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Measurement of the Steady-State Shear Characteristics of Filamentous Suspensions Using Turbine, Vane, and Helical Impellers

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ABSTRACT

The impeller viscometer technique is frequently used to characterize the rheology of filamentous suspensions in order to avoid difficulties encountered with conventional instruments. This work presents the results of experiments conducted with vane, turbine, and helical impellers. The validity of the assumptions made in the determination of the torque and shear-rate constants were assessed for each impeller type. For the turbine and vane impellers, an increase in the apparent torque constant c was observed with increasing Reynolds number even when measurements were confined to the viscous regime. The shear-rate constants determined for the vane and turbine impellers varied for different calibration fluids, which contradicts the assumptions usually invoked in the analysis of data for this technique. When the helical impeller was calibrated, consistent values for the torque and shear-rate constants were obtained. The three impeller types were also used to characterize the rheology of cellulose fiber suspensions and the results compared for consistency and reproducibility. The results have application in design of rheometers for use in process control and product quality assessment in the fermentation and pulp and paper industries.

Index Entries: Filamentous suspensions; helical impellers; non-Newtonian rheology.

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INTRODUCTION

Knowledge of the rheological behavior of filamentous suspensions is necessary for the implementation of process and quality control for several processes in the biotechnology and pulp and paper industries. Filamentous suspensions can exhibit complex, non-Newtonian behavior, and characterization of their rheology has been a challenging problem. The use of the impeller viscometer for this purpose has become common practice *(1–3)*, but the validity of a key assumption invoked in the analysis of data obtained from this technique has recently been questioned. Experiments were conducted to develop an impeller design that would yield consistent and reproducible results for non-Newtonian fluids and suspensions of widely varying properties. Turbine, vane, and helical impeller geometries were considered in this investigation.

METHODS

The vane and helical impellers used in the tests were fashioned from nylon using selective laser sintering technology. The six-bladed disk turbine used in the tests had a diameter of 0.0291 m with a blade width of 0.0079 m, a blade height of 0.0064 m, and a blade thickness of 0.0015 meters. The four-bladed vane impeller had a diameter of 0.0291 m and a height of 0.051 m. The helical impeller used in the tests had a single flight with an internal auger. It had a diameter of 0.04 m, a height of 0.055 m, and a pitch of 0.2. All tests were carried out using 800 mL samples in an unbaffled 1000 mL beaker (T = 0.104 m). Table 1 summarizes the pertinent dimensions of the various impeller and vessel combinations used in the tests.

Four different viscometers (Brookfield, Stoughton, MA) were used in the tests. The two dial-reading instruments (models LVT and LVF) had maximum spring torques of 673.7 dyno cm and maximum rotational speeds of 60 rpm. The two digital viscometers (models RV-DVIII and HB-DVIII) had maximum speeds of 250 rpm and full-scale spring torques of 7187 dyno cm and 57,496 dyno cm, respectively. Each viscometer had an experimental uncertainty of plus or minus 1% of its maximum reading. No data was recorded if the torque reading for a given instrument was less than 5% of its full-scale value. All experiments were conducted at a temperature of 25 ± 0.1°C.

The basis for the impeller viscometer technique has been well described elsewhere *(2)*. The method relies on the use of Newtonian and non-Newtonian calibration fluids to determine constants relating the measured torque and speed to viscosity and shear rate. Newtonian silicone oils and solutions of glycerin and corn syrup were used to determine the impeller constant torque, *c*, while non-Newtonian carboxymethylcellulose (CMC), xanthan gum, and guar gum solutions were used to determine the shear rate constant, *k*. The properties of the Newtonian and non-

Table 1
Relative Dimensions of the Impeller Viscometer Apparatus

Impeller	Impeller Diameter D (m)	Impeller Height L/D	Liquid Height H_L/D	Off-Bottom Clearance C/D
Turbine	0.0291	0.22	3.30	1.96
Vane	0.0291	1.75	3.30	0.57
Helical	0.0400	1.37	2.40	0.16

Table 2
Properties of Newtonian Fluids Used in the Determination of the Torque Constant

Fluid	Viscosity (Pa-s)	Density (kg/m^3)
Glycerin (diluted)	0.175	1235
Corn Syrup (diluted)	0.205	1321
Silicone I	0.100	967
Silicone II	0.201	965

Table 3
Results of Shear Rate Constant Determination for the Turbine Impeller

Calibration Solution	Range of Power Law Index	Reynolds Number Range	Range of Values for k	k_{avg}
0.75% Xanthan	0.04 - 0.08	0.001 - 8.40	10.7 - 12.6	11.4
1.0% Xanthan	0.04 - 0.10	0.040 - 8.37	11.2 - 12.8	11.8
0.75% Guar	0.42 - 0.70	0.100 - 9.75	8.75 - 12.8	10.4
1.0% Guar	0.30 - 0.60	0 005 - 1.13	10.0 - 10.7	10.2
1.0% CMC	0.82 - 0.86	3.270 - 9.77	8.67 - 12.9	11.0
1.5% CMC	0.74 - 0.84	0.109 - 1.24	8.40 - 11.4	9.40

Table 4
Results of Shear Rate Constant Determination for the Vane Impeller

Calibration Solution	Range of Power Law Index	Reynolds Number Range	Range of Values for k	k_{avg}
0.75% Xanthan	0.04 - 0.08	0.001 - 9.00	9.41 - 11.1	10.2
1.0% Xanthan	0.03 - 0.10	0.004 - 7.93	9.79 - 11.7	10.4
0.75% Guar	0.58 - 0.70	0.100 - 1.38	9.19 - 10.4	9.56
1.0% Guar	0.34 - 0.70	0.046 - 1.82	9.66 - 12.6	10.6
1.0% CMC	0.85 - 0.86	0.400 - 7.59	8.87 - 9.48	9.20
1.5% CMC	0.70 - 0.84	0.440 - 1.80	12.4 - 19.2	14.2

Table 5
Results of Shear Rate Constant Determination for the Helical Impeller

Calibration Solution	Range of Power Law Index	Reynolds Number Range	Range of Values for k	k_{avg}
0.75% Guar	0.43 - 0.78	0.100 - 9.86	9.78 - 13.2	10.7
1.0% Guar	0.30 - 0.74	0.008 - 9.69	9.77 - 12.8	10.9

Newtonian calibration fluids were measured using a cone-and-plate attachment on the RV-DVIII instrument (Brookfield spindle CP-41). The properties of the Newtonian fluids used to determine the impeller torque constants are summarized in Table 2. Ranges for the power-law indices of the non-Newtonian calibration fluids can be found in Tables 3 through 5.

The fiber suspensions used in this study were composed of various concentrations of powdered cellulose (Solka-Floc, grade KS-1016, average fiber length = 290 μm) suspended in 0.05% and 0.10% xanthan gum solutions to retard settling.

RESULTS

Newtonian Calibration Fluids

In the viscous flow regime, the power number for an impeller is inversely proportional to the Reynolds number with the constant of proportionality defined as c. Thus, the measured torque is directly proportional to the rotational speed and the viscosity of the fluid:

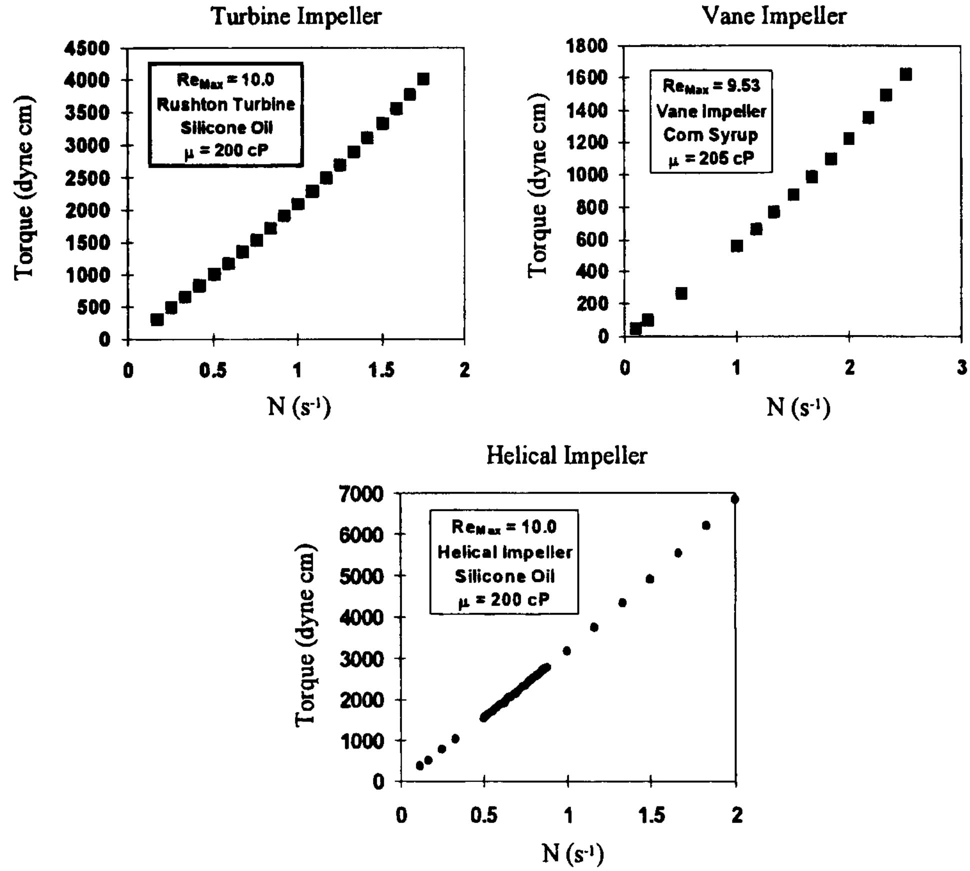

Fig. 1. Newtonian torque vs speed relationship for various impellers.

$$\Gamma = \frac{c}{2\pi}\mu N D^3 \qquad (1)$$

For a given rotational speed, the measured torque can thus be used along with the fluid viscosity and the impeller diameter to calculate the apparent impeller torque constant, c. Figure 1 illustrates typical Newtonian torque vs speed relationships for the three impellers used in this study. There is a pronounced curvature in the plots for the vane and turbine impellers, but the data for the helical ribbon seem to be linear in accordance with Equation 1. Figure 2 shows the same data plotted as the apparent value of c/c_0 where c_0 is the average value of the apparent impeller torque constant for Reynolds numbers less than 3. Based on the data of Donnelly *(4)*, the following relationships for the apparent torque constants for the vane and turbine were determined:

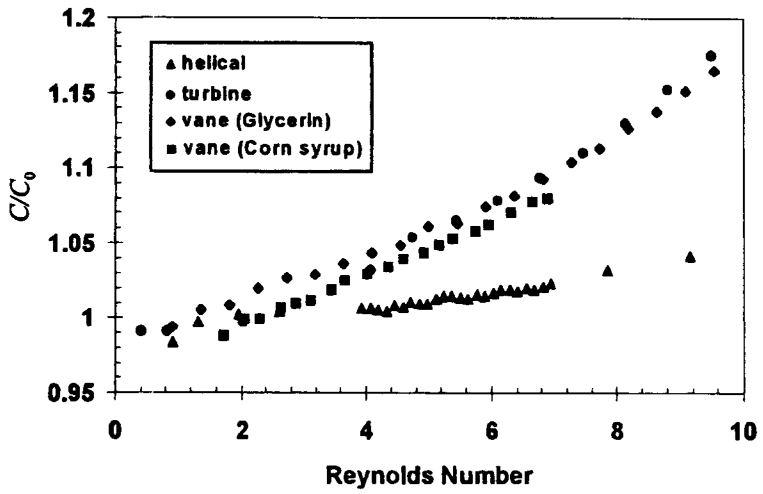

Fig. 2. Effect of Reynolds number on the apparent torque constant for various impellers.

Turbine		Vane	
$c = 67$	$(\mathrm{Re} < 2)$	$c = 244$	$(\mathrm{Re} < 2)$
$c = 67 + 2\,\mathrm{Re}$	$(2 < \mathrm{Re} < 4)$	$c = 235 + 4.5\,\mathrm{Re}$	$(2 < \mathrm{Re} < 10)$
$c = 64.4 + 1.65\,\mathrm{Re}$	$(4 < \mathrm{Re} < 10)$		

The data for the helical impeller can be adequately represented by a constant value of $c = 150$ in accordance with Equation 1.

Non-Newtonian Calibration Fluids

The impeller method is extended to non-Newtonian fluids by replacing the Newtonian viscosity μ in Equation 1 with the apparent viscosity η_a:

$$\Gamma = \frac{c}{2\pi}\eta_a N D^3 \tag{2}$$

It is also assumed that the c value for the Newtonian case applies to nonNewtonian fluids as well. The apparent viscosity of a non-Newtonian fluid can, therefore, be determined from the measured torque and impeller speed once the impeller torque constant c has been determined. The question of what shear rate to associate with the apparent viscosity determined from application of Equation 2 remains, however. The procedure usually adopted is to make use of the Metzner-Otto assumption that the average shear rate near the impeller is related to the rotational speed by a fluid independent constant, k:

$$\gamma = kN \tag{3}$$

If this approach is valid, the shear-rate constant can be determined from experimental measurements of torque vs impeller speed for non-Newtonian fluids of known properties. The apparent viscosity is determined from Equation 2, the value of shear rate that corresponds to this viscosity is obtained from the known rheogram for the non-Newtonian fluid, and the value of k then determined from Equation 3. If the Metzner-Otto assumption holds true, the same value of k will be found for all fluids, implies that the method can be applied with confidence to any non-Newtonian fluid or suspension of unknown properties.

Tables 3 through 5 summarize the results obtained from the shear rate constant calibration trials for the turbine, vane, and helical impellers. The average value of the shear-rate constant determined for the turbine was 11.0, for the vane 10.2, and for the helical impeller 10.8. The results from the CMC trials were not used in the calculation of the average shear rate constant for the turbine or the vane for reasons given in the discussion.

Filamentous Suspensions

The collection of rheological data for filamentous suspensions becomes complicated if the fibers have a tendency to settle. The fibers used in these tests tended to settle fairly rapidly in water, so small concentrations (0.05 and 0.10%) of xanthan gum were added to retard settling. The solutions were also mixed periodically throughout the trials.

Figure 3 demonstrates the ability of the Rushton turbine, vane impeller and helical impeller to measure the viscosity of the suspensions. It is evident from the figure that both the vane and Rushton turbine impellers return similar viscosities at a given shear rate. The viscosities measured by the helical impeller are slightly higher than the values given by the other impellers, but the general behavior is similar. The difference might be a result of a difference in the settling characteristics of the suspensions in the different systems since particle settling was generally not a problem with the helical impeller. Table 6 summarizes the results of the suspension tests.

DISCUSSION

Newtonian Calibration Fluids

The apparent Reynolds number dependence of the torque constants for the vane and turbine impeller is cause for some concern since this behavior has generally not been reported in the literature for Re < 10. This behavior was not observed when tests were conducted with a turbine impeller in a larger scale system (D = 0.0994 m, μ = 67.7 g/cm s) with a different torque measuring system. The possibility that the observed dependence may be an artifact because of some characteristic of the torque sensing devices built into the viscometers cannot be ruled out. The fact that

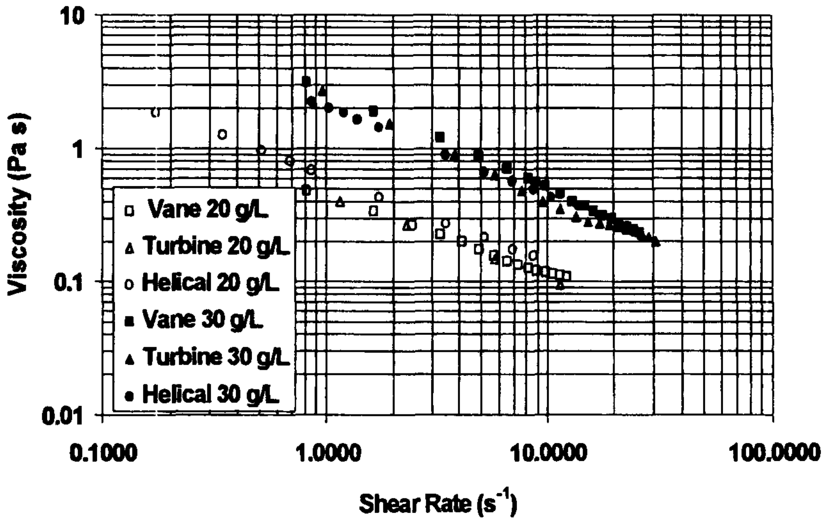

Fig. 3. Properties of cellulose fiber suspensions as measured by the different impellers.

the helical impeller gave *c* values that were very nearly constant for Reynolds numbers less than 10, may be a result of its larger diameter and the fact that the transition to turbulence for helical impellers occurs at higher Reynolds numbers than for turbines or vanes *(5)*.

Non-Newtonian Calibration Fluids

The average shear rate constant did not appear to be independent of the fluid used to determine it for any of the impellers studied. Indeed, as Tables 3–5 indicate, there was considerable point to point variation in the *k* value for a given fluid. Nevertheless, use of the average *k* value determined for each impeller did not lead to more than about 10–15% error when the cone-and-plate data were compared with the values given by the respective impeller viscometers. The CMC results were not used to compute the average *k* values for the vane and turbine impellers because the power-law indices of the two solutions were relatively close to 1. In this range, the viscosity is relatively insensitive to shear rate, which is not a particularly desirable property of a non-Newtonian calibration fluid, since it will tend to magnify any experimental errors in the torque measurement. Nevertheless, the average k values for the CMC solutions are not much different from those determined for the more highly shear-thinning solutions.

Fiber Suspensions

The rheological data for 0.1 and 0.05% xanthan gum solutions are similar, which suggests that the addition of small amounts of xanthan to

Table 6
Rheological Parameters of Fiber Suspensions Determined Using Various Impellers

Fiber Concentration (kg/m^3)	Xanthan Gum Concentration (kg/m^3)	Impeller Type	K_{pl} ($Pa\ s^n$)	n	r^2
20	1.0	Vane	0.398	0.507	0.966
30	1.0	Vane	3.04	0.228	0.999
40	1.0	Vane	13.6	0.255	0.9995
50	1.0	Vane	28.4	0.303	0.9998
20	1.0	Turbine	0.463	0.364	0.999
30	1.0	Turbine	2.45	0.263	0.988
40	1.0	Turbine	9.69	0.285	0.998
50	1.0	Turbine	27.5	0.258	0.999
20	0.5	Helical	0.624	0.361	0.999
25	0.5	Helical	0.814	0.330	0.999
30	0.5	Helical	2.062	0.337	0.999
35	0.5	Helical	5.967	0.246	0.996
10	1.0	Helical	0.347	0.458	0.9994
20	1.0	Helical	0.623	0.404	0.9997
30	1.0	Helical	2.200	0.283	0.9993

prevent particle settling did not significantly affect the measured torques and viscosities. In any case, the effect will be largest at low shear rates and will become progressively less important as the fiber concentration increases. The helical impeller was superior to the other two impellers since it allowed rheological measurements to be performed on suspensions with fiber concentrations as low as 10 g/L in 0.05% xanthan gum solution. In previous work conducted with *Aspergillus niger* broths *(1)*, the rheology of pelletal suspensions could not be accurately characterized with a turbine impeller since the suspensions were insufficiently viscous and the resulting impeller torques were too small. The helical impeller should be better suited for measurements of this type and for less viscous suspensions in general.

The power-law parameters determined for the cellulose fiber suspensions can be compared with the results reported in the literature for the same fiber grade *(3)*:

20 g/L: K (Pa s^n) = 1.46 n = 0.32
30 g/L: K (Pa s^n) = 6.13 n = 0.24

Comparison of the power-law parameters indicates that the suspensions studied here were less viscous and less-shear thinning than the suspensions used in the literature study. The differences might reflect a difference in the properties of the fibers, although the same fiber grade was used. The behavior of the suspensions was consistent with the literature results in that the increase in the consistency index as the power-law index increased was relatively moderate.

CONCLUSIONS

At a given speed, the vane and helical impellers draw more torque than the turbine, and were hence more useful for measuring the rheological properties of low viscosity fluids and suspensions. Of the three impellers studied, the helical impeller yielded results which appeared to best satisfy the assumptions inherent in the impeller viscometer approach.

NOMENCLATURE

c	impeller torque constant, dimensionless
C	off-bottom clearance of impeller, m
D	impeller diameter, m
H_L	liquid height, n
k	shear rate constant, dimensionless
K_{pl}	consistency index constant, Pa s^n
L	impeller height, m
n	power-law index
N	impeller speed, s^{-1}
Re	impeller Reynolds number, $\rho ND^2/\mu$
T	vessel diameter, m
Γ	impeller torque, Nm
γ	shear rate, s^{-1}
μ	Newtonian fluid viscosity, Pa-s
η_a	apparent viscosity of a non-Newtonian fluid, Pa-s
ρ	fluid density, kg/m^3

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