



## Review

## Shear thickening fluids in protective applications: A review

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## ABSTRACT

A thorough and critical review on Shear Thickening Fluids (STFs) is presented based on a literature survey. The rheological properties of STFs are discussed considering many factors affecting shear thickening behavior and the use of STFs in protective systems is reviewed. The main focus of this review is multi-phase STFs, relatively new to the literature (in the last five years). Multi-phase STFs include a second phase in suspensions and the influences of this additional phase on rheological behavior and protective applications are discussed extensively. Based on this extended review, STF do benefit protective applications, but the major contribution is not driven by the shear thickening behavior. Rather, STFs are responsible for the increase in friction along fabrics and enhanced fiber/yarn coupling in fabric based protective systems. As a result, of these effects, the load transfer is spread over a wider area and penetration depth is lowered in an impacted structure.

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## 1. Introduction

Shear thickening fluids (STFs) are dense colloidal suspensions exhibiting an abrupt increase in viscosity with increasing shear rate [1–4]. The main favorable feature of STFs is that the process is reversible, so that the fluids turn to the initial liquid state after removing the loading from the medium. From past to present, investigations into STFs have been performed in order to understand the rheological behavior of these “smart” fluids and to utilize them in engineering applications. Initially, shear thickening was defined as a problem in industrial processes such as coating and mixing due to jamming in small openings, and overloading mixers, thereby limiting process rate [5]. However, the unique characteristic of these fluids has been utilized in developing smart materials and structures more recently. STFs in protective applications have been in great demand since 2000. In fact, the first study was performed in 1968 by Gates [6], but studies recessed for three decades and then the concept gained considerable attention by the research at the University of Delaware. The first studies suggested beneficial outputs for protective applications and the technology was supported by the U.S. Army Research Laboratory (ARL). In 2004, a patent application [7] was filed with the cooperation of University of Delaware and ARL. In later years, hundreds of investigations were performed to improve the efficiency of protective systems, in addition to increased lightness and flexibility. Beside protective applications, these smart fluids have been suggested to absorb shock waves from earthquake or severe wind conditions [8]. In machinery, STFs can be integrated within damper systems to optimize the dynamic performance of these systems [9,10]. Structural components are combined with STFs to improve the vibration and damage resistance of whole systems [11–14]. In medical equipment, STFs are suggested to restrict the movement of shoulders, knees, elbows, ankles and hips to prevent these joints from sudden accelerations [15]. In more recent times, multi-phase STF systems including additive particles in the suspensions have been developed to take the advantage of additive particles. The best example of multi-phase STF is magnetorheological shear thickening fluid (MRSTF), a combination of STF and magnetorheological (MR) fluid [16–19]. In the last three years (2013–2016), additives of ceramic particles and carbon nanotubes have been investigated in multi-phase STFs in order to observe their influences on the rheology of these smart fluids and to adapt them for protective applications [20–25].

The following reviews the rheological properties of STFs and their use in protective applications. The mechanism of shear thickening phenomenon will be discussed in accordance with the hydro-clustering theory, order-disorder theory and a more recent model, the contact rheology model explaining the non-Newtonian property of these suspensions based on the contact of solid particles. The shear thickening mechanism is dependent on various factors such as particles, liquid medium, particle interactions, additives, temperature etc. and therefore, these factors are presented in this study. The influence of additive particles on the rheology of multi-phase STFs is also discussed. Furthermore, STFs in protective applications are given based on previous studies to provide better understanding of STFs in these applications.

## 2. Shear thickening mechanism

STF is a non-Newtonian fluid, for which the viscosity increases as shear rate or applied stress increases on the medium [26–31]. Such thickening behavior is observed in dense colloidal suspensions composed of solid particles (silica, calcium carbonate, etc.) and inert carrier liquids (water, ethylene glycol, polyethylene glycol, etc.). Carrier liquids exhibit Newtonian behavior in pure form

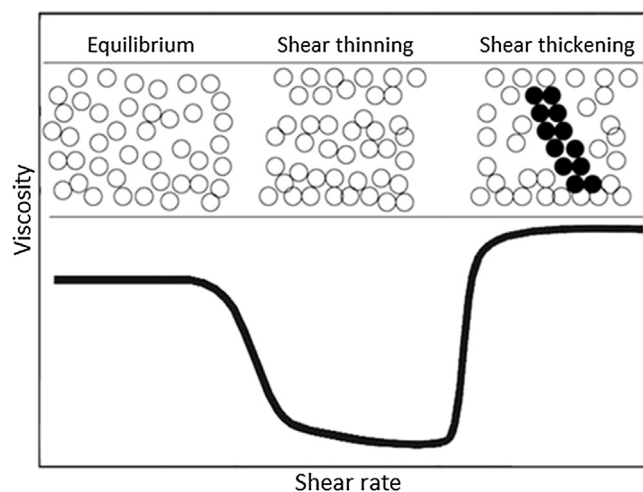


Fig. 1. Schematic illustration of shear thinning and shear thickening behavior of suspensions [33]. Copyright 2014. Reproduced with permission from Springer.

indicating the prominence of solid particles in enabling the shear thickening mechanism. Fig. 1 illustrates the particle interactions in STFs with increasing shear rate. In the schematic representation the particles are randomly suspended in a liquid medium due to dispersion at equilibrium. As the shear rate increases, particles form layered structures causing shear thinning with a reduction of viscosity. Beyond a critical shear rate for shear thickening onset, layered structures disorder and particle groups, namely hydro-clusters are formed, responsible for drastic increase in viscosity [3,32].

The shear thickening mechanism has been investigated by many researches and various models have been proposed in the literature. For example, Hoffman [34] made the pioneering study on the micromechanical structure of shear thickening. This study became the basis of the order-disorder theory, with the proposal that below a critical shear rate, particles in suspension are in a layered order, but beyond a critical shear rate, hydrodynamic forces acting on the particles become stronger and the layered orientation is disrupted; as a result of this process, layered particles disorder and the transition from order to disorder causes a drastic increase in suspension viscosity. Layered orientation in dense colloidal particle suspensions was experimentally verified in a subsequent investigation by Hoffman [35]. According to the order-disorder theory, shear thickening occurs only when the particles have a layered orientation because the viscosity increase is due to disordered particles within the suspension. Laun [11,36] conducted rheological and small angle neutron scattering (SANS) experiments for latex particles in glycols, reporting that shear thickening is reversible, and that a critical strain rate is required to trigger it. Bossis et al. [37] stated that shear thickening behavior is not fully dependent on an ordered orientation because thickening can take place with particle clusters extending in different directions while hydrodynamic forces dominate the particles. According to this approach, interactions between particles, either electrostatic or Brownian, make the suspension easily flow at low shear rates. However, at increasing shear rates, hydrodynamic forces begin to dominate suspension by suppressing the inter-particle repulsive forces and therefore, leading to the formation of stress-bearing particle clusters called hydro-clusters. These units cause a dramatic increase in viscosity by blocking the flowing and may be formed without particle orientation in the suspension, in contrast to order-disorder theory. This explanation for the thickening mechanism introduced the hydro-cluster theory, supported by neutron scattering, rheological and rheo-optical tests, as well as computer simulations in various stud-

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