NON NEWTONIAN FLUIDS AND ITS APPLICATION IN TEXTILES: REVIEW

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Abstract : During the past 300 years, Newtonian fluids are of great importance in the fluid dynamics in the field of turbulence and multi-phase flows. Most low molecular weight substances shows relationship of shear stress is proportional to the rate of shear at constant temperature and pressure and these constant of proportionality is the viscosity. Non-Newtonian fluids are a fluid that does not follow Newton's law of viscosity, i.e., constant viscosity independent of stress. These are divided into two parts: Shear thickening (Dilatant) and Shear thinning (pseudoplastic) which will be discussed later. The paper aims to review and discuss the importance of non newtonian fluids in various fields. Change in its impact strength on application of force makes it different from existing fluids. Non-Newtonian fluids vary considerably in their properties, which govern flow and pressure loss during flow. The key factors that influence non-Newtonian fluids are their shear thinning or shear thickening characteristics and viscosity time dependence on the fluid stress. Based on the solution, a graphical approach was developed to test the utility of non-Newtonian displacement.

***Index Terms* - Non-Newtonian fluids, Shear stress, Dilatant, Pseudoplastic, Bingham plastic.**

I. INTRODUCTION

Non Newtonian fluids are of great importance in textile fields and have a wide range of applications on sportswear, protective vests and in future medical textiles also.The impact of solid objects on liquid surfaces has been studied intensively over the last century due to its relevance in the water entry of military projectiles, the construction of naval vehicles and the motion of water-walking lizards[1]. In this paper, we will be understanding the forces and mechanics for the kinetic energy dissipation which is a key factor for understanding the fluid behaviour during impact [2].However, it has been known for some time that the use of non-Newtonian fluids can provide efficient ways of changing the impact dynamics, which could have many useful applications. Various characteristics of non newtonian fluids will be discussed and will be covered further are: Instabilities, unsteady and turbulent or chaotic flow characteristics in non-Newtonian fluids and multiphase flows involving complex fluids [3].

2. Theoretical background

2.1 Newtonian fluids: A Newtonian fluid is a fluid in which the viscous stresses arising from its flow, at every point, are linearly correlated to the local strain rate—the rate of change of its deformation over time. That is equivalent to saying those forces are proportional to the rates of change of the fluid's velocity vector as one moves away from the point in question in various directions.

2.2 Non newtonian fluids: A non-Newtonian fluid is a fluid that does not follow Newton's law of viscosity, i.e., constant viscosity independent of stress. In non-Newtonian fluids, viscosity can change when under force to either more liquid or more solid.

2.3 Types of non newtonian fluids:

2.3.1 Shear thickening (dilatant) fluid:

The shear rate reduces as the shear stress is increased. As more shears are applied, deformation rate slows down. Fluids can't be deformed further easily [4]. To keep on deforming the fluid, we need to increase the shear stress exponentially.

Examples- Cornstarch and water,

2.3.2 Shear thinning (pseudoplastic) fluid :

The shear rate increases with increase in shear stress. As we apply much shear stress the shear rate of fluid increases; i.e. as we increase the shear stress further, the fluid begins to deform more easily and shows to be less viscous[5].

Example- Ketchup , Nail Polish

2.3.3 Viscoplastic fluid

Viscoplatic material will deform elastically when the externally applied stress is smaller than the yield stress.As the value of external stress exceeds the yield stress, the flow curve may be linear or nonlinear but will not pass through the origin.

2.3.4 Bingham plastic

Fluids that have a linear shear stress/shear strain relationship require a finite yield stress before they start to flow.It is a kind of viscoelastic material which acts as a solid at high stresses and fluid at low stresses. In contrast, newtonian fluids have flat surfaces when they are not in motion.It is also used as a model for flow of mud in handling of slurries and drilling engineering.

Examples- clay suspensions, drilling mud, toothpaste, chocolate, and mustard.

2.4 Weisenberg number

A non-Newtonian fluid has, therefore, a simultaneously elastic and viscous nature. In fact, all fluids are non-Newtonian on an appropriate time-scale, though for many common fluids such as air and water the time-scale is extremely short. When the time-scale of a flow tf is much less than the relaxation time tr of an elastico viscous material, elastic effects dominate [7]. This typically happens when there are abrupt changes in flow geometry. When on the other hand tf is much greater than tr elastic effects relax sufficiently for viscous effects to dominate. This typically happens when there are no abrupt changes in flow geometry.

Calculation of weisenberg number:

J L White [27] stated that dimensional analysis to make the equations of motion for the steady flow of a second order fluid dimensionless. Three significant dimensionless groups arise: a group representing the ratio of inertial to viscous forces (the Reynolds number[28] of classical fluid mechanics), $Re = \rho UL/\mu$, where ρ is the density and μ is viscosity. A group representing elastic forces to viscousforces $\lambda U/L$ and a higher-order property ratio (N2/N1 which is viscoelastic number). White interpreted the group of elastic forces to viscous forces as representing the recoverable strain in the fluid and even quotes Weissenbergs paper[29] from the First International Rheological Congress held in 1948.

3. Rheology and flow in non newtonian fluids

3.1 Power law for non newtonian fluids:

Power-law fluid is a type of generalized time independent Non-Newtonian fluid for which the shear stress, τ, is given by: =K (du/dy)n K is the flow consistency index (SI units Pa sn), du/dy is the shear rate or the velocity gradient perpendicular to the plane of shear (SI unit s−1), n is the flow behavior index (dimensionless) [8]. Velocity profiles for unsteady laminar flows of Stevens' law, non-Newtonian fluids in pipes have been derived using an explicit finite difference techniques.

Three unsteady flows are:

1. The transient start-up following the sudden imposition of a constant pressure gradient to a fluid at rest.
2. Oscillating flow following the imposition of a sinusoidally variable pressure gradient with a zero mean value.
3. Rhythmic flow following the imposition of a sinusoidally variable pressure gradient with a non-zero mean.[9]

3.2 Rheological factors:

1. Molecular Weight: Polymer solutions, dispersions, and melts are usually non-Newtonian fluids. This means their viscosity depends on the applied shear rate and increases rapidly with increasing molecular weight.

2. Molecular weight distribution: Polymeric materials are characterized by their polydispersity (Mw/Mn),that is they are mixtures of fractions having different molecular mass and hence viscosity dependent on MW.

3. Structure of molecules: End groups of molecules alters the adhesive properties of non newtonian Fluids. For example vinyl terminated polymers are used for its preparation.

4. Chemical Compositions: Addition of additives like stearic acids or aluminium stearate and salts varies the properties of fluids.

4. Non newtonian Blood flow

The blood could be a non-Newtonian fluid and it follows Newtonian nature once the shear rate is higher than a hundred s-1 [10]. As the shear rate is high enough in large blood vessels for example aorta, the effect of non Newtonian behaviour is negligible. Considering the blood as a Newtonian fluid could be a satisfactory assumption for big arteries such as the aorta [11,12].In transient analysis, the non-Newtonian flow effects could become significant once the shear rate is below a hundred s-1.Some authors concluded that the non-Newtonian fluid approximation for flow in large arteries is crucial while others found it is an unimportant assumption.Gijsen gave various differences between non-Newtonian and Newtonian flow patterns when they studied flow through 90° curved tube[13]. Lia [14] simulated blood flow through an Abdominal Aortic Aneurysm (AAA) model with Stent-Graft (SG) victimisation non-Newtonian fluid assumption. They discuss blood flow conditions, aneurysm and SG geometries were major reasons for SG migration.Amblard [15] developed a methodology using non-Newtonian fluid approximation to observe the relation between the aorta's wall and endocraft to seek out once kind I endoleaks might occur.They evaluated the stresses on the aorta's wall generated by the blood flow.

5. Effect on droplet formation

Non-Newtonian multi-phase microsystem has become an intensive research subject and is widely used in biomedical engineering, food production and energy applications, especially the way in which non-Newtonian rheological effects changes break-up dynamics and in turn affect droplet formation [16].Non-Newtonian rheological properties affect breakup dynamics and challenge versatility in control of droplet size. The stretching and/or thinning of non-Newtonian liquid filaments will result in "bead-on-string" patterns being formed. These beads can further become undesirable Satellite droplets, increasing the polydispersity of the resultant droplet population. These attest to the need to understand the role of non-Newtonian viscosity effect in droplet formation using microfluidic systems in a comprehensive manner.[17]

6. Non Newtonian fluids in bullet proof vests:

The proof vest for bullets was designed to protect the main body organs from damage caused by the impact of bullets.If the bullet penetrates the body, it crushes and displaces the tissues in the organswhile making temporary and permanent cavities. As human tissues act as a semi-fluid, it damages the main organs and causes death when the bullet creates pressure and shock waves. This is known as blunt trauma.[18]The properties of the plain woven Dyneema fabric is superior to a plain woven Kevlar fabric having the same specifications currently used in flak jackets. The Oobleck solution has marked enhancement of the bulletproof properties of the Dyneema fabric[19]. Using a proper Shear thickening fluid for the bulletproof material would almost reduce the number of fabric layers necessary, while giving the required bullet proof properties.

7. Previous Works on non newtonian fluids in Textiles:

Shear Thickening Fluids made from silica nanoparticles loaded in carrier fluids, such as polyethylene glycol, and impregnated in a fabric have gained attention by the military and law enforcement to have potential for use in liquid body armor and bulletproof vests. If Shear Thickening Fluids (STFs) embedded in textiles can be used for a lightweight habitat shell to provide effective protection against micrometeoroid orbital.Jianhao Ge and Zhuhua recently discovered that the fast moving object stopping power of Kevlar body vests can be significantly improved by saturating the Kevlar layers with a suspension, which is the foundation of liquid body armour designs. The shear thickening properties of the suspension, an increase in viscosity when shear stress is applied , is responsible for the enhanced kinetic energy distribution in the Kevlar vests.Pure STF used in that experiment consists of SiO_2 nano-particles and polyethylene glycol with a molecular weight of 400 (PEG400).Viscocity curves were taken to analyse the effect of 4 different types of STFs on SiC nanowires. Results show that each curve has three processes: shear thinning, shear thickening and shear thinning. The shear thickening viscosities of the STFs with SiC nanowires have significant increases compared to the STF without SiC nanowires. This initial viscosity increases as the volume fraction of SiC nanowires increases.

Matthew W. Dunn experimented to model the flow of non-Newtonian fluid through a fabric structure. It has validity in numerous textile fields, including dyeing, filtration, and chemical protection. Understanding the flow phenomena with the corresponding environmental changes such as pressure drop, concentration gradient, etc. becomes important in many fields, such as liquid transport through geomembranes, effluent flow through filtration devices, and chemical movement through protective apparel.[28] M. Dunn, Masters Thesis, "Renitent Textile Composites: Formation and Permeability Analysis of Porous Media." Philadelphia College of Textiles & Science, 1997.

Puncture damage is one of the most common failure modes suffered in textile formations throughout their life periods. There are a number of strategies to improve the puncture performances of materials. Researchers have growing interest to shear thickening fluids (STF) due to their greatshear thickening property that has the potential to resist puncture. STF is a kind of non-Newtonian fluid in which the viscosity will increase with the increase of the shear rate.[24,25] The suspensions are like liquid when stirred weakly, but becomes very thick when stirred harder, and changes to thin once more when the stress is removed[26].Fumed silica nanoparticles mixed with polyethylene glycol is used for the formation of suspension.Formed STF is diluted using ethanol and impregnated into high modulus polypropylene (HMMP). Therefore, there has been considerable research centered on improving the puncture resistance of fabric with the help of addition of a non-newtonian fluid.

There are a significant number of researchers that are convinced that the structural response could be reduced appropriately by installing damper devices. However, the dampers that are used on buildings and bridges are generally designed only for the specific structural system under particular loading conditions.Due to this problem several researchers have developed the adjustable passive dampers in recent years. Electro rheological dampers (ER dampers) and magneto rheological dampers (MR dampers) are well known adjustable damper systems, but the strength and the stability of the outside power supply required for ER and MR dampers are flawed for the long term application during structure service life. Fang-Yao Yeh and Kuo-Chun Chang of Taipei, Taiwan R.O.C. developed a new material, shear thickening fluids (STF), which changes its properties according to different loading rate without external power needed are considered to be a good filled material for innovative damper devices[30].

Application of STF materials on a conventional viscous damper device by using a simplified piston device and changing the concentration of STF filled can develop an innovative viscous damper which behaves like the MR damper. The shear properties of STF samples under the steady state and the oscillatory state using rheometer and hysteretic loops of the STF damper developed under different loading conditions shows the smart STF damper have a good potential in practical engineering applications. [31] STF material of nanosize fumed silica particles suspended in a solvent can be used as damping elements to fill in the viscous damper device. Tests have also shown that the STF damper developed can lead simultaneously to changes in damping under dynamic loading with varied frequencies.

8. Applications:

Protective equipment made with D3O [20] has an outer surface made of thermoplastic polyurethane (TPU). TPU helps to spread the impact over the surface, and then D3O hardens and then absorbs the shock generated from the impact. The ability to absorb a large amount of energy during an impact without generation of critical damages represents an important feature of new generation composite systems [21]. The intrinsic layered nature of composite materials allows the embodiment of specific hybrid layers within the stacking sequence that can be used to increase impact resistance. It is based on the design of an impact-resistant hybrid composite obtained by injecting a thin layer of non-Newtonian silica-based fluid into a carbon fiber reinforced polymer laminates (CFRP) [22] or glass fiber reinforced polymer (GFRP).

Fabrics impregnated with shear thickening fluids are also used for stab resistance.Two fabrics: Ultra high molecular weight polyethylene and Kevlar are used for the application. When subjected to high-speed impact, the STF transforms from liquid to solid-like state and hence facilitating stab resistance performance of fabrics.

9. Conclusion

Non- newtonian fluids are those which changes its viscosity on application of sudden force making it harder or softer depending upon the stress applied. These fluids are of great importance in many areas of interest for example cricket pads, gloves, safety helmets, bullet vests , armours, shoes,etc. These are used in bullet proof vests as they provide more impact strength ,energy absorption and are lightweight as compared to present Kevlar vests. In sports, these are used to provide more comfortable gears to the players which are easy to handle. Overall they are more advantageous than the existing fluids in providing better strength and are more comfortable. In future these can be used in car bumpers to reduce the effect of collisions ,mobile covers,or inside layer of the shoes can be filled with a non-Newtonian fluid. During walking or running, when pressure acts on the shoe are weak, the non-Newtonian fluid would remain in a liquid state and the shoe interior would adapt to the position and shape of the foot. Non-newtonian fluid matrices can be of utter importance in Spacecrafts and military equipment also.

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