

A MIXER VISCOMETRY APPROACH TO USE VANE TOOLS AS STEADY SHEAR RHEOLOGICAL ATTACHMENTS

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ABSTRACT

A mixer viscometry procedure, coined the Matching Stress Method, was developed to use four-bladed vanes devices in applications requiring steady shear measurements. Based on the concept that vane tools shear fluids in a cylindrical pattern defined by their geometry, this technique determined a mixer viscometry constant to predict average shear rates for vanes. Three cylindrical bobs and three, four-bladed vanes were used to investigate the impact of attachment geometry on the mixer viscometry constant. Two Newtonian fluid standards and three carboxy-methyl-cellulose (CMC) solutions were used to examine fluids with varying rheological properties. Four cups of varying dimensions contained the sample fluids and provided a system of fluid gaps for comparison. A Bohlin VOR Rheometer collected torque and angular velocity data for vane and bob attachments. For the bob devices, torque and angular velocity measurements were converted into shear stress and shear rate rheograms. Torque responses collected using the vanes were converted into shear stress measurements, and the proposed method matched the vane rheograms with each bob of identical height, diameter, and corresponding system geometry. Variation of system geometry and flow properties revealed the mixer constant depended on fluid gap size when below a cup-to-vane diameter ratio of 2.1 and a flow behavior index of 0.86. This procedure enables vane tools to be used in steady shear applications, not limiting their employment to single point, yield stress determination.

ZUSAMMENFASSUNG

Eine Mischeranalyse (Matching Stress Method) wurde entwickelt, um die Effektivität von vierblättrigen Flügelrührern in stationären Schermessungen zu bestimmen. Unter der Annahme, dass die Flügelrührer die Flüssigkeit in einem zylindrischen Muster scheren, wurde eine Mischer-Viskositätskonstante bestimmt, um die mittlere Schergeschwindigkeit für die Flügelrührer vorherzusagen. Es wurden drei vierblättrige Flügelrührer mit drei zylinderförmigen Couettesystemen verglichen, um den Geometrieinfluss auf die Mischqualität zu untersuchen. Als Probenmaterial wurden zwei newtonsche Standardflüssigkeiten und drei Carboxy-Methyl-Cellulose (CMC) Lösungen mit verschiedenen rheologischen Eigenschaften ausgewählt. Die Kombination von vier Gefäßen mit unterschiedlichen Innendurchmessern und den Couette- und Rührereinsätzen stellten so einen Versuchsaufbau dar, der den Vergleich der Proben erlaubte. Um das Drehmoment und die Winkelgeschwindigkeit für die Flügelrührer und Couette-Einsätze zu bestimmen wurde ein Bohlin VOR Rheometer verwendet. Im Fall der Couette-Einsätze wurden Drehmoment und Winkelgeschwindigkeit in ein Schubspannungs-Scherraten Rheogramm übersetzt. Die mit den Flügelrührern bestimmten Drehmomente wurden in Schubspannungsdaten umgesetzt und mittels der „Matching Stress Method“ mit den Rheogrammen des jeweiligen Couettesystems mit identischer Höhe verglichen. Die Veränderung der Geometrie und der Fließeigenschaften hat gezeigt, dass die Mischer-Viskositätskonstante von der Spaltbreite abhängt, solange das Verhältnis von Behälter- zu Flügelrührerdurchmesser kleiner als 2,1 und der Fließindex kleiner als 0,86 ist. Dieses Verfahren ermöglicht die Verwendung von Flügelrührern in stationären Schermessungen, ohne deren Anwendung auf Messungen der Fließgrenze einzuschränken.

RÉSUMÉ

Une procédure d'analyse de mixer, appelée "Matching Stress Method" a été développée, afin d'évaluer l'efficacité des rotors à 4 lames pour des applications qui requièrent des mesures en cisaillement stable. Basée sur le concept que les outils à rotor cisailent les fluides dans une géométrie cylindrique définie par leur diamètre, cette technique a déterminé une constante de viscosimétrie de mixer, utilisée pour prévoir une vitesse moyenne de cisaillement. 3 rotors cylindriques et 3 rotors à lames, avec des dimensions équivalentes de 10 mm de diamètre et 20, 28 et 36 mm de hauteur, ont été utilisés. Des fluides Newtoniens standards, avec des viscosités de 0.965 et 11.36 Pas, ainsi que 3 solutions de cellulose carboxy-méthylque (CMC) à des concentrations de 2, 3 et 4% en poids, ont été utilisés pour l'étude de fluides aux propriétés rhéologiques variées. 4 coupes de 60 mm de haut et de diamètre intérieur de 12, 16.5, 21 et 27.5 mm respectivement, contiennent chaque fluide échantillon et offrent un système de géométries pour comparaison. Un rhéomètre Bohlin VOR fut utilisé pour mesurer les couples et vitesses angulaires, qui furent converties en contraintes de cisaillement et vitesses de cisaillement appropriées. Les réponses de couple enregistrées avec les rotors à lame furent converties en mesures de contraintes de cisaillement, et la "Matching Stress Method" égalisait les rhéogrammes obtenus avec chaque rotor cylindrique de hauteur et géométrie correspondantes. La variation de géométrie et les propriétés d'écoulement ont montré que la constante de mixer dépend de la taille de l'entrefer quand le ratio des diamètres du rotor et de la coupe est inférieur à 2.1. Ceci correspond à un index de comportement d'écoulement de 0.86. Cette procédure permet d'utiliser des rotors à 4 lames pour des applications de cisaillement constant, ne limitant pas leurs applications à la mesure de contraintes seuils.

KEY WORDS: Vanes, steady shear rheology, mixer viscometry

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Figure 1:
Vane Illustration

1 INTRODUCTION

Vanes are rheological attachments constructed with a varying number of blades, see Fig. 1. Vane rheology has been used extensively for calculating yield stresses of a variety of materials. Haimoni and Hannant [1] used vanes as an aide for evaluating processing effects of entrapped air on the settling characteristics and pumpability of cement pastes. Daubert, et al. [2] used vane rheology to predict spreadability and texture of elastoplastic foods, such as margarine and peanut butter. Yield stress measurements can also be used to compare freezing temperatures and molecular interactions affecting structure and scoopability of ice creams [3]. Foam yield stress was measured by Prud'homme and Khan [4] using vane rheology to show the dependence of foam strength on air volume. Vanes have become popular tools for calculating yield stress because they are less likely to disturb structure during sample immersion than traditional concentric cylinder attachments.

In order to correlate yield stress to the maximum torque response on the shaft of the vane, a yielding surface must be defined. Studies have shown vanes exhibit a cylindrical shearing surface as defined by vane height and diameter [5]. Yan and James [6] modeled the yielding process of a four-bladed vane immersed in a cup using the computational fluid dynamics program FIDAP. This finite element approach solved a governing set of equations simulating the elastic, viscoelastic, and plastic stages of the yielding process for a Herchel-Bulkley, Casson, and viscoelastic fluid. Shear rate surface plots were constructed for the Herchel-Bulkley and viscoelastic fluids. In further support of these results, Nguyen and Boger [7] found a rigid cylinder of material exists within the vane blades and rotates as a solid body. Also, Nguyen and Boger [8] concluded that a near uniform stress distribution resides in a region located around the outer edge of a rotating vane.

Haimoni and Hannant [1] examined the gel strength of cement slurries by determining the yield stress of four cement preparations. Variation of measurement geometry revealed the gel strength was dependent upon attachment configuration. Identical system geometry and rotational speed were studied using a six-bladed vane and a cylindrical bob. Substantially higher yield

stresses were observed using the vane than obtained with a bob of identical height and diameter, and breakdown curves for the bobs and vanes illustrated this discrepancy. From these results, Haimoni and Hannant [1] concluded that a bob produced a fluid/metal shearing surface while a fluid/fluid shearing surface was observed with a rotating vane. Due to the differences in surface area, a vane induces a negligible slip effect unlike a bob. Negligible slip promotes the use of vanes as accurate rheological devices and is considered fundamental to their employment [9].

Average shear rate calculations for complex geometries such as helical impellers, flat blade and fan turbines have been investigated using mixer viscometry [10, 11]. This approach uses a mixer constant, k' to convert a rotational speed to a shear rate. The mixer constant is used to quantify the effect of specific system geometry and fluid characteristics on the shear rate. Once k' has been established, an average shear rate can be approximated simply as the product of this constant and the rotational speed. Two widely practiced mixer viscometry techniques used to calculate mixer constants are the matching viscosity and slope methods, and development of both procedures can be found in Steffe [12].

Castell-Perez and Steffe [13] determined mixer viscometry constants using the matching viscosity and slope methods for a variety of system geometries and for Newtonian and pseudoplastic fluids. With variation of system geometry and fluid properties, these researchers concluded k' generally increased as the level of fluid pseudoplasticity decreased, fluid gap decreased, and as impeller height decreased. Rao and Cooley [14] calculated mixer viscometry constants for an eight-bladed vane and flag impeller using standard Newtonian and shear thinning fluids analyzed at numerous rotational speeds. Mixer constants were determined using both mixer viscometry methods, and larger constants were calculated for the vane impeller. Rao and Cooley [14] concluded that geometries with large surface

areas exhibit larger values of k' . The objectives of this investigation were:

- To analyze how variation of fluid pseudo-plasticity and system geometry affect rheological properties obtained using a cylindrical bob and a four-bladed vane with equivalent height and diameter geometries
- To develop a mixer viscometry-based technique to use vanes as steady shear tools

Vanes shear a material at a liquid/liquid interface, along a cylindrical surface defined by the configuration geometry. However, determining the exact strain rate has been considered a complicated process as the thickness of the sheared layer is difficult to measure [1], and this issue must be resolved before a vane can be used successfully as a steady shear instrument.

2 METHODS AND MATERIALS

2.1 RHEOMETER

A Bohlin VOR controlled strain rheometer (Bohlin Reologi, Inc. Cranbury, NJ) with a C25 concentric cylinder system was used in this analysis. To maintain a constant temperature throughout multiple tests, the system was equipped with a Bohlin TCU circulating bath, and data were recorded with a personal computer connected to the testing apparatus.

2.2 SYSTEM GEOMETRIES

Three cylindrical flat-bottomed bobs and three four-bladed vane attachments were used in this investigation, see Tab. 1. Each device was constructed of stainless steel with a diameter of 10 mm and varying in heights of 20, 28, and

36 mm. Vane blades were machined to a thickness of 0.8 mm. A standard stainless-steel cup with an inside diameter of 27.5 mm manufactured for the Bohlin Rheometer C25 system was used. In addition, three cups were constructed from PVC to fit inside the Bohlin cup, providing three new inside diameters: 21, 16.5, and 12 mm respectively. Each of the four cup arrangements had equivalent depths of 60 mm. Care was taken to insure each cup and bob combination was maintained in proper alignment throughout testing.

2.3 DATA COLLECTION

Rheological data were obtained using the viscometry mode of the Bohlin operating software. The C25 measuring system was selected, and the torque and angular velocity data were measured and used to model flow behavior of sample fluids. Angular velocity ranged from 0.28 rads^{-1} to 11.1 rads^{-1} , and the rheometer integrated torque responses for 10 second intervals at each angular velocity. Prior to advancing rotational speed, the rheometer was programmed with a 5 second delaytime. Tests were performed in triplicate, and effective replication was observed.

2.4 SAMPLE PREPARATION

Two Brookfield Standard Newtonian solutions (Brookfield Engineering Laboratories, Inc. Stoughton, MA) with viscosities of 0.965 and 11.36 Pas calibrated at 25°C along with three carboxy-methyl-cellulose (CMC) (Hercules, Wilmington, DE) solutions were analyzed. The three CMC solutions were prepared with deionized water and had weight percentages of 2, 3, and 4% respectively. After sample preparation, approximately 24 hours elapsed prior to testing to allow air bubbles to escape from the solutions.

All tests were conducted at a temperature of 25 ± 0.1 °C. Each fluid was transferred from a beaker to the cup being investigated via a 20 ml syringe. Once the transfer was completed, the filled cup was inserted into measurement position, and the selected rheological attachment was slowly immersed in the fluid to the desired height. All samples were pre-sheared at an average angular velocity of 0.18 rads^{-1} for approximately 1 minute to remove any residual structure in the solution.

Table 1:
Attachment dimensions and
classifications.

Geometry	Diameter [mm]	Height [mm]	Device Code
Vane	10	20	Vane 20
Vane	10	28	Vane 28
Vane	10	36	Vane 36
Bob	10	20	Bob 20
Bob	10	28	Bob 28
Bob	10	36	Bob 36

Three replicates were conducted for each attachment, cup, and solution. Six attachments, five solutions, and four cups resulted in a total of 360 tests for this investigation. After each replicate for each configuration, the fluid was removed, and the cup was cleaned and prepared for testing of the next sample.

2.5 RHEOLOGICAL CALCULATIONS

All solutions in this investigation were modeled as power law fluids expressed as:

$$\sigma_{B,V} = K\dot{\gamma}^n \quad (1)$$

where the shear stress, σ , is the product of the consistency coefficient, K , and shear rate, $\dot{\gamma}$, raised to a constant, n , commonly referred to as the flow behavior index. Subscripts B and V refer to either bob or vane. Newtonian solutions were assigned a flow behavior index of one.

Average shear stress values for each bob and vane device were calculated from torque data acquired as well as the effective height, h_o , correction factor, accounting for end effects for each configuration [16]. From this information, average shear stresses for vanes (V) and bobs (B) were found using:

$$\sigma_{B,V} = \frac{M_{B,V}}{2\pi(h+h_o)R_{B,V}^2} \quad (2)$$

where M is the torque exerted on the bob or vane as a result of flow patterns induced by cup rotation, h is the immersion depth of the attachment in the fluid, and R is the radius of the device. Shear rate values for the bob attachments, $\dot{\gamma}_B$, were determined from angular velocity data, Ω_B , system geometry, and flow behavior indices, n . The flow behavior index is a material property and independent of system geometry. This fluid characteristic was determined as the slope of a log-log plot of torque versus angular velocity for each solution analyzed.

$$n = \frac{d(\log M)}{d(\log \Omega)} \quad (3)$$

Values for n were found to be independent of attachment selection and fluid gap width. Both angular velocity and flow behavior were considered in calculating the shear rate at the bob

according to a Power law approximation [12]:

$$\dot{\gamma}_B = \left(\frac{2\Omega_B}{n} \right) \left(\frac{\alpha^{2/n}}{\alpha^{2/n} - 1} \right) \quad (4)$$

where α is the ratio of the cup radius, R_c , to the bob radius, R_b . Shear rate calculations for vane attachments, $\dot{\gamma}_V$, may be expressed in terms of angular velocity data, Ω_V , and a mixer viscometry constant, k' , as:

$$\dot{\gamma}_V = k'\Omega \quad (5)$$

2.6 MATCHING STRESS METHOD (MSM) FOR K' DETERMINATION

The matching stress technique was developed as a method to incorporate vane attachments in mixing and steady shear operations rather than a tool for a single yield stress calculation. Previously noted research has established that vane attachments exhibit cylindrical shearing surfaces. The average shear stress at the surface of the bob, σ_B , was assumed equal to the shear stress at the edge of the vane blades, σ_V , when operating at the same shear rate, $\dot{\gamma}$, represented mathematically as:

$$\sigma_{B,\dot{\gamma}} = \sigma_{V,\dot{\gamma}} \quad (6)$$

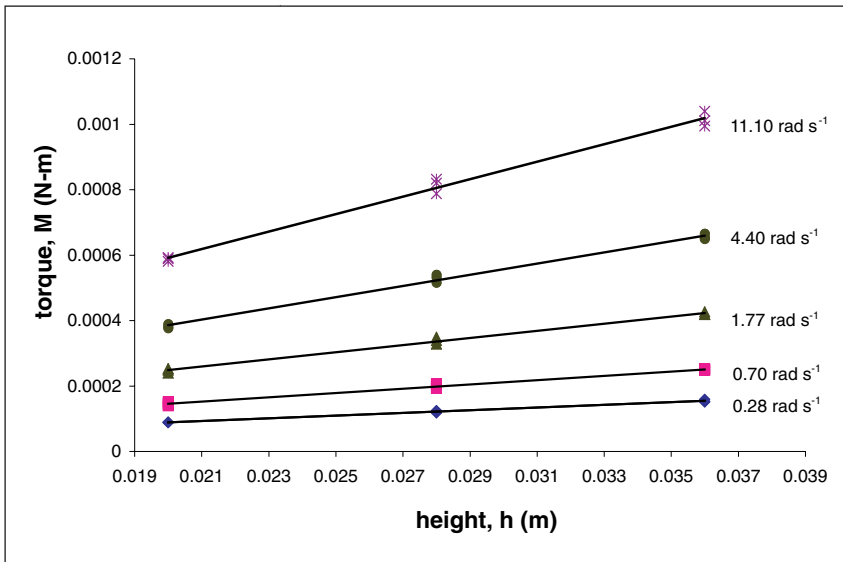
for identical fluids. Considering a plot of average shear stress versus angular velocity for each geometry, power law fluid behavior fits the following relations:

$$\sigma_B = C_B \Omega_B^n \quad (7)$$

$$\sigma_V = C_V \Omega_V^n \quad (8)$$

where C_B and C_V represent power law constants for each respective geometry, bob, and vane. Applying Eq. 6, the ratio of shear stresses becomes unity at the same effective shear rate. Dividing each side of Eq. 7 by each respective side of Eq. 8 and applying Eq. 6 yields the following:

$$1 = \frac{C_B}{C_V} \left(\frac{\Omega_B}{\Omega_V} \right)^n \quad (9)$$



Solving for the ratio of angular velocities yields:

$$\frac{\Omega_B}{\Omega_V} = \left(\frac{C_V}{C_B} \right)^{(1/n)} = \lambda \quad (10)$$

Substituting Eq. 4 into Eq. 1 for the shear stress at the bob gives:

$$\sigma_B = K \left[\left(\frac{2\Omega_B}{n} \right) \left(\frac{\alpha^{2/n}}{\alpha^{2/n} - 1} \right) \right]^n \quad (11)$$

Likewise, a power law correlation between average shear stress at the vane edges, σ_V , and shear rate, $\dot{\gamma}$, with the k' correction factor is given by:

$$\sigma_V = K(k'\Omega_V)^n \quad (12)$$

Dividing each side of Eq. 11 by each respective side of Eq. 12 and applying stipulation Eq. 6 yields the following:

$$1 = \frac{\left\{ K \left[\left(\frac{2\Omega_B}{n} \right) \left(\frac{\alpha^{2/n}}{\alpha^{2/n} - 1} \right) \right]^n \right\}}{\left\{ K(k'\Omega_V)^n \right\}} \quad (13)$$

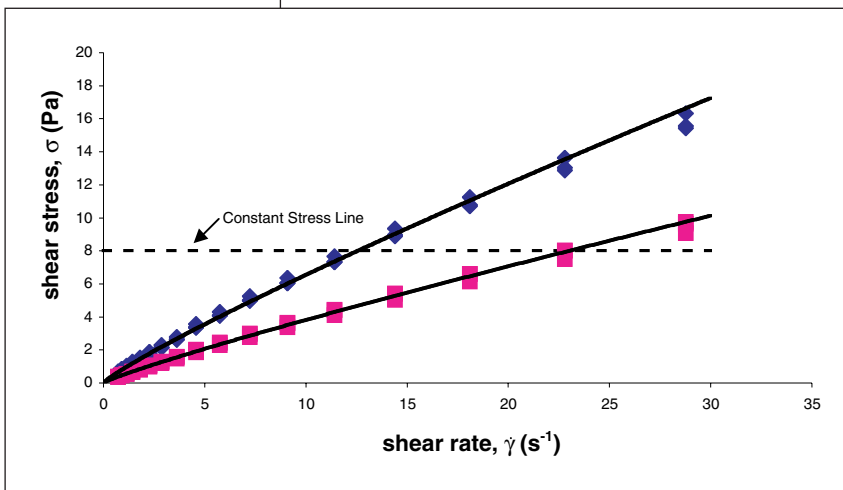


Figure 2 (upper):
Effective height
determination
(Vane Attachments,
4.0% CMC solution,
 $\alpha = 1.65$)

Figure 3: Shear rate devi-
ations using the concentric
cylinder approximation
(\blacklozenge Bob 28,
 \blacksquare Vane 28,
2% CMC Solution,
 $\alpha = 2.75$)

CMC [wt%]	α	I. h_o [mm]	II. h_o [mm]	III. h_o [mm]	Bob $h_{o, avg}$ [mm]	IV. h_o [mm]	V. h_o [mm]	VI. h_o [mm]	Vane $h_{o, avg}$ [mm]
2	1.2	3.3	3.3	1.9	2.5	5.1	2.8	3.9	2.4
3	1.2	0.1	1.4	4.2	2.1	2.8	1.5	3.6	2.4
4	1.2	2.6	3.4	3.2	3.1	2.7	3.1	-	1.4
2	1.65	3.7	2.6	3	4.8	4.4	2.4	2.1	2.6
3	1.65	1.1	2.2	3.7	2.4	3.1	5.3	6.6	5.4
4	1.65	3.4	3.9	3.1	3.9	1.4	2.8	2.1	2.4
2	2.1	7.4	6.9	6.3	7	2.8	1.2	1.3	1.4
3	2.1	0.3	1.9	4.2	2.3	2.7	1.6	3.7	2.5
4	2.1	2.6	3.4	3.2	3.1	-	-	-	-
2	2.75	6.3	4.9	5.4	5.4	11.3	8.2	7	8.5
3	2.75	5.1	2.8	7.2	4.5	3.1	2.8	4.2	3.3
4	2.75	11.5	10.9	9	10.8	7.7	2.9	2.6	2.9

I and IV: $\Omega_{B,V} = 0.28 \text{ rad/s}$; II and V: $\Omega_{B,V} = 1.77 \text{ rad/s}$; III and VI: $\Omega_{B,V} = 11.1 \text{ rad/s}$

Table 2:
Effective height
correction factors.

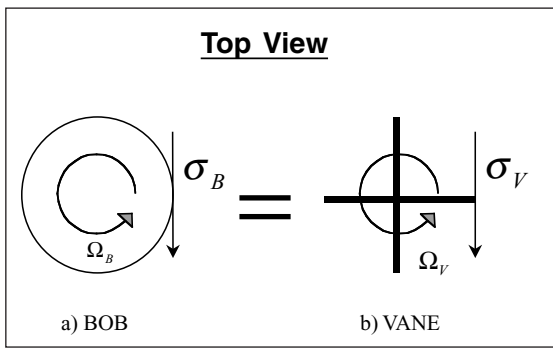


Figure 4:
Graphical illustration
of MSM assumption.

Solving and simplifying for k' :

$$k' = \left[\left(\frac{2}{n} \right) \left(\frac{\alpha^{2/n}}{\alpha^{2/n} - 1} \right) \left(\frac{\Omega_B}{\Omega_V} \right) \right] \quad (14)$$

Finally, substitution of Eq. 10 into Eq. 14 transforms k' into a measurable quantity:

$$k' = \left[\lambda \left(\frac{2}{n} \right) \left(\frac{\alpha^{2/n}}{\alpha^{2/n} - 1} \right) \right] \quad (15)$$

3 RESULTS AND DISCUSSION

3.1 END EFFECT CORRECTIONS

End effect values of h_o were calculated from a plot of torque versus immersion depth for each angular speed, analogous to Barnes and Carnali [15]. The x-intercept, h_o , was determined from regression analysis. An average end effect correction, determined from all angular velocities investigated for each solution, cup, and type of attachment, was incorporated into the average shear stress calculation shown previously in Eq. 2. Fig. 2 illustrates this graphical method for a single set of conditions, with results from this data summarized in Tab. 2 for all conditions. This table shows no noticeable trend of how the magnitude of h_o varied with system geometry, α , for each CMC solution. Deviations may be attributed to inconsistent immersion depths during probe insertion into the samples.

3.2 SHEAR RATE COMPARISONS

Shear rate calculations for concentric cylinder geometries, Eq. 4, were used for the vane device and produced inaccurate rheograms when compared with the bob results. To reveal this discrepancy, Fig. 3 shows corrected shear stress for the bobs and vanes, Eq. 2, versus shear rate calculation using Eq. 4. Following a line parallel to the x-axis that intersects both flow curves along a constant stress, indicated that a concentric cylinder shear rate is inappropriate for vanes. The

constant stress line revealed the angular velocity for the vane was greater than the bob speed to produce a similar shear stress. Assuming the shear stress calculations were correct for the bobs and vanes, deviations in the rheograms were attributed to geometrical differences between the attachments and may have resulted from the proportion of fluid/metal contact relative to each attachment. To accurately predict a shear rate for vanes, a mixer viscometry approach was applied using Eqs. 5 and 15.

3.3 MATCHING STRESS METHOD (MSM)

The MSM is based on the assumption that the shear stress at the surface of the bob is equal to the shear stress at the vane edges when shear rates are identical, and Fig. 4 illustrates this graphically. By considering the effects of system geometry, α , and flow behavior index, n , on the predicted vane shear rates, an explicit relationship between geometry and fluid characteristics was observed.

Tab. 3 reveals values of λ and k' determined for the 28 mm devices. These parameters varied for cup radius and the fluids analyzed. Considering λ a fundamental aspect of k' , λ can be classified as a shifting agent correcting deviations arising when applying shear rate calculations derived for cylindrical geometries in applications employing vane geometries. Assuming equivalent shear stress is a function of equivalent shear rate, the only difference between these two representations of a shear rate is the existence of the λ term in the vane shear rate approximation.

$$[\dot{\gamma}_B = \dot{\gamma}_V]_{\sigma_B = \sigma_V} \rightarrow \left[\frac{2\Omega}{n} \left(\frac{\alpha^{2/n}}{\alpha^{2/n} - 1} \right) = \lambda \left(\frac{2\Omega}{n} \right) \left(\frac{\alpha^{2/n}}{\alpha^{2/n} - 1} \right) \right]_{\sigma_B = \sigma_V} \quad (16)$$

$$\dot{\gamma}_V = \lambda \dot{\gamma}_B \quad (17)$$

How k' accurately manipulates a standard shear rate is dependent upon whether λ is less than or greater than unity. This shift factor, λ , when less than one, corrects for an overestimate of the apparent shear rate using the calculation. Overestimates are corrected by shifting to the left on a flow curve, reducing the vane shear rate mag-

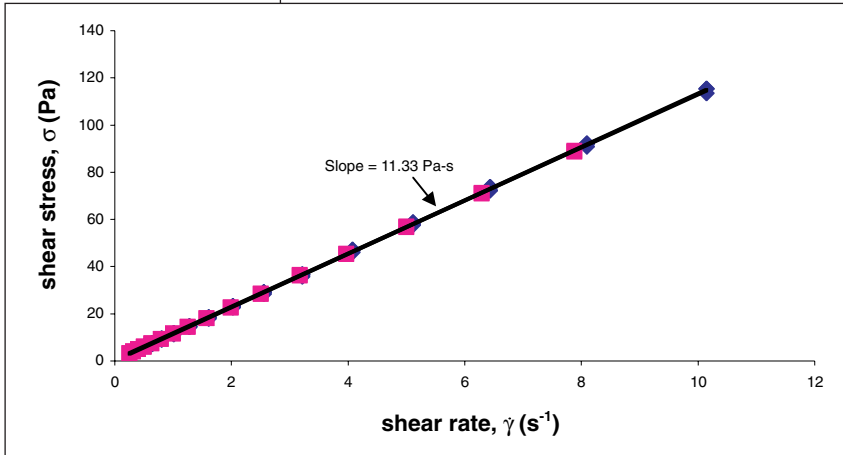
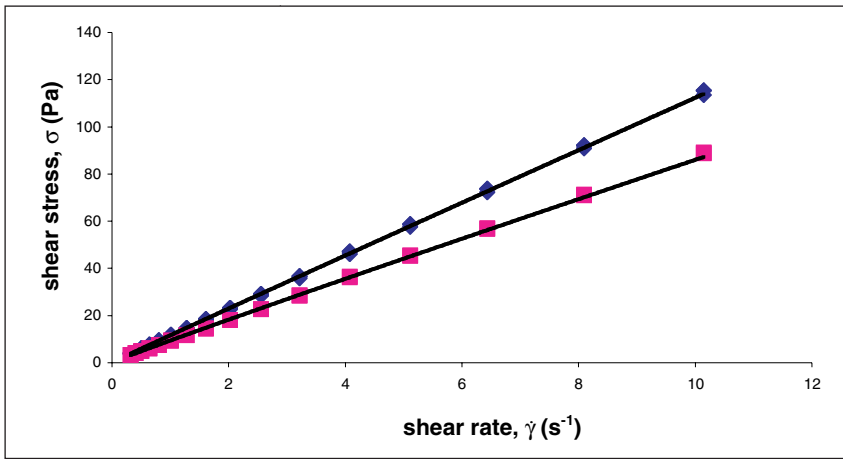


Figure 5a (upper): Shear rate deviation from concentric cylinder approximation before applying MSM (◆ Bob 28, ■ Vane 28, 11.36 Pas Newtonian Standard, $\alpha = 2.75$).

Figure 5b: Corrected rheogram using the MSM (◆ Bob 28, ■ Vane 28, 11.36 Pas Newtonian Standard, $\alpha = 2.75$, $k'_{avg} = 1.79 \text{ rad}^{-1}$).

Table 3: Shift factors, λ , and average, k' , computed using Vane 28 and Bob 28.

nitude at an identical shear stress. The shift factor, λ , corrects underestimates when greater than one, shifting to the right on a rheogram. As λ approaches unity, this correction factor is essentially negligible, and any vane influence on rheological measurements becomes identical to

CMC [wt%]	α	$C_{B, avg}$ Pa [rad/s]	$C_{V, avg}$ Pa [rad/s]	n_{avg}	λ	k'_{avg}	R^2
2	1.2	4.84	3.57	0.86	0.7	.473	0.9992
3	1.2	14.24	11.28	0.73	0.73	5.06	0.9984
4	1.2	64.4	62.58	0.52	0.95	7.22	0.9904
2	1.65	2.42	2.1	0.86	0.85	2.87	0.9991
3	1.65	14.12	9.94	0.73	0.62	2.27	0.9908
4	1.65	53.25	50.42	0.52	0.9	4.05	0.9965
2	2.1	2.29	2.01	0.86	0.86	2.43	0.9992
3	2.1	14.13	11.26	0.73	0.73	2.31	0.9984
4	2.1	50.8	48.29	0.52	0.91	3.7	0.9983
2	2.75	1.97	1.44	0.86	0.69	1.79	0.9989
3	2.75	12.35	10.89	0.73	0.84	2.46	0.9958
4	2.75	40.74	43.77	0.52	1.15	4.51	0.9983

the bob response. Referring to Tab. 3, as n decreased, vane rheological behavior mimicked the concentric cylinder response.

3.4 A STATISTICAL ANALYSIS

SAS (SAS Inc. Cary, NC) was implemented to statistically ascertain the impact α and n had on k' . The software program also indicated if any interaction between parameters had a combined significance on k' . This statistical analysis revealed that k' was independent of flow behavior indices between 0.86 and 1 ($p > 0.05$). Below a flow behavior index of 0.86, there was a noticeable effect on k' as fluid pseudoplasticity increased. The same SAS procedure considered system geometry effects and revealed that k' was independent of system geometry when $\alpha \geq 2.1$, i.e. the system becomes an infinite cup geometry ($p > 0.05$). In addition, results showed system geometry had a substantial effect on k' as α decreased below 2.1.

Castell-Perez and Steffe [13] observed a similar trend as calculated k' values were nearly identical for $\alpha \geq 1.9$ at a constant CMC concentration when applying different mixer viscometry techniques. As the fluid gap decreased, Castell-Perez and Steffe [13] also observed that geometry had a significant impact upon k' .

An increase in k' due to a diminishing fluid gap is the result of an increase in the relative pro-

portion of attachment surface area to the surrounding wall of the container in a concentric cylinder system. Rao and Cooley [14] observed increasing k' for attachments with larger surface areas. Goldeski and Smith [16] noted an exponential decrease in shear rate with an increase in distance from the impeller. Metzner *et al.* [10] concluded that mixing times were minimized by decreasing the α ratio.

3.5 MSM VALIDATION

The equivalent shear stress assumption was validated from analysis of Figs. 5a and 5b. Fig. 5a illustrates a rheogram for a standard Newtonian fluid (11.36 Pas) using bob 28 and an uncorrected flow curve obtained using vane 28, each with equivalent diameter (10 mm). Fig. 5b depicts a result of the MSM corrective procedure for the Newtonian fluid and offered supporting evidence the rheological apparatus operated correctly. When accurate rheograms were obtained for standard fluids using the MSM, it was anticipated that this procedure would be effective for power law fluids. Fig. 6 illustrates results for power law fluids.

3.6 COMPARING RESULTS OF MSM WITH OTHER TABULATED INFORMATION

Similar results to the MSM were found from some of the tabulated information of Castell-Perez and Steffe, [13] who reported k' values for a 2% CMC solution, impeller H/D ratios of 2.2 and 2.8, and an α ratio of 3.1. Castell-Perez and Steffe [13] reported k' values of 1.41 and 1.18 rad^{-1} for the H/D ratio impellers of 2.2 and 2.8 respectively. The matching stress method yielded k' values of 1.31 and 1.36 rad^{-1} for H/D ratios of 2.1 and 2.8 respectively with an α ratio of 2.75. In addition, Castell-Perez and Steffe [13] also reported k' values for the slope method with an α ratio of 3.1 and impeller H/D ratios of 2.2 and 2.8 and were 1.59 and 1.57 rad^{-1} respectively. An average of the k' values obtained from the MSM for the two Newtonian standards and 2% CMC for H/D ratios of 2.1 and 2.8 were 1.65 and 1.63 rad^{-1} respectively.

In other studies, Rao and Cooley [14] calculated mixer viscometry constants using the slope and matching viscosity methods. Mixer viscometry constants for a flag shaped impeller varied between 1.85 and 2.26 rad^{-1} and for a star shaped

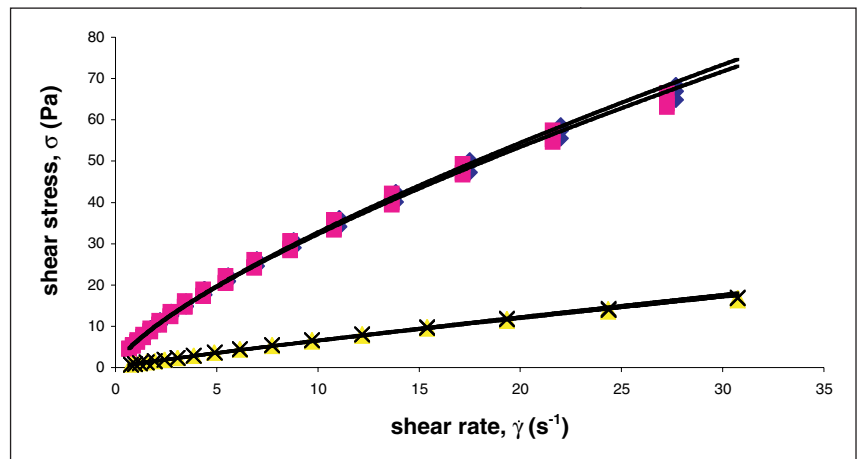


Figure 6: Corrected rheograms using the MSM for Power Law fluids (◆ 3% CMC, Bob 20; ■ 3% CMC, Vane 20; ▲ 2% CMC, Bob 20; X 2% CMC, Vane 20; $\alpha = 2.1$).

impeller, values ranged between 2.91 and 3.23 rad^{-1} . Godleski and Smith [16] reported a value of 1.75 rad^{-1} for a mixer viscometry constant using flat-bladed turbines with an α ratio of 3. Metzner *et al.* [10] used k' values ranging between 1.45 and 2.39 rad^{-1} for turbines of varying geometry to analyze mixing rates and power requirements of Non-Newtonian solutions.

4 CONCLUSION

The results of this investigation revealed that the Matching Stress Method can be used as a successful alternative to the Slope or Matching Viscosity Method for shear rate prediction of vane attachments. The matching stress method is a simple and effective technique for calculating k' for vanes requiring only stress measurements at known angular velocities for a vane and for a conventional rheometer geometry system. Additionally, $\alpha \geq 2.1$ and $0.86 \leq n \leq 1.0$ had no effect on average shear rate approximations. As $\alpha < 2.1$, geometry influenced average shear rate, and as n decreased the vane rheology responded more like a bob.

APPENDIX

An application example of the Matching Stress Method illustrates how the method performs for actual food systems. Rheological properties of Creamy French Salad dressing (Kraft Foods Inc., Glenview, IL) were determined using a concentric cylinder rheometer geometry (Bohlin, Reologi, Inc. Cranbury, NJ) and vane 36. The Bohlin C14 concentric cylinder geometry is a paired cup and bob system of the following dimensions: bob height and radius of 22 mm and 7 mm respectively, cup height and radius of 28 mm and 7.7 mm respectively. The MSM procedure used to calculate a mixer viscometry constant for the vane device is as follows:

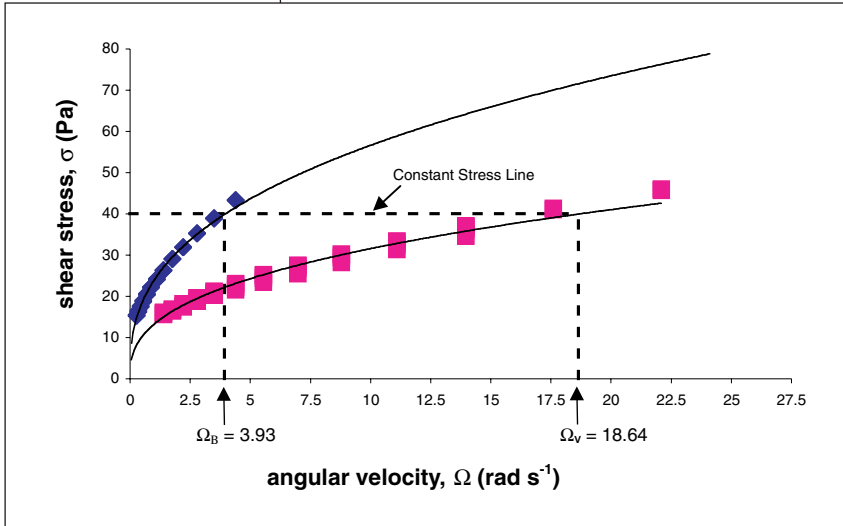
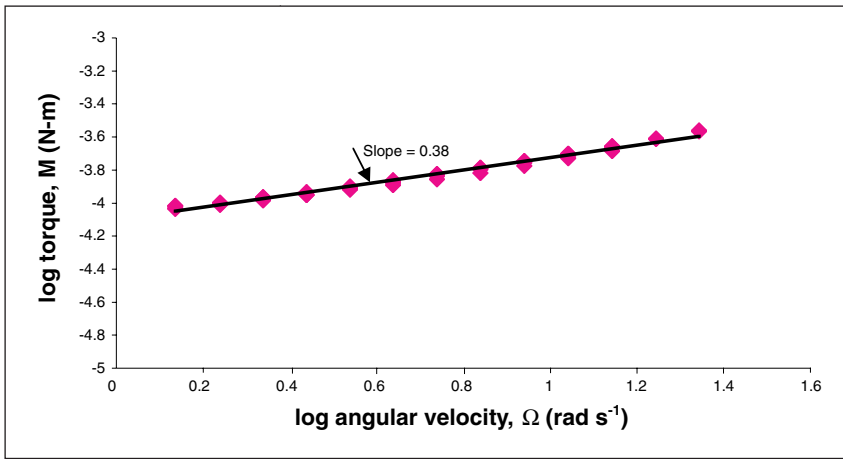


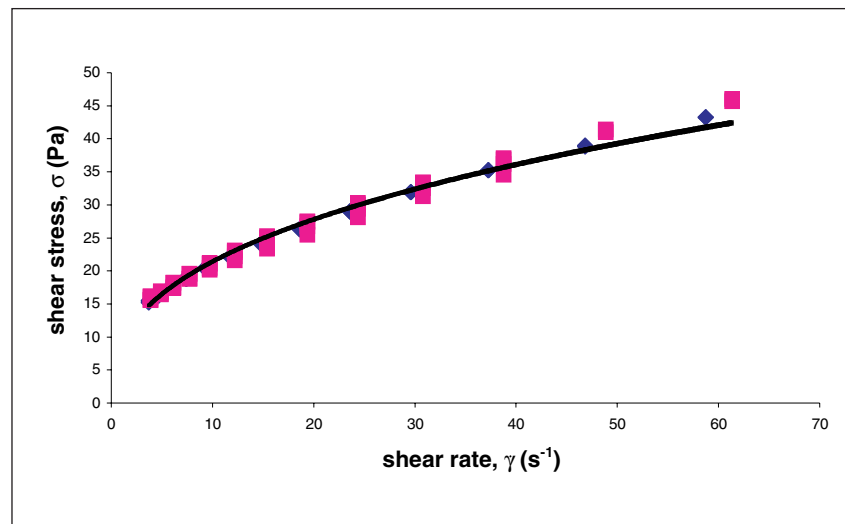
Figure 7 (upper): Determination of flow behavior index (Creamy French Salad Dressing (Kraft Foods Inc., Glenview, IL) Vane 28).

Figure 8: Shift Factor determination (Creamy French Salad Dressing (Kraft Foods Inc., Glenview, IL), \blacklozenge C14 Device, \blacksquare Vane 36, $\sigma_{C14} = 23.78\Omega^{0.38}$, $\sigma_{V36} = 13.16\Omega^{0.38}$).

Figure 9 (right): Corrected rheograms using the MSM for Salad Dressing (Creamy French Salad Dressing (Kraft Foods Inc., Glenview, IL), \blacklozenge C14 Device, \blacksquare Vane 36, $\sigma_{C14} = 28.97\dot{\gamma}^{0.38}$, $\sigma_{V36} = 8.94\dot{\gamma}^{0.38}$, $k' = 2.81 \text{ rad}^{-1}$).

STEP 1: Flow behavior index of the fluid is determined using the vane device by plotting (log-log) torque versus angular velocity and applying Eq. 3, see Fig. 7. The slope of the line is the flow behavior index, n .

$$n = 0.38 \quad (18)$$



STEP 2: The shift factor, Eq. 10, is determined from plots of shear stress versus angular velocity for the standard rheometer geometry and the vane device, see Fig. 8. Regression analysis is used to determine the appropriate constants of Eq. 10 as indicated. The shift factor is determined as the ratio of angular velocities at a matching stress of 40 Pa.

$$\lambda = \left(\frac{\Omega_B}{\Omega_V} \right) = \left(\frac{3.93}{18.64} \right) = 0.21 \quad (19)$$

STEP 3: The mixer viscometry constant for the vane device is calculated using flow behavior index, measured geometry, and the shift factor constants as shown in Eq. 15.

$$k' = 0.21 \left(\frac{2}{0.38} \right) \left(\frac{1.1^{2/0.38}}{1.1^{2/0.38} - 1} \right) = 2.81 \quad (20)$$

STEP 4: The product of angular velocity and the mixer constant are used to calculate vane shear rates and the vane rheogram is matched to that obtained using the standard rheometer geometry, see Fig. 9.

$$\dot{\gamma}_V = k' \Omega_V = 2.81 \Omega_V \quad (21)$$

BIOGRAPHY

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NOTATION

$\dot{\gamma}_B$	Shear Rate using Bob Device [s^{-1}]
$\dot{\gamma}_V$	Average Shear Rate using Vane Device [s^{-1}]
n	Flow Behavior Index
M_B	Torque using Bob Device [Nm]
M_V	Torque using Vane Device [Nm]
R_B	Radius of Bob Device [m or mm]
R_V	Radius of Vane Device [m or mm]
h	Height of Device [m or mm]
h_o	End Effect Correction Factor [m or mm]
Ω_B	Angular Velocity of Bob Device [$rad\ s^{-1}$]
Ω_V	Angular Velocity of Vane Device [$rad\ s^{-1}$]
α	Ratio of Cup Radius to Device Radius
σ_B	Corrected Average Shear Stress for Bob Device [Pa]
σ_V	Corrected Average Shear Stress for Vane Device [Pa]
C_B	Bob Constant [$Pa (rad\ s^{-1})^{-n}$]
C_V	Vane Constant [$Pa (rad\ s^{-1})^{-n}$]
K	Consistency Coefficient [Pas^n]
k'	Mixer Viscometry Correction Factor [rad^{-1}]
λ	Shift Factor [-]

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