

## Average Shear Rates in the Rapid Visco Analyser (RVA) Mixing System

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## ABSTRACT

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The principle of mixer viscometry was utilized to determine the average shear rate in the mixing system (impeller-cup combination) of the Rapid Visco Analyser (RVA). A relationship between the impeller Reynolds number and the power number was established with Newtonian standards. Using the matching viscosity technique and non-Newtonian fluids consisting of various aqueous solutions of guar gum and methylcellulose, the

average value of the mixer viscometer constant ( $k'$ ) was 20.1/rev over speeds of 1.0–3.5 rev/sec (60–210 rpm). Hence, the average shear rate in the RVA can be estimated as 20.1 multiplied by the angular velocity given in revolutions per second. Results show the RVA system has very good potential for characterizing the rheological properties of various non-Newtonian fluid foods.

The Rapid Visco Analyser (RVA) (Newport Scientific, Warriewood, Australia) is widely used to determine the viscous properties of starch slurries. In this device, the rotation of a pitched paddle impeller keeps starch particles suspended during heating and subsequent gelatinization. Unfortunately, the shear rates involved in the mixing process are unknown, making test results (though useful) highly empirical. Evaluating shear rates in the RVA impeller-cup apparatus is the first step toward evaluating the intensity of mixing, comparing results from other types of instruments, and for exploring the potential of the RVA to measure the basic rheological properties of other fluid foods. The objective of this study was to find the average shear rates in the RVA mixing system using mixer viscometry methods.

## MATERIALS AND METHODS

## Mathematical Relationships

The average shear rates in the RVA mixing system were evaluated using the matching viscosity assumption proposed by Metzner and Otto (1957). The idea involves comparing the power curves of Newtonian and non-Newtonian fluids assuming a matching viscosity. By setting the Newtonian viscosity equal to the apparent viscosity of the non-Newtonian fluid, the average shear rate for both fluids can be assumed equal during deformation. A number of researchers have successfully evaluated instrument performance with this concept (Wood and Goff 1973, Rao and Cooley 1984, Briggs and Steffe 1996).

The specific technique used in the current study for applying the matching viscosity method was developed by Mackey et al (1987) and later described as the torque curve method by Castell-Perez and Steffe (1990). Starting with the assumption that surface tension, elastic, and vortexing effects are insignificant, the physical variables involved in mixing Newtonian fluids in the laminar flow regime ( $N_{Re,I} < 10$ ) are:

$$N_{Po} = \frac{A}{N_{Re,I}} \quad (1)$$

After substituting the definitions of  $N_{Po}$  and  $N_{Re,I}$ , Eq. (1) may be rewritten as:

$$\frac{P}{d^5 N^3 \rho} = \frac{A\mu}{d^2 N \rho} \quad (2)$$

where the constant  $A$  depends on the system geometry and flow regime. Mackey et al (1987) rewrote Eq. (2) as:

$$\mu = k'' \frac{M}{N} \quad (3)$$

where  $k'' = 1/(d^3 A)$  rev/m<sup>3</sup>. Applying the matching viscosity assumption to non-Newtonian fluids yields an expression relating Newtonian viscosity, or apparent viscosity (of non-Newtonian fluids), to the average shear rate:

$$\mu = \eta = K \left( \dot{\gamma}_a \right)^{n-1} \quad (4)$$

Using Eq. (3) to describe the Newtonian viscosity, Eq. (4) becomes

$$k'' \cdot \frac{M}{N} = K \left( \dot{\gamma}_a \right)^{n-1} \quad (5)$$

Metzner and Otto (1957) assumed that fluid motion around the impeller region of a mixer could be analyzed using an average shear rate that is linearly related to impeller speed by the mixer viscometer constant ( $k'$ ):

$$\dot{\gamma}_a = k' N \quad (6)$$

Using this concept,  $k'$  and  $k''$  may be related to non-Newtonian fluids by combining Eqs. (5) and (6) (Mackey et al 1987):

$$k' = \left( \frac{1}{N} \right) \left( \frac{Mk''}{KN} \right)^{\frac{1}{n-1}} \quad (7)$$

## Equipment and Properties

To determine the mixer viscometer constant, the torque output from the RVA system is needed. Unfortunately, this information is not easily obtained from the RVA, so an adaptor (Fig. 1) was made to connect (and provide center alignment) the RVA impeller-cup apparatus to a conventional rotational viscometer, a Haake RV12 (Haake, Paramus, NJ). The RV12 allowed precise speed control and simultaneous torque measurement. Because the average shear rate depends solely on the mixing geometry, the actual RVA instrument was not needed (and for our purpose was unsuitable) to drive the impeller. Measurements of all fluid properties (except when testing the RVA apparatus) were made using standard rheological methods (Steffe 1996) with data collected on a Haake VT550 concentric cylinder system. All experiments were conducted at  $23 \pm 1.5^\circ\text{C}$ .

Determination of  $k''$  and  $k'$ 

The mixer coefficient was calculated with data from several Newtonian fluids (Table I) over a speed range of 1.67 rev/sec (rps) to 5 rps

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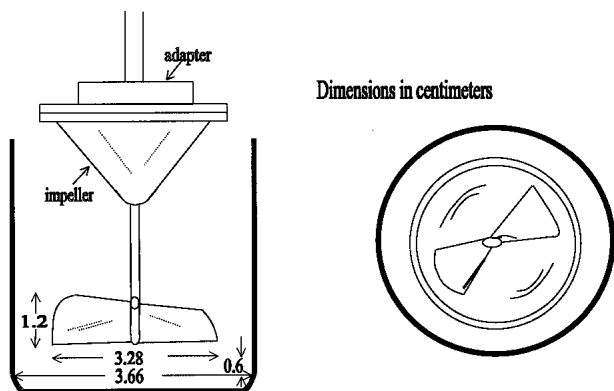


Fig. 1. Dimensions of Rapid Visco Analyser (RVA) pitched paddle impeller and cup (side and top view).

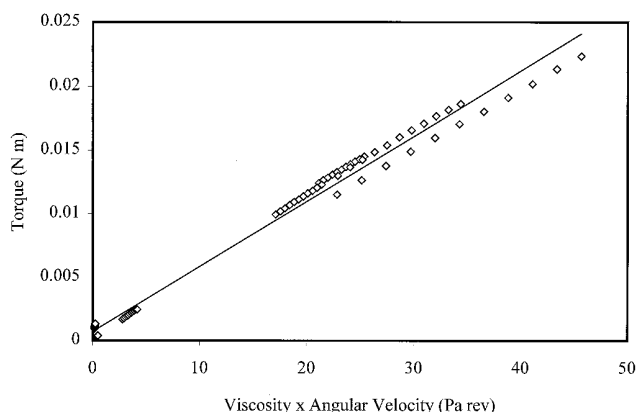


Fig. 2. Mixer torque vs. product of viscosity and angular velocity.

(100–300 rpm). The reciprocal of  $k''$  was determined from Eq. (3) using linear regression analysis, as the slope of:

$$M = \frac{\mu N}{k''} \quad (8)$$

Using the constant value of  $k''$  and various non-Newtonian fluids (Table II),  $k'$  was determined at different angular velocities using Eq. (7).

### Evaluation of Food Products

The utility of the mixer viscometer constant was tested by examining typical food products: corn syrup, mustard, and ketchup (Table III). A bread flour slurry was also tested (Table III). Slurry samples were prepared in the RVA at a concentration of 3.5 g of flour/25 mL of distilled water. The profile STD1 in the RVA with a run time of 13 min was selected to prepare the slurry. The initial temperature was 50°C, and then samples were heated to 95°C and cooled back to 50°C. Samples were allowed to cool to room temperature before testing.

Fundamental rheological properties determined using a concentric cylinder geometry were compared to results from the RVA apparatus. Apparent viscosity was calculated using Eqs. (3) and (4) and data from the RVA apparatus as:

$$\eta = k' \frac{M}{N} \quad (9)$$

at an average shear rate determined with Eq. [6]. Information was collected over a speed range of 0.5 rps to 3.5 rps (30 rpm to 210 rpm). Rheological properties were evaluated using the power law form of the apparent viscosity equation as the mathematical model for the data:

$$\eta = K(\dot{\gamma}_a)^{n-1} \quad (10)$$

True shear rate, calculated using established equations for concentric cylinders (Steffe 1996), was substituted for the average shear rate when examining data from the concentric cylinder viscometer.

TABLE I  
Newtonian Fluids for Acquiring Torque Curve Data

Fluid	Newtonian Viscosity (Pa sec)
Silicone oil <sup>a</sup>	0.10
Silicone oil <sup>a</sup>	0.49
Glycerine <sup>b</sup>	0.83
Silicone oil <sup>a</sup>	5.1
Polybutene <sup>c</sup>	14.0
Pure clover honey <sup>d</sup>	13.7

<sup>a</sup> Brookfield Engineering (Stoughton, MA).

<sup>b</sup> Columbus Chemical Industries (Columbus, WI).

<sup>c</sup> Cannon Instrument Co. (State College, PA).

<sup>d</sup> Meijer, Inc. (Grand Rapids, MI).

TABLE II  
Rheological Properties of Non-Newtonian Standards<sup>a</sup>

Non-Newtonian Standard	$K$ (Pa sec <sup>n</sup> )	$n$
2.0% Hydroxypropyl methylcellulose <sup>b</sup>	7.1	0.58
2.5% Hydroxypropyl methylcellulose <sup>b</sup>	12.0	0.64
1.0% Guar gum <sup>c</sup>	11.0	0.26

<sup>a</sup>  $K$  = consistency coefficient;  $n$  = shear-thinning indices.

<sup>b</sup> Dow Chemical Co. (Midland, MI).

<sup>c</sup> Sigma Chemical (St. Louis, MO).

TABLE III  
Comparison of Consistency Coefficient ( $K$ ) and Shear-Thinning Indices ( $n$ ) for Typical Food Products

Food Product	RVA		Haake VT550	
	$K$ (Pa sec <sup>n</sup> )	$n$	$K$ (Pa sec <sup>n</sup> )	$n$
Karo corn syrup <sup>a</sup>	6.1	1.0	4.9	1.0
Mustard <sup>b</sup>	41.2	0.21	26.8	0.23
Ketchup <sup>c</sup>	49.2	0.17	44.8	0.11
Flour slurry <sup>d</sup>	108.6	0.22	66.8	0.34

<sup>a</sup> Best Foods Division (Englewood Cliffs, NJ).

<sup>b</sup> Reckitt & Colman (Wayne, NJ).

<sup>c</sup> H. J. Heinz Co. (Pittsburgh, PA).

<sup>d</sup> The Pillsbury Company (Minneapolis, MN).

## RESULTS AND CONCLUSIONS

Torque curve results for the Newtonian fluids are shown in Fig. 2. The mixer coefficient was calculated as the reciprocal of the slope of the curve:  $k'' = 2,000 \text{ rev/m}^3$ . Only data in the laminar flow regime, where the impeller Reynolds number was  $<10$ , were included in the determination. The linear relationship observed in Fig. 2 confirms the assumption of laminar flow behavior.

Results show that the mixer viscometer constant was influenced by both the angular velocity and the flow behavior index (Fig. 3). However, at speeds  $>1.0$  rps (60 rpm), the value of  $k'$  is relatively constant. An estimate of the constant was the average of those values for speed of  $>1.0$  rps (Fig. 3) yielding  $k' = 20.1/\text{rev}$ . Similar variations of  $k'$  with speed and rheological properties were observed by Castell-Perez and Steffe (1990) and Mackey et al (1987). Also, comparable values of  $k'$  have been reported. Briggs and Steffe (1996) found  $k' = 20.1/\text{rev}$  for a flag impeller in a Brookfield small sample adapter; Rao and Cooley (1984) found  $k' = 19.7/\text{rev}$  for a star impeller; and Ford and Steffe (1986) found  $k' = 28/\text{rev}$  for a pitched paddle impeller in a Haake MV1 cup.

Taking  $k' = 20.1/\text{rev}$ , and applying Eq. (6) over a speed of 1.0–3.6 rps predicts average shear rates in the RVA of 20.1–70.4/sec. For the purpose of comparison, the maximum shear rates can be estimated as the tip speed of the impeller divided by the clearance between the impeller and the cup:

$$\dot{\gamma}_{\max} = \frac{2\pi d N}{D-d} \quad (11)$$

Substituting the appropriate dimensions and using the same speed range (1–3.5 rps), calculations using Eq. (11) show the maximum shear rate can vary from  $\approx 54.2$  to 189/sec.

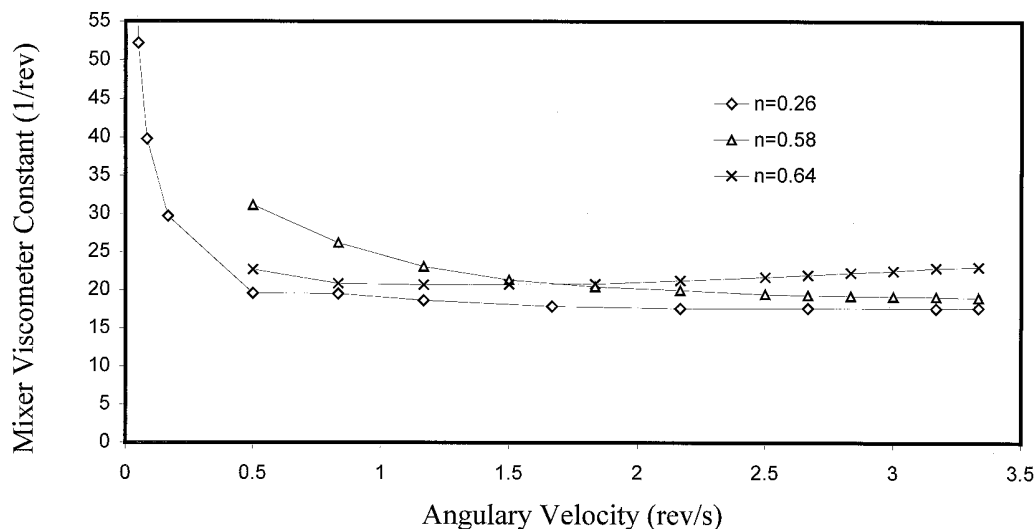


Fig. 3. Mixer viscometer constant vs. angular velocity of non-Newtonian fluids with varying flow behavior indices ( $n$ ).

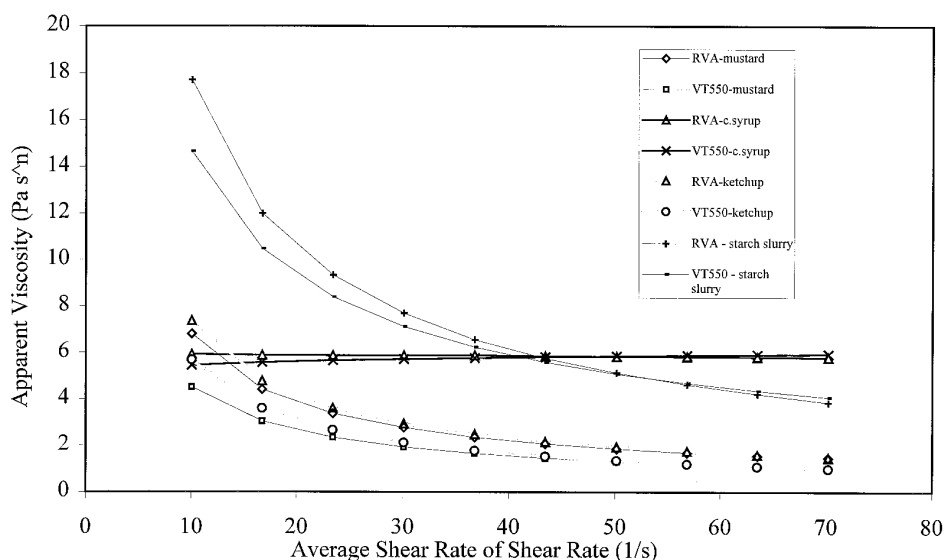


Fig. 4. Apparent viscosity and average shear rate (RVA data) or shear rate (VT550 data) for various food products.

Comparing rheograms for three food products produced using the RVA impeller-cup apparatus and a conventional rheometer shows curves with similar trends and magnitudes (Fig. 4). Rheograms based on average shear rates versus true shear rate are not expected to be identical. The greatest deviation is shown in the magnitudes of the consistency coefficients ( $K$ ), while the shear-thinning tendencies reflected in the  $n$  values are quite close (Table III). In addition, differences in apparent viscosities decrease at higher shear rates (Fig. 4).

Under the conditions of this study, a constant value of the mixer viscometer constant equal to 20.1/rev (Eq. 6) provides a good estimate of the average shear rate present in the RVA impeller-cup apparatus at mixing speeds of  $\approx 1.0$ – $3.5$  rps (60–210 rpm). Overall results show the RVA mixing system has very good potential for characterizing the rheological properties of various non-Newtonian fluid foods.

#### NOMENCLATURE

$A$ , system constant, 1/rev;  $d$ , impeller diameter (m);  $D$ , cup diameter(m);  $k'$ , mixer viscometer constant, 1/rev;  $k''$ , mixer coefficient, rev/m<sup>3</sup>;  $K$ , consistency coefficient (Pa sec <sup>$n$</sup> );  $M$ , torque (N m);  $n$ , flow behavior, dimensionless;  $N$ , angular velocity, rev/sec;  $N_{po}$ , power number, dimensionless;  $N_{Re,I}$ , impeller Reynolds number, dimensionless;  $P$ , power (N m/sec);  $\eta$ , apparent viscosity (Pa sec);  $\mu$ , Newtonian viscosity (Pa sec);  $\rho$ , density, kg/m<sup>3</sup>.

#### ACKNOWLEDGMENTS

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