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Microfibrillated Cellulose Suspensions in Slot Flow

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ABSTRACT

We report slot geometry to determine the rheology of Microfibrillated Cellulose (MFC) suspensions. Flow behaviour of MFC suspensions in a slot with varying gaps was studied intensively. Rheology of MFC suspensions was determined at three different mass concentrations: 1, 2 and 3%. Very high shear rates, up to 100,000 s^{-1}, were achieved especially at narrower slot gaps.

INTRODUCTION

MFC has recently garnered considerable attention for its unique properties. For example, it is an interesting building block for functional materials due to its mechanical robustness, large surface area and biodegradability (Kumar et al.[1]). One of the main challenges in processing of MFC is its very high viscosity even at low concentrations. The rheological behaviour of MFC suspensions plays a vital role during their processing as thin films or coating onto paper. Rheology of pulp fibre suspensions is well known; however, scientific interest on rheology of MFC suspensions is growing at a rapid pace and has been a subject of discussion in various recent publications (Nechyporchuk et al.[2], Naderi et al.[3], Moberg et al.[4], Mohtaschemi et al.[5], Iotti et al.[6], Haavisto et al.[7,8]).

The unique behaviour of MFC suspensions makes it challenging to produce reliable information on their rheology using conventional rheometers. Therefore, we used slot geometry to study the flow behaviour of MFC suspensions. A slot with varying gaps was used for this purpose, and the rheology of MFC suspensions was determined at different mass concentrations up to shear rates as high as 100,000 s^{-1}. Rheology results from slot geometry are also compared with those obtained from parallel plate geometry in Modular Compact Rheometer (MCR), and Couette geometry in high shear Hercules Viscometer.

MATERIALS AND METHODS

MFC was produced using a mechanical treatment at the Process Development Center of the University of Maine as described by Kumar et al.[1]. Briefly, a bleached softwood Kraft pulp was dispersed with a beater at 2.5 % solids and circulated through a refiner equipped with specialized plates, operating at low clearance and careful gap control, until the fines content reached over 90% as measured with a standard fiber size analyzer (Morfi, Techpap). The rheology of the resulting MFC suspension was studied at three different mass concentrations: 1, 2 and 3%; using slot geometry. MCR with parallel plate geometry with a gap of 1 mm, and high shear Hercules Viscometer with

Couette geometry (bob A) were also used to study the rheology of these MFC suspensions.

Slot geometry design and equations

A schematic of the slot geometry is shown in Fig. 1. It consists of a distribution chamber of radius, $R = 1.5\,mm$, a slot of length, $L = 34\,mm$, and width, $W = 74\,mm$. The slot gap, h can be altered to 500, 750 and 1000 µm. The MFC suspension is fed into the inlet from an air pressurized vessel.

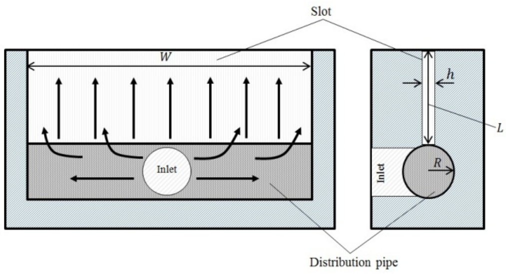

Figure 1. Schematic of the slot geometry.

The pressure drop, ΔP in the slot for Newtonian flow is calculated using the Eq. 1, where Q is volumetric flow rate, and η is viscosity.

$$\Delta P_{slot} = \frac{12\eta L Q}{W h^3} \quad (1)$$

The wall shear stress, σ_w and wall shear rate, $\dot{\gamma}_w$ are expressed in Eq. 2 and Eq. 3 respectively. The viscosity is given in Eq. 4.

$$\sigma_w = \frac{-\Delta P}{L}\frac{h}{2} \quad (2)$$

$$\dot{\gamma}_w = \frac{6Q}{W h^2} \quad (3)$$

$$\eta = \frac{\sigma_w}{\dot{\gamma}_w} = \frac{-\Delta P}{L}\frac{W h^3}{12Q} \quad (4)$$

The true wall shear rate and apparent viscosity in case of non-Newtonian flow are calculated using Eq. 5 and Eq. 6 respectively (Barnes[9]). The correction used here is analogous to the Rabinowitch correction for non-Newtonian flow in a capillary tube.

$$\dot{\gamma} = \left(\frac{2Q}{Wh^2}\right)\left(2 + \frac{1}{n}\right) \quad (5)$$

$$\eta_a = \frac{\sigma_w}{\dot{\gamma}} = \frac{-\Delta P}{L}\frac{W h^3}{4Q\left(2+\frac{1}{n}\right)} \quad (6)$$

Here n is the power-law index of the non-Newtonian fluid, and can be expressed as in Eq. 7.

$$n = \frac{d[log(\sigma_w)]}{d[log(6Q/Wh^2)]} \quad (7)$$

RESULTS & DISCUSSION

The slot geometry was first tested with Newtonian liquids of known viscosity to ensure its accuracy for the rheology measurements of MFC suspensions. The viscosity vs shear rate data for silicone oil (v100) and honey using the slot geometry is given in Fig. 2. Honey and silicone oil had a Brookefield viscosity of 25 Pa·s and 100 mPa·s respectively, at room temperature. The viscosities of these Newtonian liquids from the MCR device and slot device were found within.

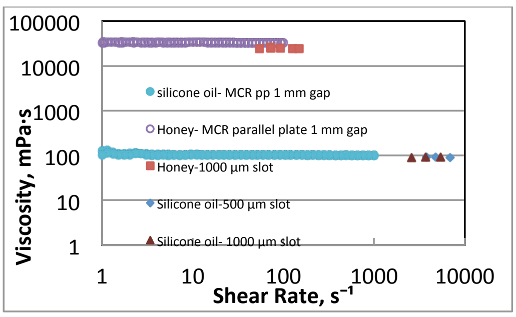

Figure 2. Viscosity of silicone oil and honey with the slot geometry and parallel plate geometry in MCR.

Fig. 3 shows the viscosity vs shear rate for MFC suspensions at three mass concentrations (1, 2 and 3%) in a 1000 μm slot. The viscosity drops initially quickly indicating a highly shear thinning behaviour with a power law index of ca. 0.15-0.4. At high shear rates, beyond ca. 10000 s^{-1}, the shear thinning transforms into a Newtonian plateau. This behaviour can be useful for MFC coating application using the slot geometry.

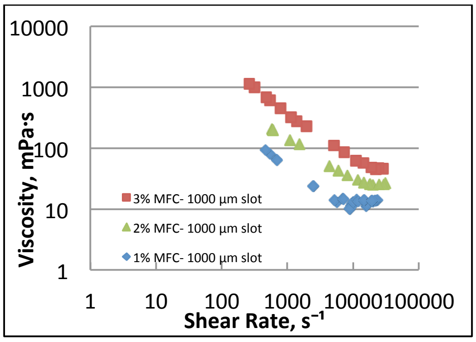

Figure 3. Viscosity vs shear rate for MFC suspensions at different concentrations.

The slot gap h did not have much influence on the viscosity at low shear rates as shown in Fig. 4. However, at high shear rates, reducing the gap decreased the apparent viscosity. This could be due to wall slip.

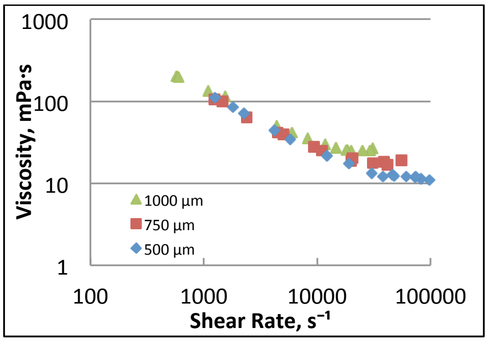

Figure 4. 2% MFC in different slot gaps.

Considering the use of slot geometry for coating application of MFC; Fig. 5 shows the evidence that the slot gap has a notable impact on the flow characteristics of the MFC suspension. The uniformity of flow is maintained better with a larger slot gap. However, a larger gap poses challenge during drying due to obviously higher wet thickness of the coating layer.

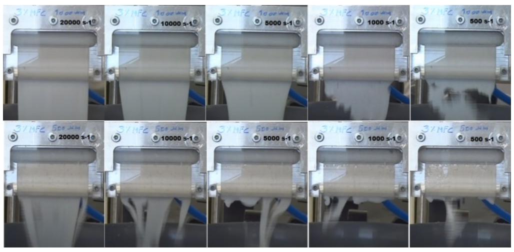

Figure 5. 3% MFC suspension in slot flow. (Top: 1000 µm and Bottom: 500 µm gap).

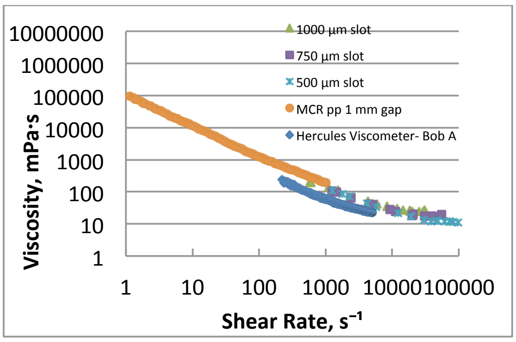

Figure 6. Viscosity vs Shear rate for 2% MFC suspension with different devices.

Fig. 6 shows the viscosity for 2% MFC suspension using different rheometers. It can be established form Fig. 6 that the slot geometry can work as a suitable rheometer for studying the rheology of MFC suspensions especially at high shear rates as the viscosity measured with slot flow agrees with that measured with the other rheometers.

CONCLUSIONS

In slot flow experiments, MFC suspensions exhibited a shear thinning behaviour at low shear rates, which transformed into a constant Newtonian viscosity at high shear rates. The slot gap had a significant impact on the flow behaviour of these suspensions at different mass concentrations at high sear rates, possibly due to boundary slip effects. The slot geometry can provide an opportunity for processing of MFC at higher concentrations into films and coatings.

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