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RHEOLOGY OF FLUIDS IN TEXTILE COATING PROCESSES: A GENERALIZED APPROACH

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Abstract: *Surface coating and thin film formation processes are critical stages determining product performance across numerous industries, including coatings, textiles, electronics, and biomedicine. Although classical coating theories are generally established upon Newtonian fluids with constant viscosity, some of the modern industrial inks, polymeric solutions, and suspensions exhibit rheological behaviors that deviate from Newtonian characteristics. Particularly, many coating materials used in the textile sector fall into the category of non-Newtonian fluids. However, this theoretical foundation is not sufficiently taken into account in industrial textile coating processes. Applications in industrial production are generally carried out based solely on initial viscosity measurements and process conditions. The extent to which operating conditions change the rheological properties of the fluid throughout the process is also vital for coating processes. This study reviews the effects of non-Newtonian fluids on the coating processes of textile substrates through rheological models and application cases. Within the scope of the study, the effects of parameters such as shear rate, temperature and pressure on viscosity were initially analyzed, and the viscosity variation of non-Newtonian fluids is modeled on the basis of the Power Law model. Research indicates that static viscosity values alone are insufficient for optimizing coating quality; instead, the rheological responses at application-specific shear rates must be accurately modeled. In this context, this study moves beyond traditional 'initial viscosity' measurements, presenting a roadmap for a rheological modeling-based optimization approach.*

Key words: *textile, coating, rheology, non-newtonian fluids, shear rate.*

1. INTRODUCTION

Surface coating and thin film formation constitute dynamic processes that determine the final properties of a material. Therefore, a detailed investigation of the rheological models of the fluids used in these applications is of great importance. A wide range of fluids with distinct rheological behaviors are utilized in textile coating applications. Over the past years, research on shear-thickening fluid (STF) coated textiles has progressed from early studies on Kevlar-based fabrics for ballistic protection to advanced applications in woven structures. The initial phase established STF's role in high-energy impact absorption, lateral researches emphasized spacer fabrics, composites, and simulation-based modeling. The latest studies focused on multifunctional protective textiles, integrating artificial intelligence-driven performance prediction. This evolution highlights the transition of STF textile research from defense-oriented applications to broader industrial and high-performance protective innovations The success of these processes is directly related to the science of rheology, which examines the deformation and flow characteristics of the employed fluid. In addition to STFs, various types of non-Newtonian fluids are also utilized in textile coatings. A thorough analysis of the rheological behaviors of these fluid types is essential for the standardization of high-quality products in industrial-scale production.

During coating operations, the fluid is subjected to varying mechanical stresses at different stages such as pumping, spreading, leveling, and drying. Therefore, defining the relationships among the fundamental characteristics of the fluid—namely shear rate (γ), shear stress (τ), and viscosity (μ), which is a measure of resistance to flow—is of critical importance.

2. RHEOLOGICAL BEHAVIOR AND CLASSIFICATION

Fluids are generally classified into two primary categories, Newtonian and non-Newtonian, based on their response to applied shear stress. In Newtonian fluids, the viscosity remains constant, being independent of the shear rate.The schematic representation of a Newtonian fluid in laminar flow between two layers separated by a distance dy is illustrated in Fig. 1. Under steady-state conditions, when a shear stress is applied to the fluid by a force F, it is balanced by an equal and opposite internal frictional force within the fluid. The shear stress ($\frac{F}{A}$, τ_{yx}) is defined as the product of the shear rate ($-\frac{\mathrm{dV}_x}{\mathrm{dy}}$, γ_{yx}) and the viscosity of the fluid medium (μ). For Newtonian fluids, this relationship is mathematically expressed in Equation 1 [1].

$$\frac{F}{A} = \tau_{yx} = \mu\left(-\frac{\mathrm{dV}_x}{\mathrm{dy}}\right) = \mu\gamma_{yx} \qquad (1)$$

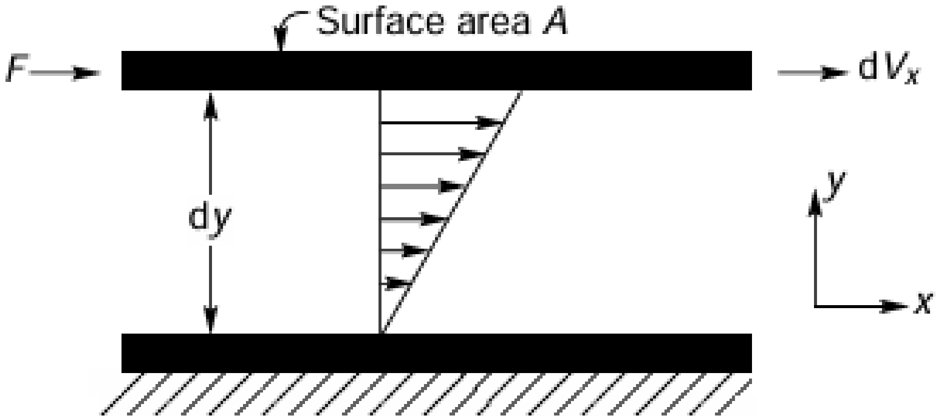

Fig. 1*: Schematic representation of unidirectional shearing flow*

However, the majority of modern coating formulations exhibit non-Newtonian behavior, giving rise to a more complex rheological response.

2.1. Dynamic Parameters Influencing Viscosity

In coating processes, viscosity is not solely governed by shear rate; surrounding environment and time-dependent effects also play a critical role in defining the flow regime:

- **Temperature Effects:** An increase in temperature reduces intermolecular interaction forces, resulting in a decrease in viscosity. This temperature–viscosity relationship is commonly described by the Arrhenius model. Precise temperature control during coating operations is therefore essential for accurate regulation of film thickness and uniformity.
- **Pressure:** Although frequently neglected, pressure effects become significant in high-pressure spraying and extrusion coating processes. Elevated pressure can reduce the available free volume within the fluid, leading to an increase in viscosity.
- **Shear Duration (Time-Dependent Flow Behavior):** Certain fluids exhibit time-dependent viscosity variations even under constant shear conditions. Thixotropy refers to a progressive decrease in viscosity over time due to microstructural breakdown, whereas rheopexy describes a time-dependent increase in viscosity resulting from structure buildup. Following coating application, the thixotropic recovery rate is a critical parameter governing the material's ability to rebuild its internal structure and remain adhered to the surface without flowing or sagging [2].

2.2.Non-Newtonian fluid behaviour

The viscosity of non-Newtonian fluids varies depending on the magnitude or the duration of the external force applied to the fluid. In contrast to Newtonian fluids, the relationship between shear rate and shear stress is non-linear; thus, these materials do not adhere to the linear Newtonian Law of Viscosity. The viscosity of such fluids may exhibit variations that are either time-independent or time-dependent in nature [1].

2.2.1. Time-independent fluid behaviour

Time-independent fluids are characterized by the fact that the shear rate at any given point is determined solely by the shear stress at that point. These fluids can be classified into three categories: shear-thinning (pseudoplastic) fluids, viscoplastic fluids, and shear-thickening (dilatant) fluids.

In shear-thinning (pseudoplastic) fluids, viscosity decreases with increasing shear rate. However, this behavior may vary at extreme shear rates. Many shear-thinning polymer solutions exhibit Newtonian behavior at both very low and very high shear rates.

In the case of viscoplastic fluid behavior, materials possess a certain yield stress that must be exceeded for flow to commence. As long as the applied stress remains below this threshold, the material does not exhibit fluid-like behavior and instead behaves as a solid body. Once the required yield stress is exceeded, materials that display a linear flow curve are referred to as Bingham plastics and are characterized by a constant plastic viscosity. In contrast, materials that do not exhibit a linear flow relationship beyond the yield point are classified as yield-pseudoplastic materials.

In shear-thickening or dilatant fluid behavior, viscosity increases with increasing shear rate. Although less commonly encountered than other fluid types, concentrated suspensions of kaolin [3], metal oxide [4], and cornstarch [5] in water can be given as examples of this category.

The flow curves of fluids exhibiting time-independent behavior are presented in Fig. 2 [1].

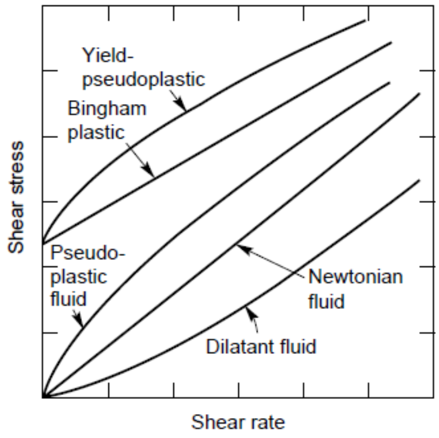

***Fig. 2**: Time-independent Fluids*

2.2.2 Time-dependent fluid behaviour

The flow behavior of many fluids used in industry cannot be described solely on the basis of shear rate. In materials exhibiting time-dependent flow behavior, viscosity varies as a function of the duration for which the fluid is subjected to a constant shear. As discussed among the dynamic parameters influencing viscosity, the decrease in viscosity with increasing duration of shear exposure is referred to as thixotropy, whereas an increase in viscosity over time is defined as rheopexy [1].

3. MATHEMATICAL MODELS OF VISCOSITY IN NON-NEWTONIAN FLUIDS

In non-Newtonian fluids, viscosity is not constant and varies as a function of shear rate, shear stress, and, in some cases, time. To describe this complex behavior, several mathematical models have been developed. These models aim to capture the relationship between shear stress (τ) and shear rate (γ) under different flow conditions.

One of the most widely used models is the **Power-Law (Ostwald–de Waele) model**, which expresses the shear stress–shear rate relationship in Equation (2).

$$\tau = K\gamma^n \tag{2}$$

Here, n is referred to as the power-law index (or flow behavior index), while K denotes the consistency index. For shear-thinning fluids, n < 1, whereas for shear-thickening fluids, n > 1 [6].

4. FORCE BALANCE IN FLUID COATING PROCESSES

The fluid coating process is essentially a fluid in motion. The net force acting upon a given volume is defined by the rate of change of momentum of the fluid surrounding it at any instantaneous moment (specifically, the sum of the momentum flux integrated over the entire control surface and the rate of change of momentum within the volume).

The net force F_x acting in the x-direction on a fluid element moving with the velocity of the fluid is the sum of the force due to the weight of the volume element (body force) F_{xB} and the force resulting from the stresses acting upon it along the x-axis, F_{xS}, as shown in Equation 3. The same expression is defined for a differential mass element as in Equation 4. Here, u_x denotes the velocity of the fluid element in the x-direction; ρ is the density of the fluid element; g is the acceleration due to gravity; β is the angle the fluid element makes with the x-axis; t represents time; and τ_{xx}, τ_{yx}, τ_{zx} define the stress components acting in the x-direction [6].

$$F_x = F_{xB} + F_{xS} \tag{3}$$

$$\rho \frac{du_x}{dt} = g\cos\beta + \left(\frac{\partial\tau_{xx}}{\partial x} + \frac{\partial\tau_{yx}}{\partial y} + \frac{\partial\tau_{zx}}{\partial z}\right) \tag{4}$$

Determination of Coating Thickness

Coating thickness varies depending on the application method, viscosity, applied force, the gap distance between the substrate and the applicator, density, and velocity. Taking blade coating as a representative example, the coating thickness (W) is calculated as shown in Equation 5. Here, h defines the height between the blade and the surface, η represents the fluid viscosity, σ denotes the surface tension of the fluid, ρ signifies the fluid density, g is the acceleration due to gravity, and u_0 defines the coating velocity.

$$W = \frac{h}{2} + \frac{1}{12\eta}\left(\frac{\sigma}{2h^2} + \rho g\right)\frac{h^3}{u_0} \tag{5}$$

In blade coating, the coating thickness is fundamentally equivalent to half of the blade gap; however, an additional minor term is incorporated, which is directly proportional to the surface tension and the gap width, while remaining inversely proportional to the fluid viscosity and the line speed [6].

5. COATING METHODS ACCORDING TO FLUID PROPERTIES

The application of fluids onto textile surfaces can impart a wide range of functional properties to the material. These properties vary depending on the type of fluid applied, including coloration, water repellency, flame retardancy, and antibacterial activity.

Various methods can be employed to coat textile surfaces with different fluids, such as knife coating, roller coating, dip coating, and spray coating. [6].

5.1. Newtonian Fluids and Textile Coating

In Newtonian fluids, viscosity is independent of the shear rate. More clearly, the fluid viscosity remains constant throughout the process. It is not affected by the application speed. In the textile industry, these are generally encountered in low-viscosity solutions, dyes, and simple polymeric finishes. Application is generally performed using well known dip coating method at foulards, as illustrated in Figure 3.

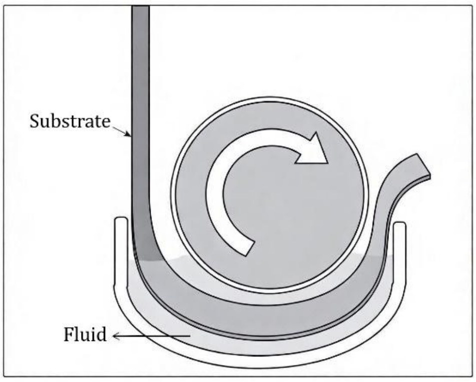

Fig. 3: *Application example of dip coating*

5.2. Shear-Thinning Non-Newtonian Fluids and Textile Coating

In the textile industry, coatings applied using shear-thinning fluids include those based on polyurethane [7], PVC [8], acrylate [9] and polyacrylamide systems [10].These coatings can be applied through various coating techniques. Due to the reduction in viscosity with increasing application rate, such fluids can more readily penetrate into the fabric structure.

Although numerous coating applications utilizing shear-thinning fluids are present in the literature, very few studies specifically address their rheological behaviors. For instance, in their study, Karim et al. (2021) examined the utilization of shear-thinning, non-Newtonian xanthan gum solutions alongside Newtonian polyethylene glycol (PEG) solutions in curtain coating processes, systematically assessing the resultant coating performance. For the assessment of coating performance, the contact line, air entrainment, air bubble formation, and heel (buildup) formation were taken into consideration.

While heel formation at low speeds and air entrainment at high speeds were observed in Newtonian liquids, air entrainment was significantly delayed in non-Newtonian liquids. Heel formation initiated at lower speeds as the concentration increased (as viscosity rose). The maximum operable flow rate increased with viscosity. Shear-thinning prevented air entrainment by reducing viscous bending near the contact line [11].

5.3. Shear-Thickening Non-Newtonian Fluids and Textile Coating

The development of shear-thickening fluid (STF) coated textiles has followed a distinct trajectory over the past two decades, reflecting both technological advancements and evolving application demands. In the early phase (2000–2015), research was primarily directed toward Kevlar-based fabrics and ballistic protection, establishing STF impregnation as a viable strategy for enhancing energy absorption and mitigating high-energy impacts. This foundational work laid the groundwork for subsequent investigations into the protective potential of STF-treated textiles. During the middle phase (2016–2020), the scope of research expanded to include spacer fabrics and composite structures, with particular emphasis on numerical simulation and performance modeling. These studies provided deeper insights into the mechanisms of impact resistance and structural stability, thereby broadening the scientific understanding of STF–textile interactions. In the most recent phase (2021–2026), attention has shifted toward advanced applications in woven fabrics, integrating artificial intelligence-driven performance prediction and multifunctional protective capabilities. This progression underscores the maturation of STF textile research, transitioning from defense-oriented ballistic studies to versatile industrial and protective fabric innovations that combine mechanical robustness with adaptive functionality.

Shear-thickening fluids (STFs) represent advanced colloidal suspensions that enable the transition of textiles from passive protective materials to dynamic, impact-responsive systems, owing to their intrinsic capacity to absorb and dissipate mechanical energy. An STF system generally consists of two main phases:

- **Solid Phase (Dispersed Particles):** Silica nanoparticles constitute the predominant solid-phase component in shear-thickening fluid formulations. Additionally, calcium carbonate, corn starch, or polymer spheres (PMMA) can be utilised. Particle size (generally between 100 nm and 500 nm) and concentration determine the degree of fluid hardening.
- **Liquid Phase (Carrier Medium):** The liquid phase serves as the dispersing medium for suspended particles. Polyethylene glycol (PEG) is most commonly employed in textile and defense-related applications due to its non-volatile nature, thermal stability, and favorable physicochemical interactions with silica nanoparticles.

Numerous studies in the literature focus on the coating of textile products for defense applications. Egres et al. (2005) investigated the resistance of shear-thickening fluids (STF) composed of silica nanoparticles and polyethylene glycol (PEG) specifically against cutting tools. Aramid fabric was utilized as the substrate in their study. The STF materials were applied to the fabric through a dip-coating and soaking process, followed by drying. The shear rate of the fluids was kept constant at 20 s^{-1}. Upon completion of the application, the amount of STF on the fabric increased the fabric weight by 20%. The results of the study indicated an improvement in cut resistance across all fabric samples [12].

In a study conducted by Yanen et al. (2024), STFs were prepared by dispersing materials such as silica, silicon carbide, carbon nanotubes, and graphene in PEG, which were then applied to Twaron fabric using the dip-coating method. Subsequently, ballistic tests were performed on the fabrics. Fabrics coated with a 5% weight addition exhibited superior performance compared to untreated fabrics [13].

6. DISCUSSION AND CONCLUSION

There are many processes in the textile industry, such as finishing, functional treatment, dyeing, printing, and coating, where materials are exposed to and treated with a fluid. Particularly in traditional textile coating processes, essential information regarding the coating material is limited with fluid’s viscosity, and it is usually assumed that viscosity remains constant. Many fluids used in coating processes are non-Newtonian, and their viscosity generally changes during the procedure.

Wheras in shear-thinning processes—where viscosity decreases with movement—process conditions should be evaluated individually, and standards should be established accordingly for different operating conditions. Studies on STFs show that application on fabrics is generally performed using the dip-coating method. Although the increase in viscosity in moving systems brings application challenges, studies should be conducted to determine optimum application speeds to enhance the applicability and effects of these materials.

Research on STF-coated textiles is expected to advance toward multifunctional protective systems that combine mechanical robustness with adaptive responsiveness. Emerging directions of STF coated textile products include the integration of nanostructured fillers to optimize rheological behavior, the use of artificial intelligence for predictive modeling of coating performance, and the development of hybrid textile architectures that enhance flexibility without compromising protection. Furthermore, future studies are expected to address long-term durability, scalability and the environmental sustainability of STF formulations. Transition from laboratory-scale innovations to widespread industrial applications is another rising expectations to built such novel product platforms of medical protective gear, sports equipment, and aerospace textiles.

In this context, for coating applications, not only the initial viscosity but also the complete rheological behavior of fluids must be analyzed according to variable operating parameters such as temperature, shear rate, and time. These evaluations, based on rheological modeling, are a necessity for achieving industrial consistency and standardization.

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