladed impeller
K : Metzner–Otto constant
m : Power law parameter
n : Power law index
N : Impeller rotational speed
Np : Power number
P : Power consumption
T : Tank diameter
t : Time
Re : Reynolds number
Re' : Generalized Reynolds number for fluid
t_m : Mixing time
V : Velocity
W : Height tank
τ : Shear stress
τ_0 : Critical shear stress
ρ : Fluid density
η : Fluid viscosity
η_a : Apparent viscosity
$\dot{\gamma}$: Shear rate
ω : Angular velocity

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