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 Geometrieeinfluss 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 recquièrent des mesures en cisaillement stable. Basée sur le concept que les outils à rotor cisaillent les fluides dans une géomètrie 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-methylique (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 géomètries 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 géomètrie correspondantes. La variation de géomètrie 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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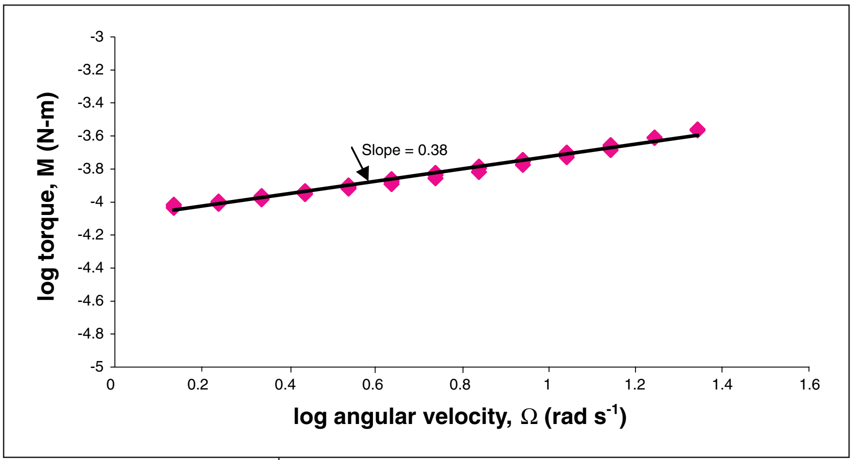


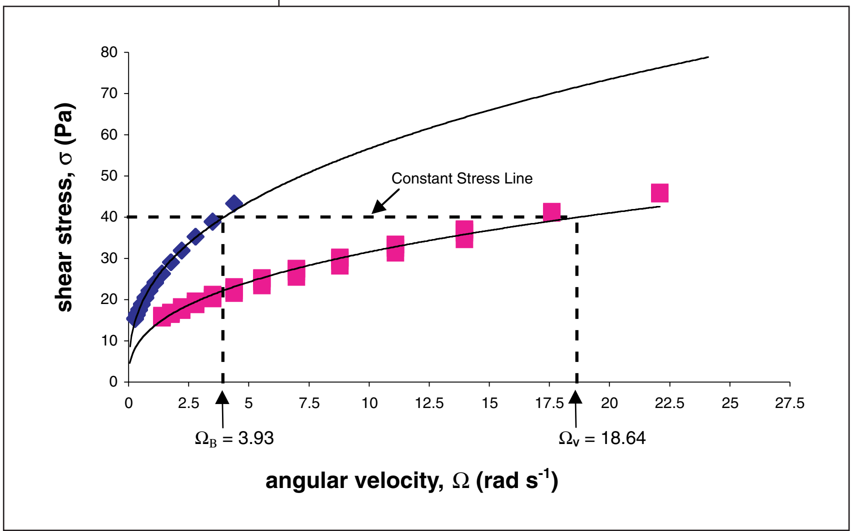


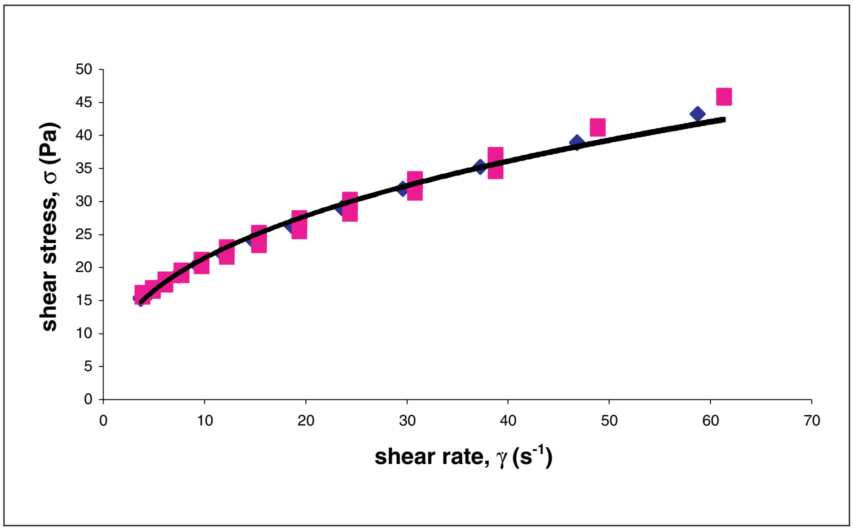
Figure 7 (upper): Determination of flow behavior index (Creamy French Salad Dressing (Kraft Foods Inc., Glenview, IL) Vane 28).

Figure 8: Shift Factor determination (Creamy French Salad Dressing (Kraft Foods Inc., Glenview, IL), ◆ C14 Device, ■ 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), ◆ C14 Device, ■ Vane 36, $\sigma_{C14} = 28.97\gamma^{0.38}$, $\sigma_{V36} = 8.94\Omega^{0.38}$, $k' = 2.81\ rad^{-1}$).

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*.

$$n = 0.38 \tag{18}$$



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.

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

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.

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

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.

$$\dot{\gamma}_V = k'\Omega_V = 2.81\Omega_V \tag{21}$$

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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 [$rads^{-1}$]
Ω_V	Angular Velocity of Vane Device [$rads^{-1}$]
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 $(rad\text{-}s^{-1})^{-n}$]
C_V	Vane Constant[Pa $(rad\text{-}s^{-1})^{-n}$]
K	Consistency Coefficient [Pas^n]
k'	Mixer Viscometry Correction Factor [rad^{-1}]
λ	Shift Factor [-]

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