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# The rheology of shear thickening fluids with various ceramic particle additives

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In this paper, shear thickening fluids (STFs) and three different types of additive particles such as silicon carbide, aluminum oxide and boron carbide are presented. STFs were fabricated based on nanosize fumed silica suspended in a liquid medium, polyethylene glycol at a constant concentration of 20 wt%, and then varying amounts of different types of particle additives were added. Their rheological properties under various temperatures were tested using a rheometer, and the effects of silica loading on the rheology of pure STF were investigated. The suspensions exhibited different systematic variations with respect to the varied parameters.


## 1. Introduction

Shear thickening fluid (STF) is non-Newtonian fluid with an increasing viscosity under applied stress. Hoffman [1] conducted a pilot study into the thickening mechanism of STF, and suggested that below a critical shear rate, particles in STF are in a hexagonally packed order, but beyond this point, particle formation decays such that the packed particles become disordered and aggregate. This transition from order to disorder increases in the viscosity of this suspension. After this pioneering study, STF was discussed by hydro-cluster theory which suggests that particles contact each other under high stress and cause strong hydrodynamic forces to act inside the suspension, which is why these particles aggregate into hydro-clusters that increase viscosity and cause the fluid to jam [2,3]. Hydro-cluster theory was verified via simulations of Stokesian dynamics by Bossis et al. [4] and computational simulations by Boersma et al. [5] and Melrose et al. [6–8].

Due to their unique characteristics, STFs have attracted attention in areas such as body armor systems, damping devices, and smart structures. Gates [9] made the first study to utilize STFs in armor systems. Early studies [10–20] focused on STF impregnated ballistic fabrics to enhance their protective performance while reducing weight. It was stated as a common point that STFs have a positive influence on the protective performance of ballistic fabrics. As a component of damping devices, STF was used in viscoelastic dampers to control the vibration of structural parts [21]. In order to absorb shock waves from earthquakes or severe wind conditions, structural components were combined with STF and the thickening response was adapted for damping [22]. Zhang et al. [23] studied STF filled dampers to observe the dynamic performance of these new systems. Fischer et al. [24] demonstrated the potential for integrating STFs into structures exposed to dynamic flexural deformation by controlling their vibrational response. Laun et al. [25] and Helber et al. [26] investigated the damping behavior of STFs and suggested they could be used in damping and mounting of industrial machinery. STFs have also been studied in the applications of smart structures. Chu et al. [27] verified an improvement of their thickening behavior by modifying the surface chemistry of silica particles. It was stated that controlling the rheology of colloidal suspensions provides important benefits in the application of energy absorbing materials. Hunt et al. [28] investigated how to minimize damage to controlled pulse fracturing (CPF) devices using STFs. Moreover, STFs could also be used to control the stiffness of composite structures by tailoring their rheological properties. These composite structures were said to be applicable for sports equipment, aeronautics, aerospace, consumer goods, or any other suitable field. William et al. [29] investigated STF based medical equipment to restrict the movement of shoulders, knees, elbows, ankles and hips to prevent these joints from sudden

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acceleration. Galindo-Rosales et al. [30] developed environmentally friendly composites such as micro-agglomerated cork sheets with a network of micro-channels filled with STF. These composites were investigated under low velocity impact where their mechanical properties exhibited a combination of the mechanical properties of micro-agglomerated cork sheets and the thickening response of STF inside the micro-channels.

Despite several studies into STF applications, there have only been limited investigations in the literature about integrating particle additives to STFs. Zhang et al. [31,32] Li et al. [33] and Peng et al. [34] studied a combination of STFs and magnetorheological (MR) fluids; they called this new fluid magnetorheological shear thickening fluid (MRSTF), and then investigated its rheological properties. It was noted that MRSTFs have features of both fluids, but they are more like MR fluids. As well as the magnetic particles in STFs, Petel et al. [35,36] investigated the ballistic resistance of bulk STFs, including carbide particles. According to their studies, carbide particles change the thickening behavior of the STFs while improving its ballistic resistance by increasing the density of this suspension and the dynamic material strength of the fluids. With this in mind, we decided to investigate the influence of ceramic particle additives due to their rigidity, even under loading. The effects of additives on the rheological behavior of STFs were investigated to provide some insights into the response of STFs and control the thickening behavior of these smart fluids. Systematic variations in the characteristics of STFs will help to determine where these novel suspensions may best be utilized in the engineering applications. In this study, silica based STFs were mixed with three different types of particle additives silicon carbide, aluminum oxide, and boron carbide because they are preferred for ceramic suspensions. The suspension temperature, type of additives, and amount of additives were varied to observe the influence of different parameters, and the effect of silica loading on the rheology of pure STF was also investigated. It was expected to provide new experience for STF applications with this novel approach.

## 2. Experimental details

The STF used in this study was based on fumed silica (Aerosil 90, from Evonik) which has a primary particle size of 20 nm and specific surface area of 90 $m^2/g$. The liquid medium was polyethylene glycol (PEG) with a molar mass of 400 g/mol (81172, from Sigma-Aldrich). Three different types of ceramic particles, silicon carbide (SiC), aluminum oxide ($Al_2O_3$), and boron carbide ($B_4C$), were used as additives in the STFs. The particle size and surface area of these additives were measured with Zetasizer Nano ZS and Autosorb 1-C analyser machines respectively. Table 1 summarizes the measurements and densities of the additives, which were obtained from the suppliers. Particle size distribution of the additives is shown in Fig. 1.

In the sample preparation stage, fumed silica was mixed with PEG, as suggested in previous studies [31,32,34]. The silica loading was 5 wt%, 10 wt%, 15 wt% and 20 wt% to investigate the pure STFs. In the experiments of STFs with additives, silica loading was kept constant at 20 wt%. The mixtures were blended for 40 min. After obtaining pure STFs, additives were added to the suspensions according to the weight percentages, and then the same blending procedure was applied to the mixtures.

In this study, a three factor-three level factorial design was used to analyze how the temperature, and the type and amount of additives affected the rheological behavior of the suspensions. According to the full factorial design, 27 ($3^3$) samples were prepared as given in Table 2.

## 3. Rheological testing and results

Rheological tests were performed using an MCR 301 Anton Paar stress controlled rheometer with 20 mm diameter parallel plate apparatus. The gap between the plates was kept at 0.20 mm, and the shear rate was increased from 0 to 1000 $s^{-1}$ during the experiments. The suspension temperature was set with the help of a temperature control device connected to the bottom plate of the rheometer.

Before experimenting on the suspensions with additives, the effects of silica loading on pure STFs with various silica loadings were tested at a constant temperature of 20 °C. Fig. 2 shows the rheological curves of pure STFs with different silica loadings, which indicate that silica loading has four main influences on the characteristics of the STFs. First, the viscosity profile of the STF increases as the silica loading increases, which means the viscosity curve of the STF shifted upward on the graph by increasing the silica loading. Second, the critical shear rate at which shear thickening begins, decreases as the silica loading increases. Third, the formation is thickened fast if the silica loading expands in the STF. This can be also explained as the difference between the critical shear rate and the shear rate at the maximum viscosity after thickening, which decreases as the silica loading increases. Finally, the thickening ratio (*TR*) which is defined in Eq. (1), increases when the silica loading expands in the suspension. The rheological curves show that the effects of silica loading on the thickening of the STFs are consistent with the results stated in previous studies [17,18,37,38].

$$TR = \frac{\eta_{max}}{\eta_{cr}} \tag{1}$$

$\eta_{max}$: Maximum viscosity of the suspension beyond the thickening point.

$\eta_{cr}$: Viscosity of the suspension at the critical shear rate.

### 3.1. Effects on viscosity profile

The rheological results indicated that the additives enhanced the viscosity profile of the suspensions in a similar manner, and to illustrate this effect, the rheological curves of the suspensions with different additives are shown in Fig. 3. Note that the viscosity profile increases as the amount of additives in the suspension increases. In denser suspensions, solid particles exhibit stronger inter-particle adhesion and thus the viscosity of the fluid increases [39]; this is verified by the rheological measurements of STFs with various additives taken in earlier studies [31,32,35]. In fact the volume fraction of the particles becomes the main topic at this point. Unlike these other types of additives, $B_4C$ particles enhance the viscosity profile of the suspension much better. It is known that additive densities differ from each other, so the volume fraction of the additives varies for each three-level mass fraction of the additives in the STFs. This is why $B_4C$ particles occupy the largest volume in the suspensions; their density is lower than the other additives for each level of additive amounts. This indicates that the increase in the volumetric concentration of solid particles in the suspension contributes to the growth of the viscosity profile. Table 3 summarizes the volume fraction of the additives for the corresponding mass fractions. On the other side, temperature is another parameter that has an intense effect on the

**Table 1**
Summary of the additive particles.

| Additive | Average particle size (μm) | Surface area ($m^2/g$) | Density ($g/cm^3$) |
|---|---|---|---|
| SiC | 1.114 | 7.61 | 3.23 |
| $Al_2O_3$ | 0.978 | 6.78 | 3.97 |
| $B_4C$ | 1.006 | 7.88 | 2.51 |