Numerical study of shear thickening fluid with discrete particles embedded in a base fluid

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ABSTRACT
The Shear Thickening Fluid (STF) is a dilatant material, which displays non-Newtonian characteristics in its unique ability to transit from a low viscosity fluid to a high viscosity fluid. The research performed investigates the STF behavior by modeling and simulation of the interaction between the base flow and embedded rigid particles when subjected to shear stress. The model considered the Lagrangian description of the rigid particles and the Eulerian description of fluid flow. The numerical analysis investigated key parameters such as applied flow acceleration, particle distribution and arrangement, volume concentration of particles, particle size, shape and their behavior in a Newtonian and non-Newtonian fluid base. The fluid-particle interaction model showed that the arrangement, size, shape and volume concentration of the particles had a significant effect on the behavior of the STF. Although non-conclusive, the addition of particles in non-Newtonian fluids showed a promising trend of improved shear thickening effects at high shear strain rates.

1. INTRODUCTION

Many civil and military structures and systems need to be designed to withstand shock loading. Different types of energy dissipative materials have been studied in order to mitigate the shock loading. They include multi-composites sandwich panels, ‘soft’ condensed matter such as granular materials or foams [1], and non-Newtonian fluids such as Shear Thickening Fluid (STF).

Shear Thickening Fluids have been well researched in terms of their capabilities in enhancing the performance of body armor against ballistic impact [2] and for stab-resistance [3]. However, an area in which more could be studied is the potential effects of STF on shock and blast wave mitigation. The motivation herein is to harness the strength of the STF while being able to be flexibly deployed and relatively easily transportable, yet able to withstand and dissipate pressure wave loading when required.

In the past, empirical analysis was a common research approach in studying STF. This was largely due to the high computational cost and lengthy time required for modeling STF at the particle level. However, with the available experimental data further emphasizing the importance of the STF in blast mitigation technologies, it seemed logical to model and study the material numerically to further understand the physics and mechanisms of STF.

In order to study the mechanism of shear thickening, only Eulerian CFD models had been used in research thus far to study the specific behavior of non-Newtonian Fluids, such as the shear thickening fluids [4] and the shear thinning fluids [5]. Other computer models used various techniques such as the Stokesian dynamics techniques [6], the dissipative particles dynamics [7] and the Lagrange multiplier fictitious domain method [8], to simulate particle

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behavior in suspensions for particulate or granular flows. Lagrangian models would offer a different dimension of studying the STF.

This study investigates shear thickening effects using the combined Eulerian and Lagrangian models. The base fluid is modeled using an Eulerian model while embedded particles are modeled using a Lagrangian model. Furthermore, the particles are assumed to be rigid. Using this model, the research examines the effects of various discrete parameters associated with rigid particles on shear thickening. Such parameters include particle shapes, distributions, volume fractions, sizes, etc.

The next section provides a brief review of STF, which is then followed by the description of the numerical modeling and analysis. Then, the numerical results and discussion are presented followed by conclusions.

2. REVIEW OF SHEAR THICKENING FLUID

A Newtonian fluid is a fluid that displays a linear relationship between the stress and strain rate. The constant of proportionality is known as viscosity. The equation used to describe Newtonian fluid behavior is

$$\tau = \mu \frac{du}{dy} \tag{1}$$

where τ is the shear stress exerted by the fluid, μ is the fluid viscosity, and $\frac{du}{dy}$ is the strain rate, or the velocity gradient perpendicular to the direction of shear.

Figure 1 shows the aforementioned relationship and compares Newtonian and non-Newtonian fluids, such as Shear Thickening Fluid and Shear Thinning Fluid. The shear

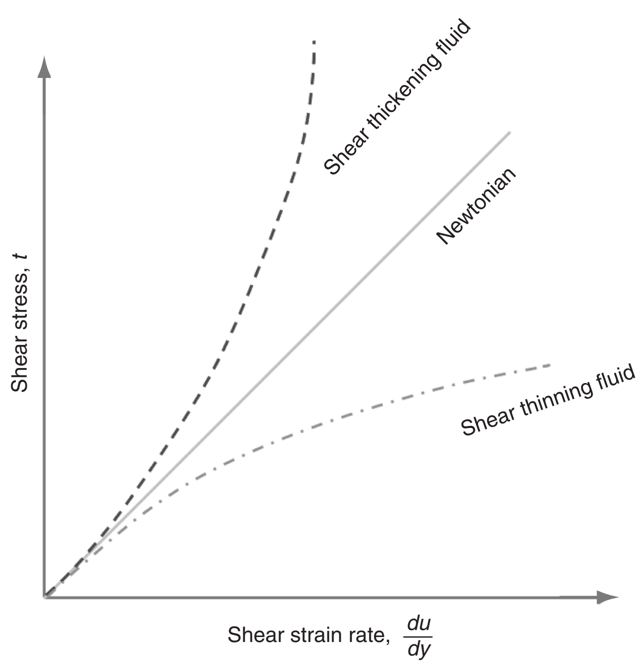


Figure 1 Shear Stress and Shear Strain Rate Relationship.

thickening effect in STF is illustrated by the lower rate of increase in shear stress at low shear strain rate regions, but higher rates of increase in shear stress at higher shear strain rates. The converse is true for Shear Thinning Fluid.

A Non-Newtonian Fluid (NNF) is a fluid whose flow properties differ from that of the Newtonian fluid described above. The viscosity of NNF is not independent of shear rate or shear rate history. If the viscosity of a fluid decreases with increasing shear rate, the fluid is called shear thinning. On the other hand, if the viscosity increases as the fluid is subjected to a higher shear rate, then the fluid is called shear thickening.

One of the most widely used forms of a general non-Newtonian model used to describe NNF is the Power-Law Model. It is also called the Ostwald-de Waele relationship. The mathematical relationship is given by

$$\tau = K\left(\frac{du}{dy}\right)^n \tag{2}$$

where K is the flow consistency index, and n is the flow behavior index. The quantity

$$\mu_{apparent} = K\left(\frac{du}{dy}\right)^{n-1} \tag{3}$$

represents the apparent or effective viscosity as a function of the applied shear strain rate.

For a Newtonian fluid, the flow behavior index, n, is equal to unity, and the flow consistency index, K, is equal to the viscosity of the fluid. For the Shear Thickening Fluid, n is greater than one. This relationship is summarized in Figure 2 where a Newtonian fluid

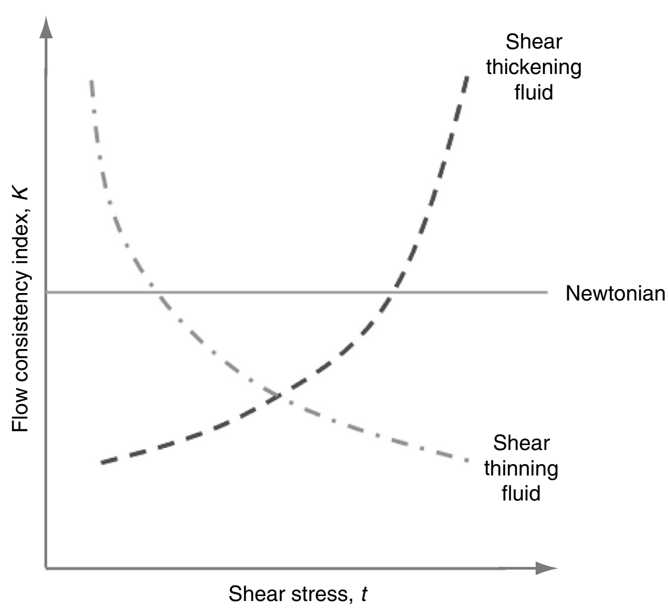


Figure 2 Shear Stress and Flow Consistency Index Relationship.

shows a constant Flow Consistency Index value at all levels of shear stress. For the STF, the Flow Consistency Index increases as the shear stress increases.

Shear Thickening Fluid is a dilatant material, which displays non-Newtonian characteristics. The material is typically made up of particles such as silica or silicon dioxide dispersed in a fluid base, which can be Newtonian in nature, such as water or Polyethylene Glycol (PEG). In STFs, the particles dispersed within the colloid are usually smaller and will not settle like in the case of sedimentation of larger solids. This is due to the fact that the particles are subjected to Van der Waals forces evident between mostly spherical particles as the dominant force compared to the gravitational pull. [8] The magnitude of the effects of these forces have on the particles is inversely proportional to the size of these particulates where gravitational forces are greater than particle-particle interactions for large particulates, and the opposite being true for small particulates.

Dilatancy in a colloid or its ability to order in the presence of shear forces is dependent on the ratio of inter-particle forces. As long as the inter-particle forces such as Van-der-Waal forces dominate, the suspended particles remain in ordered layers. However, once shear forces dominate, particles enter a state of flocculation and are no longer held in suspension. They then begin to behave like solids. When the shear forces are removed, the particles spread apart and once again form a stable suspension.

When shearing a concentrated stabilized solution at a relatively low shear rate, the repulsive particle-particle interactions keep the particles in an ordered, layered, equilibrium structure. However, at shear rates elevated above the critical shear rate, the shear forces pushing the particles together overcome the repulsive particle interactions, forcing the particles out of their equilibrium positions. This leads to a disordered structure, causing an increase in viscosity. The critical shear rate is defined as the shear rate at which the shear forces pushing the particles together are equivalent to the repulsive particle interactions.

One of the key characteristics of the STF is a behavior where dynamic viscosity increases with an applied shear stress. The dilatant effect occurs when closely packed particles are combined with enough fluid to fill the gaps between them. At low velocities, the fluid acts as a lubricant, and the dilatant flows easily. At higher velocities, the liquid is unable to fill the gaps created by the particles, and friction greatly increases, causing an increase in viscosity. STF is also non-Newtonian in nature where its viscosity is not dependent on shear rate or shear rate history. This behavior is one type of deviation from Newton's Law and is controlled by factors such as particle size, shape and distribution. Empirical studies have also shown that the shear thickening effects would differ due to the different concentration of particles and additives, as well as the molecular chain of the additives. [9] The larger the concentration of the additive, the more obvious the shear thickening effect. Similarly, the longer the molecular chain of the additive, the stronger the non-Newtonian behavior. It was also discovered that energy dissipation is also greater with a larger additive concentration and longer chain of additives.

3. NUMERICAL MODELING AND ANALYSIS

3.1. MODELING OF SHEAR THICKENING FLUIDS

Most modeling of STF like blood or industrial slurries have been modeled using a two-phase or multi-phase Eulerian approach. However, the Eulerian model could only provide an overall performance of the fluid, which contains both the fluid base and the particulates as dual-phases. The model would only allow the variation of general particulate properties in a defined phase, as well as the change of volume concentration based on the volume fraction determined.

In this study, the Lagrangian approach was adopted to analyze the performance of the STF at the particle-level, based on interaction with an Eulerian fluid base. The Lagrangian methodology allowed the tracking of particle movements when subjected to shear forces. It also allowed the investigation of the behavior of the particles based on the user-defined distribution and size.

As the numerical analysis focused on the behavior of each individual particle, the ANSYS CFX Rigid Body Solver was used to analyze the particles at micro-level, allowing each rigid body to model the movement of every particle subjected to shear loading.

The ANSYS CFX software was chosen for use in the simulations due to its ability to handle fluid flows at both an Eulerian and Lagrangian level, as well as having the integrated rigid body solver to handle the particles displacement and disposition.

3.2. MESH

Although the study focused on a two-dimensional model, a three-dimensional model had to be defined with a single cell thickness on the z-dimension as required by CFX for meshing and analysis. A hexahedral mesh, as shown in Figure 3, was used to define the three-dimensional model.

3.3. TRANSIENT MODELING

The objective of the study required the modeling to be transient, in order to observe the behavior of the particles at various time steps when subjected to a shear loading. The time step size was selected to allow sufficient resolution in observing time dependent data such as displacement of particles and force exerted on particles at a particular time step. An initial condition was required to define the start state of the simulation.

The time interval for output was chosen based on the size of the particles of diameter of 1 and 2 mm, and control volume of 0.06 m by 0.025 m, as well as the applied flow acceleration of 0.1 to 0.4 m/s^2. It would allow the observation of the critical behavior of the STF.

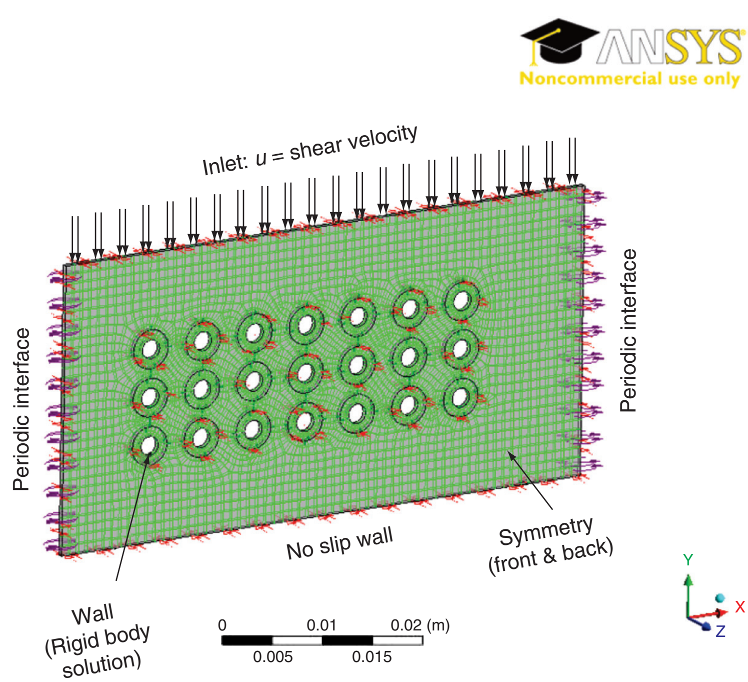


Figure 3 Finite Element Mesh and Boundary Conditions.

3.4. MATERIALS

The fluid base of the STF is typically a Newtonian fluid. In the model, water with a viscosity of $8.90 \infty 10^{-4}$ Pa.s was used. Sand particles were used for the material properties of the particles placed inside the fluid base. A uniformly shaped particle, with a baseline diameter of 2 mm, was modeled as a rigid body to limit the variability of the parameters examined in the study.

3.5. BOUNDARY CONDITIONS

Boundary conditions were important in defining the model and ensuring the correct conditions were enforced for the study. The study required a shear force being applied on the fluid domain, containing the pre-determined particle distributions.

A shear force was applied to the upper boundary through a shear velocity. The bottom boundary was defined as a no slip wall condition to achieve the shear development of the flow between the top and bottom boundaries. Since the shear fluid flow would require a long channel to be fully developed, periodic boundary conditions were applied to the left and right interfaces. As CFX does not have a separate 2-D and 3-D solver, a thin 3-D volume was created with a single cell thickness, and symmetry boundaries were applied to the front and back faces of the control volume created.

The Rigid Body Solver required the interfaces of the extruded cut particles be defined as walls since it did not allow mesh deformation. The mesh motion for the Rigid Body boundary interfaces was set to “Rigid Body Solution”, instead of the default setting of “Stationary”. The boundary conditions are as shown in Figure 3.

3.6. MULTIPHASE MODELING

The simultaneous flow of phases in a domain is called a multiphase flow. The two general components of the STF are the base fluid and the granular particle phase. To simulate the two phases, the interaction between the two phases is defined. Multiphase flows are broadly classified as either segregated or dispersed. [10] In segregated flows, each phase flow through the domain is separated by macroscopic interfaces. For dispersed flows, at least one of the phases is a particle, bubble or droplet.

The particles in the STF require the fluid to be modeled as a dispersed multiphase flow. The dispersed phase also takes the form of solid particles, which epitomizes a granular flow. The particles exhibit a fluid-like character due to the emergent behavior of many individual particles. The rheology of the particles is a function of flow condition and would be addressed as part of the solution.

3.7. RIGID BODY MODELING OF PARTICLES

The fluid forces and external forces, if any, dictates the motion of the rigid body. The solver does not require the rigid body to be meshed and mesh motion is used to move rigid body faces in accordance with the rigid body equations of motion.

Simulating the motion of a rigid body is similar to simulating the motion of a particle. [11] In addition to the definition of particles, rigid bodies have rotations, as well as a volume of space and a particular shape. A function $x(t)$ denotes the particle location in space at a particular time, t. The function $v(t) = \dot{x}(t) = \frac{d}{dt}x(t)$ gives the velocity of the particle at time, t. The state of the particle at time t is the particle’s position and velocity, which gives a state vector, $X(t) = \begin{pmatrix} x(t) \\ v(t) \end{pmatrix}$.

For rigid bodies, there would also be a requirement to define the rotation of the body, in terms of $R(t)$. Thus, $x(t)$ and $R(t)$ makes up the spatial variable of the rigid body. If the assumption is made that the rotation of the body is fixed, the only movement that the rigid body can undergo is a translation.

To simulate the motion of a particle or rigid body, the sum of all forces acting on the particle would also be required and can be defined as $F(t)$. For a particle with mass m, the change of X over time would be given by,

$$\frac{d}{dt}X(t) = \frac{d}{dt}\begin{pmatrix} x(t) \\ v(t) \end{pmatrix} = \begin{pmatrix} v(t) \\ \dfrac{F(t)}{m} \end{pmatrix}. \tag{4}$$

The linear momentum p of a particle with mass m and velocity v is defined as $p(t) = m(t)v(t)$. According to Newton's second law, the rate of change of momentum of a particle is proportional to the resultant force acting on the particle and in the direction of the force. Based on the conservation of linear momentum, the change in linear momentum is equivalent to the total force acting on a body as shown as $\dot{p}(t) = F(t)$.

Similar to the relation for linear momentum, the angular momentum $L(t)$ of a rigid body can be defined by the equation $L(t) = I(t)\omega(t)$, where $I(t)$ is the inertia of mass which describes how the mass in the body is distributed relative to the body's center of mass, and $\omega(t)$ is the angular velocity.

In summary, for a rigid body, the overall equation of state is defined as

$$X(t) = \begin{pmatrix} x(t) \\ R(t) \\ P(t) \\ L(t) \end{pmatrix} \tag{5}$$

where the position and orientation describes its spatial information and the linear and angular momentum describes the velocity information. The mass m and the inertia I are constants, which need to be defined during the pre-processing of the model.

3.8. PARAMETERS OF PARTICLES FOR MODELING

The following variables were chosen and separately modeled to study the effects of the shear thickening fluid: applied flow acceleration on the control volume, particle distribution arrangement, volume concentration of particles, particle size, particle shape and orientation, and particles in non-Newtonian fluid. The shear stress and shear strain rate of the modeled STF were computed to determine the effects of the parameters on the effective viscosity, and the results are documented in the next section.

4. RESULTS AND DISCUSSION

4.1. EFFECT OF APPLIED FLOW ACCELERATION

Four different shear velocities were applied at the top boundary of the control volume to determine the behavior of the STF. Velocities of 1 m/s, 2 m/s, 3 m/s and 4 m/s were applied in the horizontal component of the velocity at the top boundary to model a shear flow across the control volume on the STF. The velocity applied at the top boundary increased from zero to the specified velocity with acceleration, and the average accelerations are shown in Figure 4. The flow acceleration was obtained by taking the gradient of the velocity-time graph in Figure 4. The average flow acceleration achieved for velocities of 1 to 4 m/s are 0.0969 m/s^2, 0.195 m/s^2, 0.301 m/s^2 and 0.425 m/s^2 respectively. The flow acceleration for the respective flows would be simplified and named as 0.1 m/s^2, 0.2 m/s^2, 0.3 m/s^2 and 0.4 m/s^2 henceforth in the report.

The shear stress versus shear strain rate relationship curve was used to compare the STF behavior of the fluid model under the four different flow accelerations applied, and the results were presented in Figure 5. It could be seen that the model showed a stronger shear

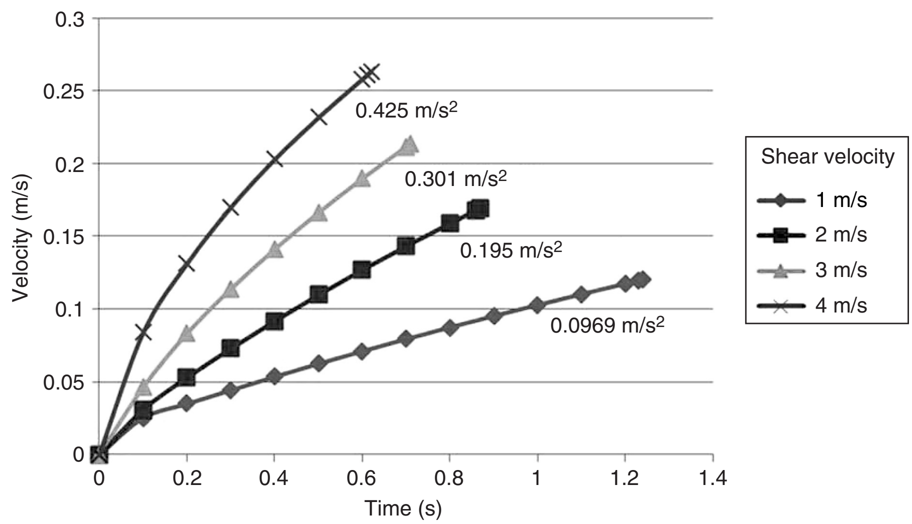


Figure 4 Flow Acceleration Applied to Fluid.

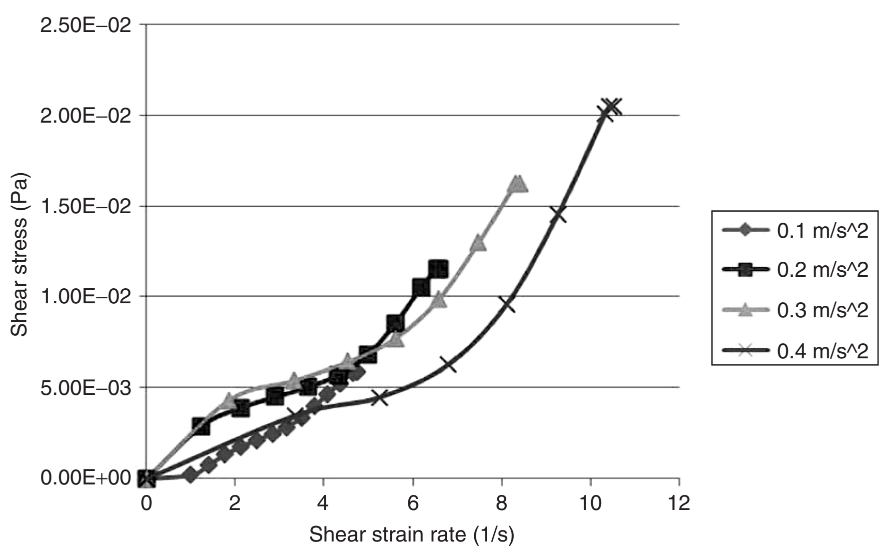


Figure 5 Shear Stress vs. Shear Strain Plot for Different Flow Accelerations.

thickening behavior for a higher flow acceleration because the higher acceleration curve has a greater change in the slope (i.e. higher viscosity) as the shear strain rate increases.

The shear thickening effect is observed from the apparent-viscosity and shear stress curve in Figure 6. The apparent viscosity was calculated based on the gradient of the shear stress and shear strain rate at each shear stress value, which was sampled at every 0.1 s time step. The shear thickening effect is observed in Figure 6, especially beyond the 0.005 Pa regions, where the shear force induced by the applied velocity had reached the top layer of particles shown in Figure 7. Beyond 0.005 Pa, the graph in Figure 6 shows a consistent increase in viscosity as a higher shear stress is experienced. The overall viscosity with the 15 particles

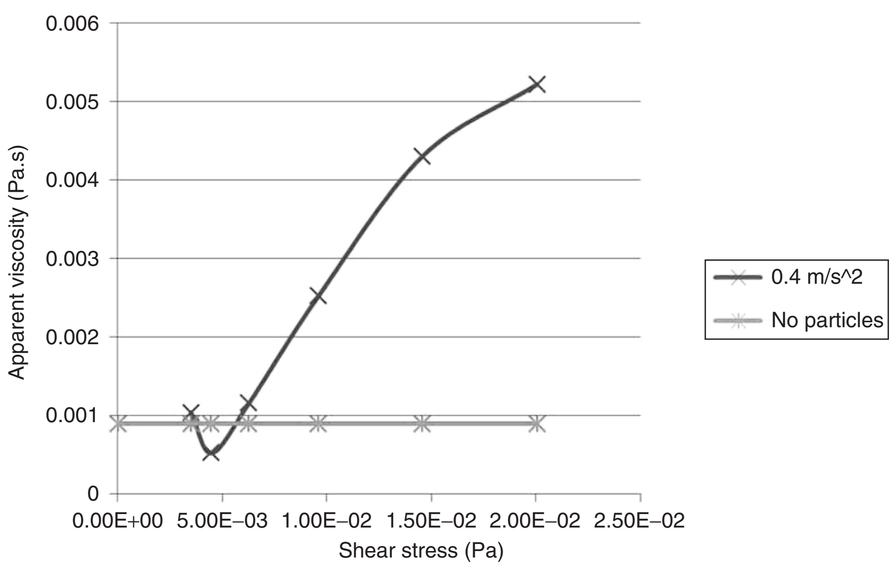


Figure 6 Apparent Viscosity vs. Shear Stress Curve at Acceleration 0.4 m/s^2.

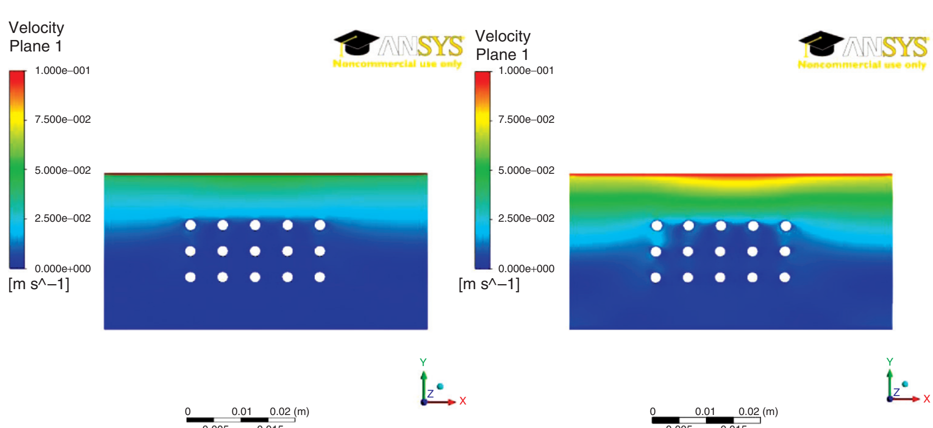


Figure 7 Velocity Profile for Applied Flow Acceleration of 0.3 m/s^2 at 0.1 sec (left) where $\frac{du}{dy} = 1.85$, and 0.2sec (right) where $\frac{du}{dy} = 3.32$.

embedded in the fluid control volume also showed a higher viscosity as compared to the Newtonian fluid base without particles as shown in the Figure 6.

At a lower shear stress and shear strain rate (below shear stress of 0.005 Pa and shear strain rate of 2 s^{-1}), the fluid was observed to behave like a Shear Thinning Fluid where the viscosity decreased with higher shear stress. This was likely due to the effect of the shear force travelling along the top slice of the Newtonian fluid domain and yet to reach the top layer of particles in the STF model. Figures 7 and 8 show the transition when the shear force interact with the top most layer of particles, resulting in an increase in viscosity when the shear stress is increased. In Figure 7, at a time step of 0.1 s with a shear strain rate of $\frac{du}{dy} = 1.85$, the flow acceleration applied had not affected the top layer of particles in the control volume. However, at 0.2 s where $\frac{du}{dy} = 3.32$, it could be observed from the velocity plot that the first row of particles had started to interact with the flow induced. This also caused a corresponding increase in the shear stress experienced in the flow. A similar effect could be seen in Figure 8 when a flow acceleration of 0.4 m/s^2 was applied.

4.2. EFFECT OF PARTICLE DISTRIBUTION ARRANGEMENT

Two different configurations for the initial particle distribution were studied. One configuration has all of the 15 particles arranged in a 3 by 5 uniform matrix arrangement while the other configuration has the second layer of particles staggered as shown in Figure 9.

The results are presented in Figure 10 which shows that a greater shear thickening effect is observed when a higher flow acceleration is applied for both the uniform or staggered configurations. It is also seen from Figure 10 that the uniformly arranged particles show greater shear thickening, especially at the higher acceleration flow. The effect of particle arrangement was much less obvious at the lower applied flow acceleration of 0.3 m/s^2 compared to 0.4 m/s^2. This was probably due to the smaller shear force exerted on the

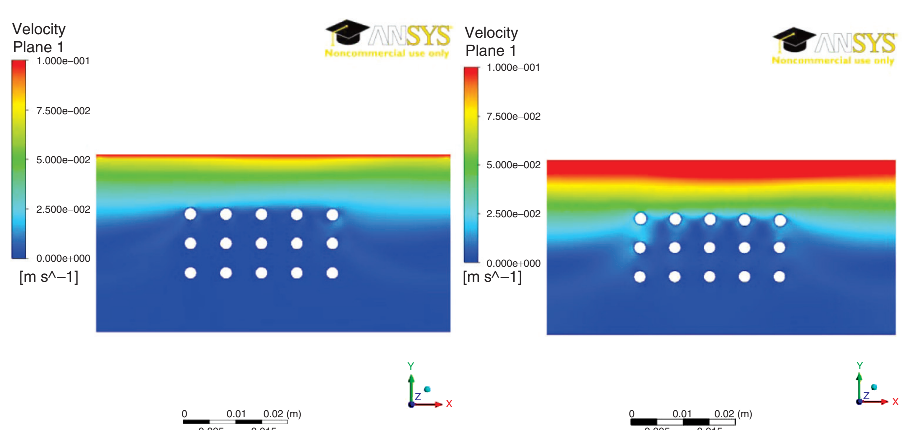


Figure 8 Velocity Profile for Applied Flow Acceleration of 0.4 m/s^2 at 0.1 sec (left) where $\frac{du}{dy} = 3.34$, and 0.2 sec (right) where $\frac{du}{dy} = 5.24$.

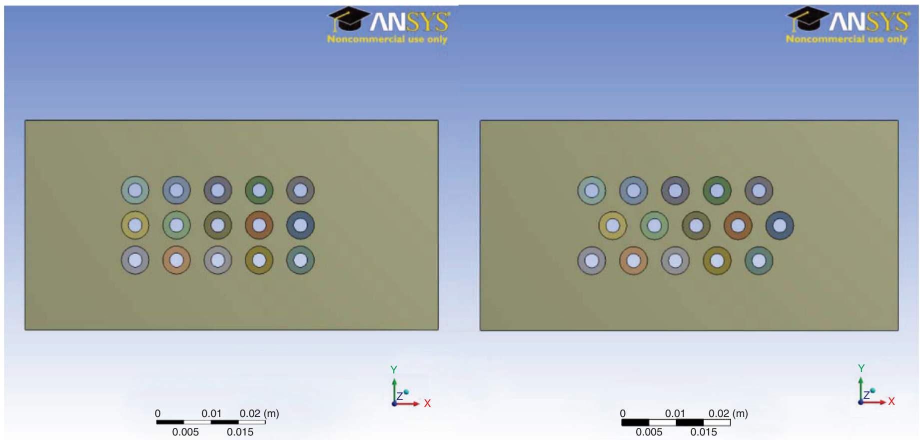


Figure 9 Particle Distributions – Uniform (Left) and Staggered (Right).

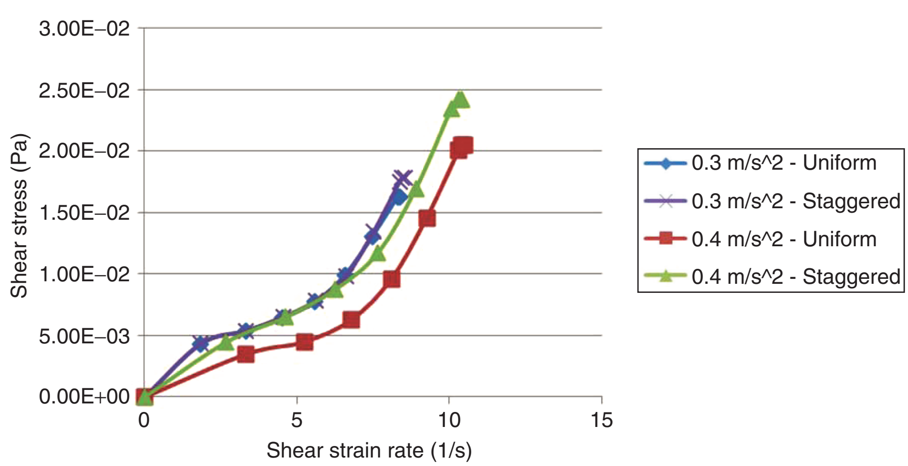


Figure 10 Shear Stress vs. Shear Strain Rate Plot for Different Particle Distribution Arrangements.

particles and correspondingly a slower rate of reaction from the particles in the top layer, and then aligning themselves to the second layer before the shear force could cause a displacement in the second layer of particles.

From the transient velocity plot for flow acceleration of 0.3 m/s^2 as shown in Figure 11 taken at 0.7 sec for both the uniform and staggered particle arrangements, the particles align themselves in a diagonal pattern, with the top layer in a forward position relative to the direction of the applied shear velocity and the bottom layer trailing behind. It was true for the cases for flow acceleration of 0.4 m/s^2 as shown in Figure 12.

4.3. EFFECT OF FLUID-PARTICLE VOLUME CONCENTRATION

The shear thickening effect affected by the volume concentration of the number of particles in the fluid domain was investigated. More particles were added to the original model of 15

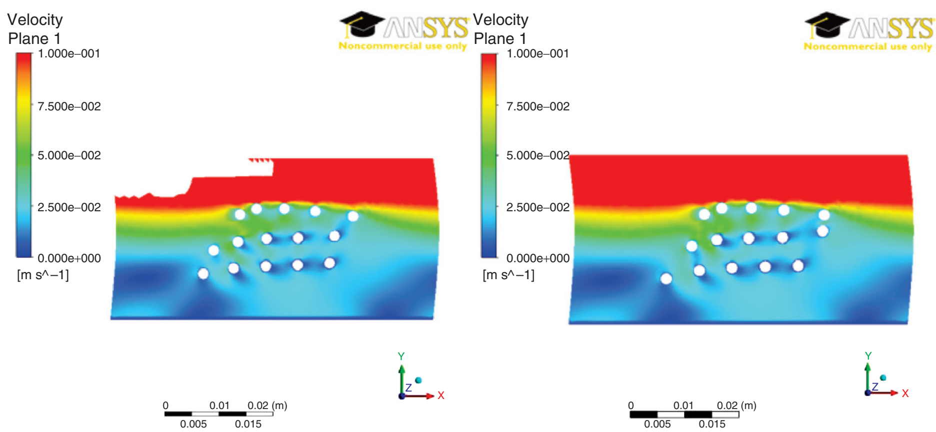


Figure 11 Transient Velocity Plot at 0.7sec for Uniform (Left) and Staggered (Right) Particle Distribution for Flow Acceleration of 0.3 m/s^2.

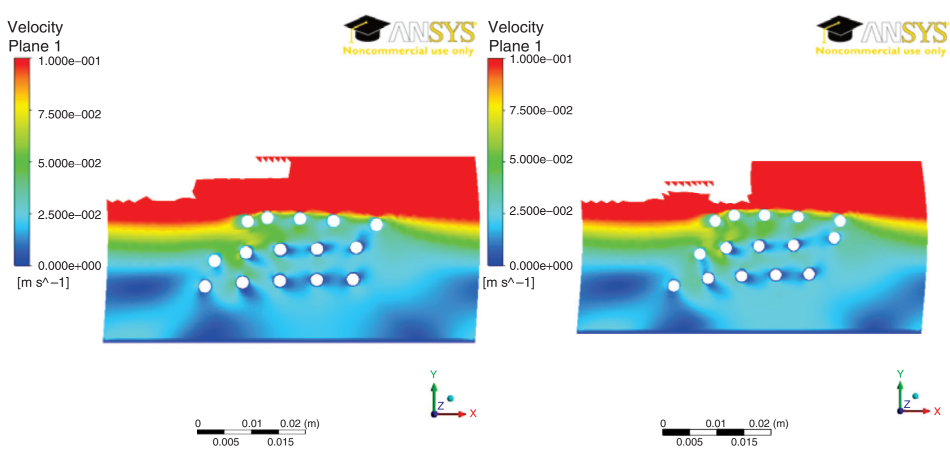
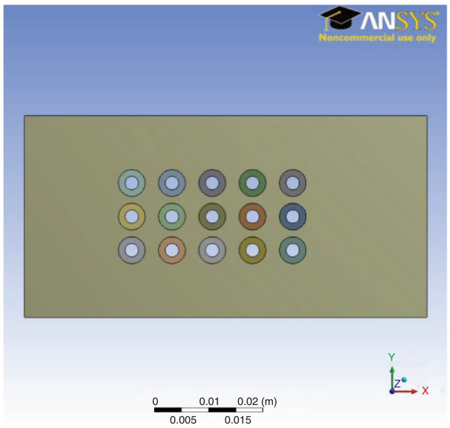


Figure 12 Transient Velocity Plot at 0.6 sec for Uniform (Left) and Staggered (Right) Particle Distribution for Flow Acceleration of 4 m/s^2.

particles to study the changes in the shear thickening effect at a different flow acceleration applied. Instead of a 3 by 5 particle arrangement, the number of particles was increased to a 3 by 7 configuration of 21 particles, as shown in Figure 13.

The results, seen in Figure 14, suggest that a higher number of particles in the fluid yield a stronger shear thickening effect showing a larger slope change in the curve. However, due to the high distortion of the mesh resulting in the termination of the modeling, further data was unobtainable for the models with more particles inserted for higher shear strain rate beyond 8 s^{-1}. The observation is consistent with empirical studies [2, 9] that compared the shear thickening effect for fluids with different volume concentration of particles. In Ref. [9], which experimented with different concentrations of shear thickening fluid, it was observed that energy dissipation was greater with a larger concentration of particles in the STF.



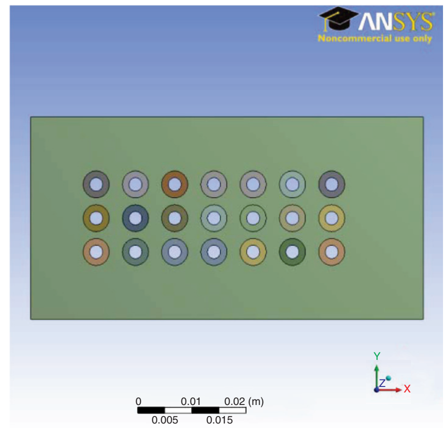


Figure 13 Increase in Number of Particles (Right).

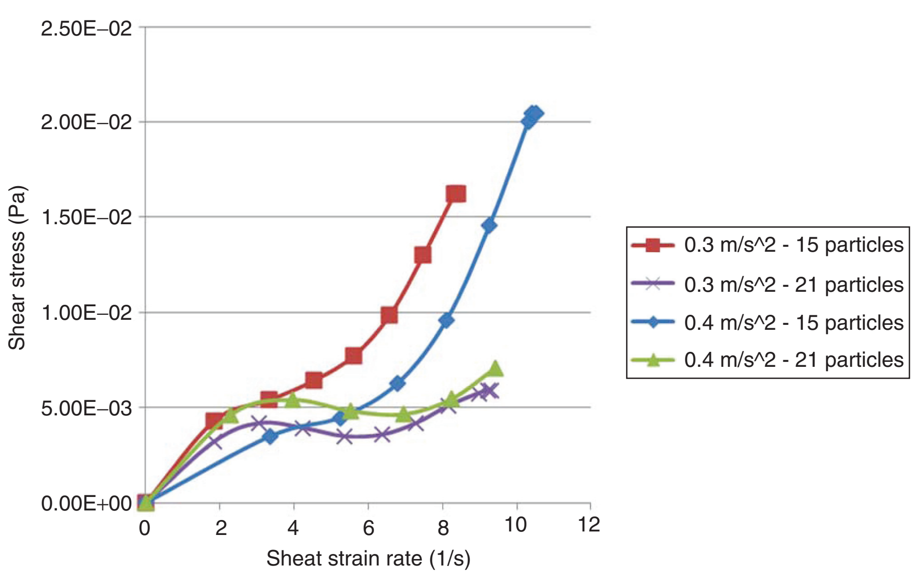


Figure 14 Shear Stress vs. Shear Strain Plot for Different Concentrations of Particles.

4.4. EFFECT OF PARTICLE SIZE

Two particle sizes were studied to observe their effects on STF as shown in Figure 15. In the first configuration, ten 2 mm diameter particles were used. For the second configuration, the particle size was reduced to 1 mm diameter, but the number of particles was increased to 40 particles to keep the total wet area constant.

The plots in Figure 16 do not show any conclusive result because the simulation with smaller particles was terminated at 4 s^{-1} such that the data for high shear stress levels could not be determined. The smaller particle curves have much lower slopes than the larger particle curves. This possibly suggests that the fluid with the smaller diameter particles has a greater chance for a larger change of the slope as the shear strain rate increases. The result is consistent with a previous empirical study [12] on the shear thickening effect due to

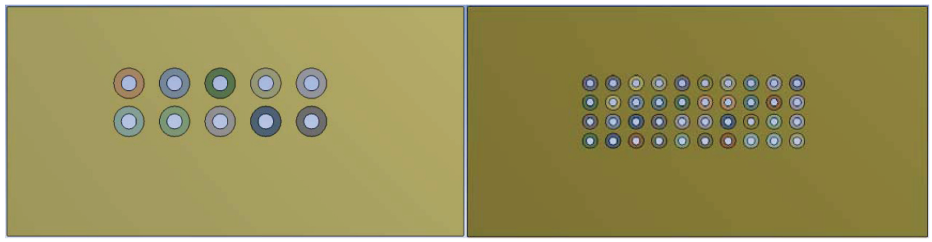


Figure 15 Particle Size – 2 mm Diameter Particles (Left) and 1 mm Diameter Particles (Right).

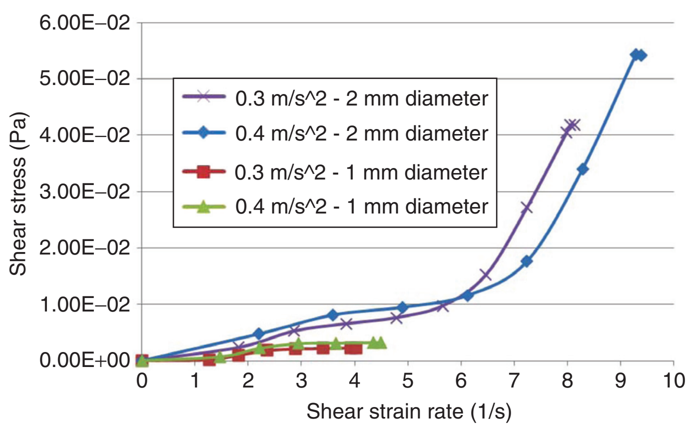


Figure 16 Shear Stress vs. Shear Strain Rate Plot for Different Particle Sizes.

particle size. In that particular study, it was shown that the silica colloidal suspension using smaller particles yielded a better ballistic performance compared to that of larger particles.

4.5. EFFECT OF PARTICLE SHAPE AND ORIENTATION

The behavior of the STF affected by the shape and orientation of particles in the fluid base was studied. Elliptically shaped particles as shown in Figure 17 were used instead of circular particles in order to study the effect of particle shape orientation on shear thickening effect. The presented areas of the circular and elliptic particles were kept the same to compare the effects of particle shape. The particles were also arranged in two different alignments to study the effect of the shear flow on the longitudinal or lateral ends of the elliptic particles.

The results for vertically and horizontally arranged elliptic particles, as well as circular particles in a fluid base subjected to a flow acceleration of 0.3 m/s^2 are compared in Figure 18. The plots show that the elliptical particles generally have lower viscosity at low shear stress and shear strain rate, but significantly higher viscosity at high shear strain regions. This showed that by changing the aspect ratios of the particles dimensions, the shear thickening effect could be improved with the same number of particles.

Due to the early termination of the simulation with the vertically arranged elliptical particles, the study could only conclude that the vertical arrangement had a higher viscosity at lower shear strain rate levels of up to 6 s^{-1} compared to horizontally arranged elliptic particles.

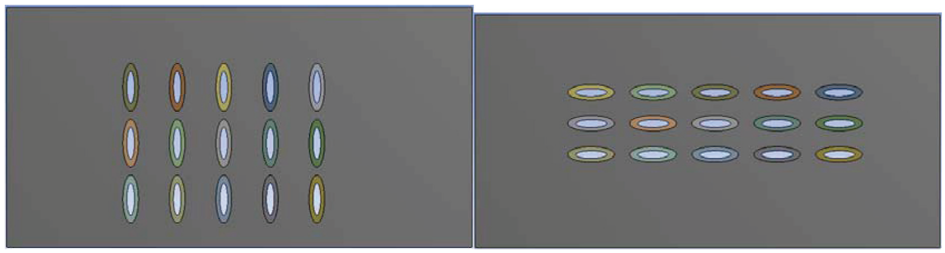


Figure 17 Elliptically-Shaped Particles Arranged in Two Configurations – Vertical (Left) and Horizontal (right).

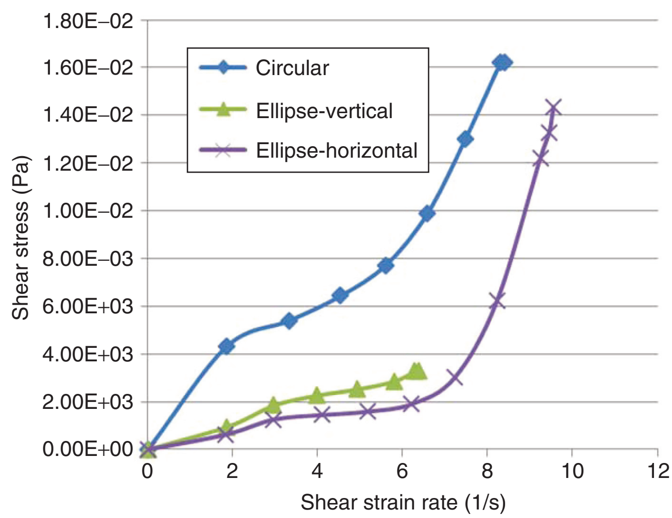


Figure 18 Shear Stress vs. Shear Strain Rate Plot for Different Particle Shapes and Orientations.

4.6. EFFECT OF NON-NEWTONIAN FLUID BASE

The numerical model studied the behavior of particles and their effect on non-Newtonian fluids, as compared to Newtonian fluids. The non-Newtonian fluid used had a viscosity consistency of 1.63 ∞ 10^{-5} Pa.s, and using the Ostwald de Waele model, a power law index of 1.5 was assigned.

Flow accelerations of 0.3 m/s^2 and 0.4 m/s^2 were applied to the non-Newtonian fluid, with the baseline 3 by 5 particle configuration. The plots in Figure 19 have half-sign shape curves at the low strain rates before an increasing trend at high strain rates. The expected performance of the non-Newtonian fluid without particles was also plotted in Figure 19 for comparison. The apparent viscosity is greater for the particle-embedded non-Newtonian fluid than for the base non-Newtonian fluid at high shear strain rates.

The negative slopes for the particle embedded non-Newtonian fluid are considered to be resulted from the simplistic average calculation of the shear strain rate rather than calculation of locally varying shear strain. In order to study the overall STF effect, the average calculation of the shear strain rate is useful as plotted.

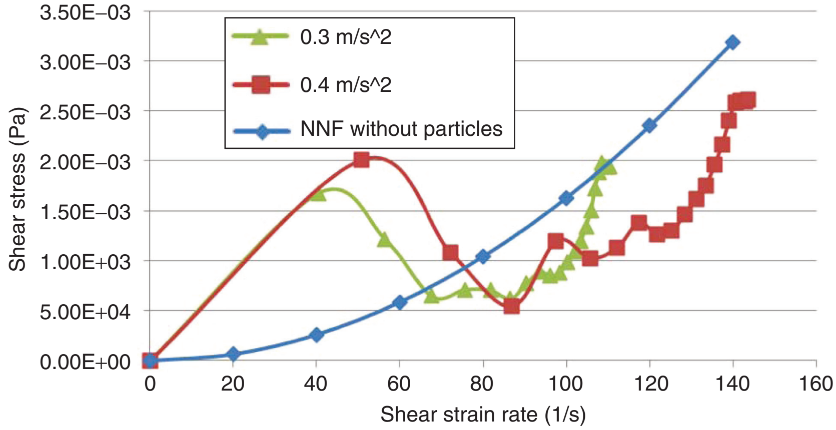


Figure 19 Shear Stress vs. Shear Strain Plot for Non-Newtonian Fluid Base.

4.7. SUMMARY OF RESULTS

In summary, the following parameters were examined to study their shear thickening effects on the STF: applied flow acceleration, particle distribution arrangement, volume concentration of particles, particle size, particle shape and orientation, and particles in both Newtonian and non-Newtonian fluid. The study on the applied flow acceleration showed that the model with the boundaries conditions used was able to simulate the shear thickening effect of the STF. It was found that the higher the applied flow acceleration, the larger the shear thickening effect. These characteristics showed the potential for the application of the STF against loadings with high shear effects, such as the pressure blast wave, while maintaining the flexibility of the material in low shear forces, during transportation or at-rest phase.

The study on the distribution of the particles within the fluid base showed that the position of the particles should be as much perpendicular to the expected shear force loading as possible to break up the shear forces exerted on the fluid body. By staggering the particles, the effect on the second layer to resist the shear force was reduced. However, further study is necessary to examine whether this observation is still true if more layers of the particles are modeled, and when the staggered or uniform arrangements are placed more compactly together.

The numerical model suggested that a higher volume concentration of particles contributed to a better shear thickening effect. However, a high concentration of particles could mean an increase in rigidity and weight of the STF. Thus, a trade off study would have to be performed to obtain the desired level of the SFF effect with the lowest particle concentration.

The model also suggested that a smaller particle size contributed to better mitigation of shear stress applied at low shear stress regions. Further modeling would be required to study if a combination of particle sizes could improve the shear thickening effect.

The study on the shape of the particles showed that the aspect ratio of particles played an important role in shear thickening performance. By aligning the particles with higher surface area in the direction of the shear force, a better shear thickening effect could be achieved. This could also translate to savings in the number or volume concentration of particles with a higher aspect ratio required in a STF for the same shear thickening effect.

The results for the study of particles in non-Newtonian fluid showed a half-sign shape of shear stress-strain rate curve at low shear strain levels. On the other hand, as the shear strain rate increased further, the increase in the apparent viscosity was greater than the base non-Newtonian fluid without particles.

5. CONCLUSIONS

The numerical analysis on shear thickening was conducted by modeling the base fluid and embedded particle interactions. The combined Eulerian and Lagrangian approach allowed the study of key particle parameters that could affect the performance of the STF. Some of the numerical results agreed with previous experimental results. In summary, greater shear thickening effects could be achieved through the following particle parameters; applying higher flow acceleration, aligning particle layers perpendicularly to the expected shear force loading, employing a higher concentration of particles, using a smaller particle size to improve the wet surface area, and using particles with h igh aspect ratios and with the longer surface aligning perpendicular to the expected shear flow. This study suggested that particles could further improve the shear thickening effect of non-Newtonian fluids, although a further investigation is required for the non-linear response at low shear strain rates. Successful numerical analysis of the shear thickening effect would allow more optimized and improved STF design.

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