Continuous Monitoring of Yield Stress and Solid Fraction of a Solid Suspension Using a Microfluidic Yield Rheometer

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ABSTRACT

Solid suspensions are widely encountered in oil and gas industry as well as mining industry: from extracting oil from oil sands to discarding solid waste to the tailing ponds. In various applications, the quality of the suspensions is often assessed through the measurement of rheology of the suspensions. Yield stress, τ_y, which is one of the commonly used rheological parameters in industry, denotes the ability of a fluid to prevent the flow under the applied shear stress. τ_y is associated with the network of solid particles in the suspending fluid, emerging due to an attractive or a repulsive force of interaction among particles. τ_y is a function of the weight fraction of the particles ($X\%$), as it governs the structural strength of the particle network[1-3]. For example, a dilute suspension or a weaker network leads to a small τ_y. Thus, the measurement of τ_y enables determination of $X\%$, provided a prescribed relationship between τ_y and $X\%$ can be formulated.

In Canada, bitumen is extracted from Athabasca's oil sands using Clark's hot water extraction process. In this process, a mixture of bitumen, hot water, clay, and sand particles is sent to an extractor. Majority of bitumen oil is recovered through froth flotation, and solids are subject to gravity settling. Settling clay and sand particles split into two sections within the extractor, middlings and tailings, based on the size of the particles. It was demonstrated that both middlings and tailings exhibit a yielding behaviour[4-6] with τ_y varying between 10^{-4} and 10 Pa[4,5]. τ_y influences the transport of the trace amount of bitumen present in the middlings to the top in the flotation section of the extractor. A higher τ_y of middlings may lead to a lower total recovery of bitumen[7]. Further, both τ_y and $X\%$ of tailings determine the transportability and packing efficiency of tailings to the tailing pond. Thus, a continuous or in-line monitoring of τ_y and $X\%$ of middlings and tailings will enable feedback on the extraction process to enhance oil recovery from middlings as well as improve the transportation of tailings to the tailing ponds. Commercially available rheometers are unlikely to measure τ_y as low as 10^{-4} to 1 Pa, except for the ones which are prohibitively expensive. Further, they cannot be employed

for continuous or in-line measurement of τ_y. We propose using a microfluidic platform for the continuous monitoring of low τ_y, and determining X% through the measurement of τ_y.

We employ a microfluidic extensional flow device (MEFD), which is an extension to four-roll mills[8] and has been used in our group for studying properties of emulsions such as interfacial tension[9] and solubility[10]. The MEFD exhibits a characteristic shear stress distribution such that the material exhibits unyielded, solid region where the shear stress is lower than τ_y. On the other hand, in other regions where shear stress is higher than τ_y, the material yields and flows. We measure the size of the unyielded or solid region for a range of flow rates by tracking the flow using a camera. We have developed a scaling theory to determine τ_y of the material flowing in the MEFD through the measurement of the size of the unyielded region, the experimental parameters such as flow rate and device geometry. Since the MEFD enables both the flow of the yielded material through it as well as solid, non-moving regions to exist simultaneously, we are able to measure a τ_y in-line or continuously.

We characterized the MEFD platform using carbopol gel, a model yield stress fluid, of various concentrations ranging between 0.025 and 0.3% by weight, and measured τ_y between 60 mPa and 1.4 Pa. We compared τ_y measured using the MEFD with the rheometer measurements, and we found a fair agreement between the two. We also corroborated the experimental results with the simulation results using COMSOL Multiphysics®. The smallest τ_y we have measured is 4 mPa of wastewater filtrate, and our scaling analysis suggests that the MEFD should be able to measure a τ_y of the order of 0.1 mPa with the current version of the device, as required for middlings. We are working towards measuring a τ_y of the order of 10^{-4} Pa of dilute carbopol solutions. Further, we demonstrated the application of the MEFD to measure τ_y of solid suspensions. We used a suspension of cloisite clay and water as a model for middlings and tailings. We measured τ_y ranged from 65 mPa to 5.9 Pa of cloisite-water suspension of $X\%$ ranging between 3 to 6%. τ_y and $X\%$ was fitted to a cubic polynomial, and this relationship between the two was used to determine $X\%$ through the measurement of τ_y. We also performed in-line measurement of τ_y of a cloisite suspension sample at four different flow rates. τ_y was measured continuously for 15 min at an interval of 15 s, and $X\%$ was estimated accurately through $\tau_y - X\%$ relationship. We are in the process of measuring τ_y of kaolinite suspension of $X\%$ between 5 to 30%, which is more representative of middlings and tailings. We have planned to use the samples of middlings and tailings from oil industry in the future to substantiate the application of the MEFD technique.

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