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Shear thickening of corn starch suspensions: Does concentration matter?

Nathan C. Crawford, Lauren B. Popp, Kathryn E. Johns, Lindsey M. Caire, Brittany N. Peterson, Matthew W. Liberatore *

Colorado School of Mines, Department of Chemical and Biological Engineering, Golden, CO 80401, USA

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ABSTRACT

Suspensions of corn starch and water are the most common example of a shear thickening system. Investigations into the non-Newtonian flow behavior of corn starch slurries have ranged from simplistic elementary school demonstrations to in-depth rheological examinations that use corn starch to further elucidate the mechanisms that drive shear thickening. Here, we determine how much corn starch is required for the average person to "walk on water" (or in this case, run across a pool filled with corn starch and water). Steady shear rate rheological measurements were employed to monitor the thickening of corn starch slurries at concentrations ranging from 0 to 55 wt.% (0–44 vol.%). The steady state shear rate ramp experiments revealed a transition from continuous to discontinuous thickening behavior that exists at 52.5 wt.%. The rheological data was then compared to macro-scopic (~5 gallon) pool experiments, in which thickening behavior was tested by dropping a 2.1 kg rock onto the suspension surface. Impact-induced thickening in the "rock drop" study was not observed until the corn starch concentration reached at least 50 wt.%. At 52.5 wt.%, the corn starch slurry displayed true solid-like behavior and the falling rock "bounced" as it impacted the surface. The corn starch pool studies were fortified by steady state stress ramps which were extrapolated out to a critical stress value of 67,000 Pa (i.e., the force generated by an 80 kg adult while running). Only the suspensions containing at least 52.5 wt.% (42 vol.%) thickened to high enough viscosities (50–250 Pa s) that could reasonably be believed to support the impact of a man's foot while running. Therefore, we conclude that at least 52.5 wt.% corn starch is required to induce strong enough thickening behavior to safely allow the average person to "walk on water".

1. Introduction

The rheological behavior of corn starch and water suspensions is a popular topic found in many scientific domains: polymers, food science and technology, ceramics, cosmetics, ballistics, and others [1,2]. Aqueous slurries of corn starch, affectionately named "oobleck" after a children's story by Dr. Seuss, transition from fluid-like to solid-like behavior under high shear forces. This transition, typically denoted by an abrupt increase in viscosity, is termed shear thickening (or dilatancy). Shear thickening fluids have been exploited for commercial use in shock absorbing and force damping applications such as skis, tennis rackets, and more recently, flexible body armor [3,4]. The unique ability of corn starch suspensions to shear thicken makes them an intriguing system for study.

Shear thickening was first examined in detail by Hoffman [5] over 40 years ago and was thought to be a shift in suspension microstructure from an ordered, layered state to a disordered state with increased particle interactions (coined the order-to-disorder transition (ODT) theory) [6–8]. In the decades following Hoffman's work, researchers discovered that the onset of shear thickening is actually a result of particle hydroclustering (clusters of particles held together solely by hydrodynamic lubrication) and an order-to-disorder transition is not a requirement for dilatant behavior [9–14]. At large shear rates and stresses, convective and hydrodynamic forces dominate over interparticle forces and cause hydroclustering (or clumping) of particles [15–17]. Hydroclusters create fluctuations in particle motion and make movement throughout the suspension more difficult. The restriction in particle motion is represented by a higher rate of energy dissipation and an increase in viscosity (i.e., shear thickening). Hydroclusters (by definition) are reversible and a decrease in applied shear will disband the shear-induced clusters. Hydrocluster formation has been thoroughly studied through rheo-optical experiments [18,19], neutron scattering [13,14], stress-jump rheological measurements [20,21], and *in situ* rheological small-angle neutron scattering (termed rheo-SANS) [22]. Currently, hydroclusters are regarded as the defining aspect of the shear thickened state [23].

* Corresponding author. Address: Colorado School of Mines, Department of Chemical and Biological Engineering, 1500 Illinois St., Golden, CO 80401, USA. Fax: +1 303 273 3730.

E-mail address: mliberat@mines.edu (M.W. Liberatore).

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A suspension of corn starch particles in water is the most well-known example of a shear thickening system. The unparalleled combination of fluid and solid-like behavior displayed by corn starch suspensions has allowed people to perform the seemingly impossible feat of "walking on water". Childlike curiosity and the yearning for divine aptitude has sparked numerous online videos in which people are able to "walk on water" by taking advantage of the thickening response. At low shear forces, a suspension of corn starch and water behaves as a liquid, where it will flow, take the shape of its container, and resist compression. Yet, when a person applies a strong force by either running or jumping on the mixture, the suspension solidifies and keeps anything (or anyone) from penetrating its surface. One of the most popular videos of this type is from the Discovery Channel's show MythBusters (Fig. 1a) [24]. In this episode the famed duo takes turns running across a large storage tote (~5 ft deep) filled with over 200 gallons of water and 1000 lbs. of corn starch (~50/50 mix by weight). Another widely observed video is from a television show originating in Barcelona, Spain. The film makers created a ~15 foot long pool filled with corn starch and water and examined the thickening behavior by running and jumping on the mixture (the actors even swim around in the pool) [25]. In both videos, the performers were able to run across their respective pools as if they were running across a rigid, solid surface. However, once the person stood still, removing nearly all applied stress, they sank. The observed sinking action is a consequence of the reversible nature of shear thickening, once the applied force is released the suspension's viscosity returns to its original liquid-like state."Corn starch monsters" is yet another popular genre of online videos utilizing corn starch and water suspensions (Fig. 1b). In these films, a mixture of corn starch and water is placed upon a speaker amplifying music. The vibrations from the music apply a stress on the suspension and cause it to stand up, acoustically growing "monsters". The corn starch globs stay intact until the music is terminated; again, displaying the reversibility of the shear thickening response. These online video sensations (both the corn starch pools and acoustic "monsters"), although entertaining, provide little scientific insight into the shear thickening of corn starch suspensions.

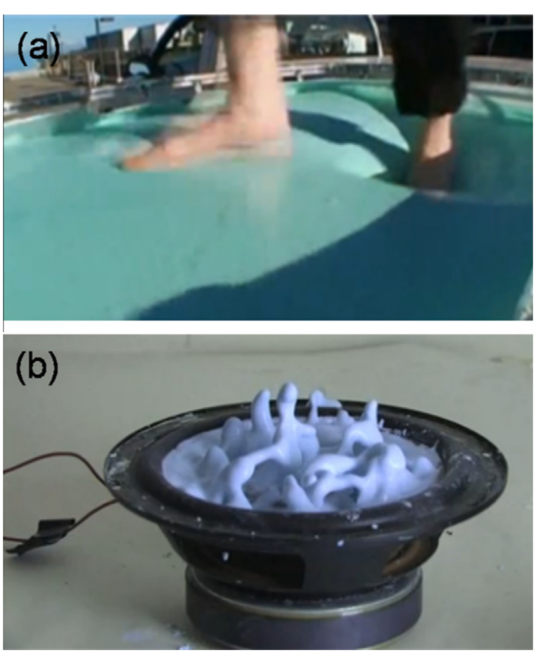

Fig. 1. (a) MythBusters walking on "water" YouTube video: MythBusters – Walking on water – Ninja part 5/5 (http://www.youtube.com/watch?v=IhJE0VRh_zY) and (b) "Corn starch monsters" in YouTube video: Non-Newtonian fluid on a speaker cone (http://www.youtube.com/watch?v=3zoTKXXNQIU).

Other studies used corn starch as a model suspension to further investigate the underlying mechanisms behind shear thickening [26–32]. Recently, Brown and Jaeger used corn starch slurries to help elucidate the jamming phenomenon [29] and to distinguish jamming from discontinuous shear thickening behavior [31]. While Fall et al. [26–28] show that corn starch shear thickening can be viewed as re-entrant solid transition, where the suspension's viscosity changes from a solid to a liquid and then back to a solid with increasing shear stress. All of the above studies use corn starch slurries as a means to investigate a specific aspect of shear thickening, where thickening behavior is the focal point. The authors only operate at a finite starch concentration range (somewhere between 40 and 60 wt.%) where shear thickening is most prevalent. Although these previous examinations have provided a detailed insight into the shear thickening response, many questions still exist pertaining to the mysterious shear thickening behavior of corn starch. What happens at lower concentration regimes? Does shear thickening cease? If you apply a strong enough force can you get a low concentration (< 20 wt.%) corn starch slurry to shear thicken? What is the required amount of thickening in order for someone to "walk on water?" Is there a connection between bench scale rheological measurements and these online videos? The objective of this work is to perform a comprehensive investigation of corn starch shear thickening, where concentration is the focus. We examine the shear thickening behavior of aqueous corn starch slurries as a function of solids concentration, ranging from 0 to 55 wt.% (0–44 vol.%). More specifically, we determine the concentration at which a suspension of corn starch and water will thicken enough to allow the average person to "walk on water". At last, we tie together bench-top rheological measurements and macroscopic corn starch "pool" experiments.

2. Experimental methods

2.1. Sample preparation

Suspensions of corn starch and water were prepared using both refined (Argo corn starch, ACH Food Companies, Inc., Memphis, TN) and bulk corn starch (Honeyville Food Products, Inc., Brigham City, UT) in ultrapure DI water at varying concentrations of: 10, 20, 25, 30, 40, 45, 47.5, 50, 52.5 and 55 wt.%. Measured weight fractions were converted to calculated volume fractions assuming a corn starch density of 1.55 g/cm^3 [32]. Mixtures were thoroughly stirred and allowed to equilibrate for approximately 24 h at room temperature to ensure consistent hydration of the corn starch grains. Prior to experimentation, samples were re-stirred and then sonicated for 10 min to break up any aggregates, as well as to ensure sample homogeneity.

2.2. Rheological measurements

All rheological measurements were conducted using TA Instruments' AR-G2 stress controlled rheometer (New Castle, DE). All rheology measurements were performed at 25 °C and repeated in triplicate (at a minimum) to quantify measurement error. Temperature control of ±0.1 °C was provided by a Peltier heating jacket. Each sample was run through the following three-step experimental procedure to probe for shear thickening behavior: (1) a stress ramp from 0.01 to 100 Pa with a step termination greater than 100 s^{-1} to quantify yield stress, and (2) a steady-state shear rate ramp from 0.01 to 1000 s^{-1} and a steady-state shear rate reduction from 1000 to 0.01 s^{-1} to confirm the reversible nature of any shear thickening event. Samples were initially sheared using a 40 mm