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Non-Newtonian Fluids: Classification, Characteristics, and Applications — A Review

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Abstract:

Non-Newtonian fluids are amazing characteristics that do not act like water and any other normal liquids. They are not continuous, and may bizarrely depend on the level of force applied to them. This review describes the various kinds of these exceptional fluids. There are shear-thinning fluids like ketchup, that get thinner with stirring. Next, they are shear-thickening fluids where you make it more thick (almost solid) through agitation; cornstarch and water slurry kind of thing. Then we go much deeper into viscoelastic fluids, where the fluid possesses some solid-like qualities and also thixotropic or rheopectic fluids, which thin out after being stirred for a long time to subsequently regain viscosity over time or vice versa, respectively. This type of general knowledge can help with how the fluids behave is essential to many industries, including developing new food and medicine as well as new materials. By analyzing their unique characteristics and the way they flow, scientists and engineers are able to create improved products as well as enhance our overall understanding of these remarkable materials.

Keywords. Non-Newtonian fluids; Second grade fluid; Third grade fluid; Fourth grade fluid.

Graphical Abstract.

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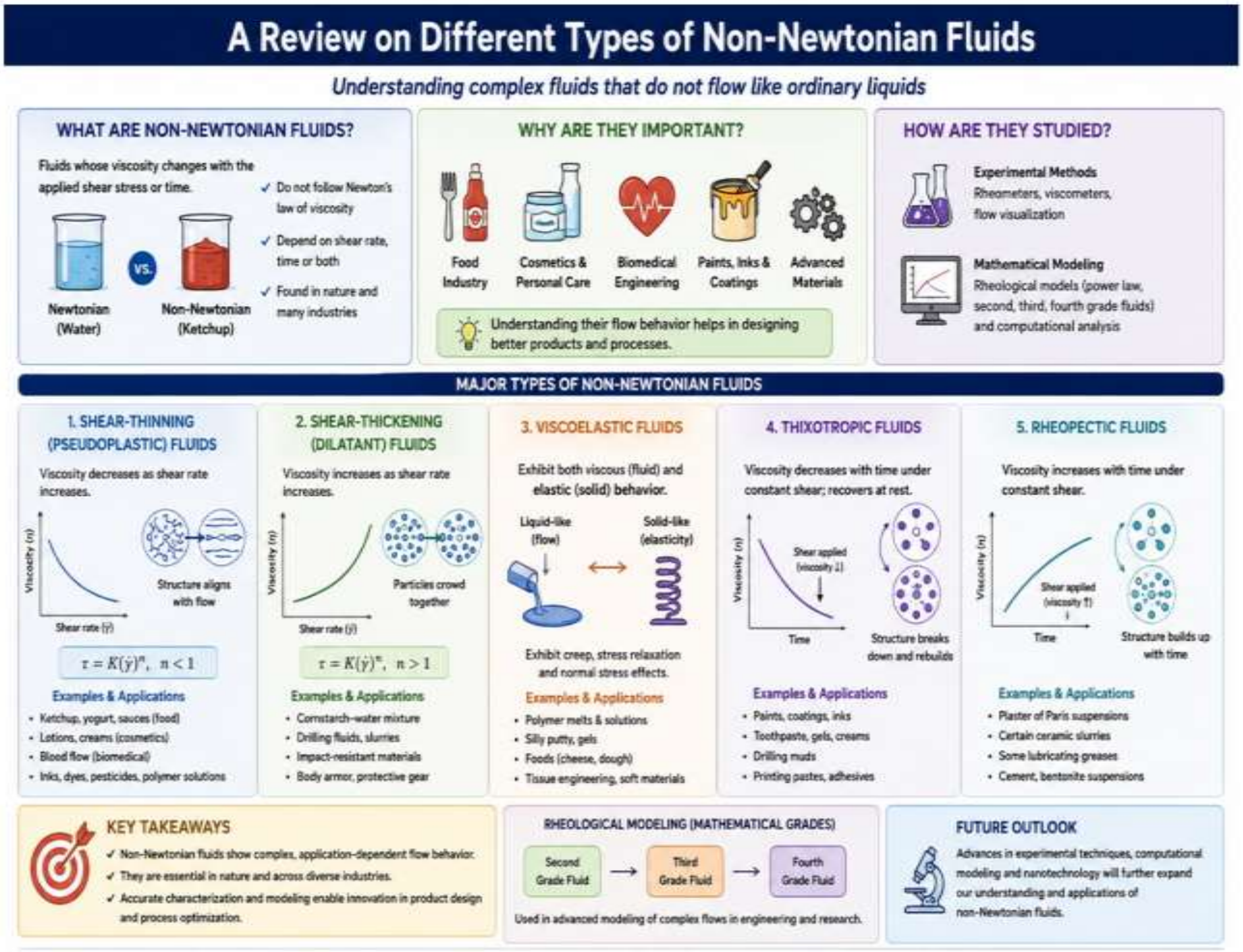

A Review on Different Types of Non-Newtonian Fluids

Understanding complex fluids that do not flow like ordinary liquids

WHAT ARE NON-NEWTONIAN FLUIDS?

Fluids whose viscosity changes with the applied shear stress or time.

- ✓ Do not follow Newton's law of viscosity
- ✓ Depend on shear rate, time or both
- ✓ Found in nature and many industries

WHY ARE THEY IMPORTANT?

Understanding their flow behavior helps in designing better products and processes.

HOW ARE THEY STUDIED?

Experimental Methods
Rheometers, viscometers, flow visualization

Mathematical Modeling
Rheological models (power law, second, third, fourth grade fluids) and computational analysis

MAJOR TYPES OF NON-NEWTONIAN FLUIDS

1. SHEAR-THINNING (PSEUDOPLASTIC) FLUIDS

Viscosity decreases as shear rate increases.

$\tau = K(\dot{\gamma})^n, \ n < 1$

Examples & Applications
- Ketchup, yogurt, sauces (food)
- Lotions, creams (cosmetics)
- Blood flow (biomedical)
- Inks, dyes, pesticides, polymer solutions

2. SHEAR-THICKENING (DILATANT) FLUIDS

Viscosity increases as shear rate increases.

$\tau = K(\dot{\gamma})^n, \ n > 1$

Examples & Applications
- Cornstarch-water mixture
- Drilling fluids, slurries
- Impact-resistant materials
- Body armor, protective gear

3. VISCOELASTIC FLUIDS

Exhibit both viscous (fluid) and **elastic (solid) behavior.**

Exhibit creep, stress relaxation and normal stress effects.

Examples & Applications
- Polymer melts & solutions
- Silly putty, gels
- Foods (cheese, dough)
- Tissue engineering, soft materials

4. THIXOTROPIC FLUIDS

Viscosity decreases with time under constant shear; recovers at rest.

Examples & Applications
- Paints, coatings, inks
- Toothpaste, gels, creams
- Drilling muds
- Printing pastes, adhesives

5. RHEOPECTIC FLUIDS

Viscosity increases with time under constant shear.

Examples & Applications
- Plaster of Paris suspensions
- Certain ceramic slurries
- Some lubricating greases
- Cement, bentonite suspensions

KEY TAKEAWAYS

- ✓ Non-Newtonian fluids show complex, application-dependent flow behavior.
- ✓ They are essential in nature and across diverse industries.
- ✓ Accurate characterization and modeling enable innovation in product design and process optimization.

RHEOLOGICAL MODELING (MATHEMATICAL GRADES)

Second Grade Fluid → Third Grade Fluid → Fourth Grade Fluid

Used in advanced modeling of complex flows in engineering and research.

FUTURE OUTLOOK

Advances in experimental techniques, computational modeling and nanotechnology will further expand our understanding and applications of non-Newtonian fluids.

1. Introduction

Now consider liquids that do not flow as easily as water. Such fluids are known as non-Newtonian and they have some really interesting properties. So, you might say that they do not have the "simple" behavior of normal fluids. They flow, based on how much force you put behind them and for how long. This paper delves into the myths surrounding some of these strange fluids. You are familiar with types, such as those that thin when you stir them and those that thicken under pressure. We will also talk about how these fluids can be studied experimentally and mathematically. Special, that help interpreting these complex fluids which are very useful in many fields from engineering to the products we use daily. And so, it's time to discuss the aspects about these captivating compounds.

In recent decades a lot of research has been done in this regard. Mohanty et al. [1] described characteristics of Heat Transfer in a Reactive Third-Grade Fluid Flow through Porous Plates with Uniform Suction/Injection. Reza-E-Rabbi [2] provided discussion about non-linear radiative second-grade nano fluid with sinusoidal magnetic force and arrhenius activation energy. Gowtham et al. [3] analyzed Third-Grade fluid flow in an inclined Microchannel utilizing the Hermite wavelet technique for second law analysis. Gbadeyan et al. [4] discussed dynamic behaviour of fluid-transporting axially functionally graded non-uniform Rayleigh pipes lying on variable two-parameter elastic foundation. Jiao et al. [5] provided notion about Free vibration analysis of fluid-conveying functionally graded metamaterial subsea cylindrical shells. Shah et al. [6] studied Gyrotactic microorganism's and heat transfer analysis of water conveying MHD SWCNT nanoparticles using fourth-grade fluid model over Riga plate. Mahesh and Panda [7] analyzed Longwave modeling of thin film flow of a generalized second-grade fluid down a slanted plate. Motallebi et al. [8] provided size-dependent flutter analysis of a nanobeam made of metal-ceramic functionally graded materials subjected to supersonic fluid flow. Swain [9] discussed dual solutions and linear temporal stability analysis of mixed convection flow of non-Newtonian special third grade fluid with thermal radiation. Joseph [10] studied different families of new exact solutions for planar and nonplanar second grade fluid flows.

2. Classification of Non-Newtonian Fluids

Non-Newtonian fluids can be classified based on their flow characteristics and response to shear forces. The major categories include:

2.1 Shear-Thinning (Pseudoplastic) Fluids

Shear-thinning fluids experience a decrease in viscosity as the shear rate increases. This behavior is prevalent in polymers, paints, and blood.

$$\tau = K(\gamma^{\cdot})^{\mathrm{n}} \tag{1}$$

where τ is the shear stress, $\gamma^{\cdot}$ is the shear rate, K is the flow consistency index, and $n < 1$ for shear-thinning fluids.

Applications:

- **Food Industry (ketchup, yogurt):** In the food industry, shear-thinning fluids are essential for products like ketchup and yogurt. These products need to be thick and stable when at rest but flow easily when squeezed or stirred. This property enhances the ease of use and improves product texture and consistency.
- **Cosmetics (lotions, creams):** Many cosmetic products, such as lotions and creams, exhibit shear-thinning properties. This ensures the products spread smoothly on the skin without being overly runny or sticky. The consistency of these products at rest prevents leakage and helps in even application.

- **Biomedical (blood flow modeling):** Blood is a natural shear-thinning fluid. Understanding and modeling its behavior is crucial in biomedical applications, including the design of artificial organs, medical devices, and blood flow simulation in the circulatory system.
- **Ink and Dye Production:** In the printing and dyeing industry, shear-thinning properties ensure that inks and dyes flow efficiently through nozzles and rollers without excessive dripping or splattering. This enhances print quality and reduces material waste.
- **Pesticides and Fertilizers:** Shear-thinning fluids are commonly used in agricultural formulations, such as pesticides and fertilizers. These products must remain thick during storage but flow easily during spraying or application, ensuring uniform distribution and minimizing runoff.

2.2 Shear-Thickening (Dilatant) Fluids

In contrast to shear-thinning fluids, shear-thickening fluids exhibit an increase in viscosity with an increase in shear rate. This behavior can be modeled by the same power-law relation, with $n > 1$ for dilatant fluids.

Applications:

Protective Gear (bulletproof vests): Shear-thickening fluids are utilized in advanced protective gear, including bulletproof vests and body armor. When subjected to sudden high-impact forces, the viscosity of these fluids increases, providing enhanced resistance to penetration and shock absorption. This unique property enables lightweight and flexible protective equipment that hardens upon impact.

Industrial Slurries: In industrial applications, shear-thickening fluids are used in slurries that transport abrasive materials. The increase in viscosity under shear prevents excessive wear and tear on pipelines and equipment by reducing fluidity during high-speed transport, enhancing durability and efficiency.

Cornstarch-Water Mixtures: A common example of shear-thickening behavior is the cornstarch-water mixture (often called oobleck). This mixture flows like a liquid under slow movement but solidifies under rapid force. Such materials are studied for recreational, educational, and scientific applications to understand non-Newtonian behaviors.

High-Performance Concrete: Shear-thickening behavior is leveraged in the development of high-performance concrete, which requires controlled flow during mixing and application but hardens under stress. This property improves the material's mechanical performance and resistance to cracking, enhancing the longevity and strength of structures.

Sports Equipment: Shear-thickening fluids are integrated into sports equipment such as padding and footwear. When exposed to sudden impacts or stress, these materials stiffen, providing better protection and energy absorption. This technology improves the safety and performance of athletic gear.

2.3 Viscoelastic Fluids

Viscoelastic fluids display both viscous and elastic properties. They can store energy like elastic solids and dissipate energy like viscous fluids. Their behavior is characterized by models such as the Maxwell and Kelvin-Voigt models. These fluids often show stress relaxation and creep behavior, crucial for understanding their complex dynamics.

Applications:

Polymer Solutions: Viscoelastic polymer solutions are used in the production of various industrial products such as coatings, lubricants, and adhesives. Their ability to stretch and return to their original shape under stress makes them ideal for flexible materials.

Biological Tissues: Many biological tissues, including muscles and tendons, exhibit viscoelastic properties. This behavior is crucial for their function, allowing them to absorb shock and return to their original form, contributing to movement and flexibility.

Adhesives and Sealants: Viscoelastic fluids are essential in adhesives and sealants, providing both flexibility and strength. These materials can deform under stress but recover when the stress is removed, ensuring long-lasting bonds.

Foams and Emulsions: In the production of foams and emulsions, viscoelastic fluids provide stability and improve texture. This property enhances the durability of foams used in packaging and insulation.

Automotive Lubricants: Viscoelastic properties in automotive lubricants help reduce wear and tear by providing a cushioning effect between moving parts, enhancing engine performance and longevity.

2.4 Thixotropic Fluids

Thixotropic fluids reduce in viscosity over time under constant shear. This time-dependent behavior is reversible when the shear is removed. Thixotropy is beneficial in materials requiring controlled spreading or application under mechanical action.

Applications:

Paints and Coatings: Thixotropic behavior in paints and coatings ensures easy application and prevents dripping or sagging. When stirred or brushed, the viscosity decreases, allowing smooth and even spreading, while it thickens when left at rest, providing a stable finish.

Drilling Muds: In the oil and gas industry, drilling muds exhibit thixotropic properties that help in stabilizing boreholes. The fluid's viscosity decreases during drilling, allowing easy flow, but increases when drilling stops, preventing the collapse of bore walls.

Printing Inks: Thixotropic inks are used in screen printing and other applications where viscosity must decrease during application but quickly recover to avoid smudging or running. This ensures sharp and clear prints.

Mayonnaise and Sauces: In the food industry, mayonnaise and sauces utilize thixotropic behavior to remain thick and stable during storage while flowing easily when stirred or spread. This improves the texture and user experience.

Gel-Based Pharmaceuticals: Pharmaceutical gels display thixotropic properties, ensuring they remain firm in containers but spread smoothly on application. This enhances patient comfort and dosage accuracy.

2.5 Rheopectic Fluids

Rheopectic fluids are the opposite of thixotropic fluids, increasing in viscosity over time under constant shear. This behavior is less common but critical in specific industrial processes requiring viscosity build-up over time.

Applications:

Gypsum Suspensions: In construction and building materials, gypsum suspensions display rheopectic properties that allow them to flow during mixing but gradually thicken, aiding in forming stable structures once applied.

Lubricants: Rheopectic lubricants are used in machinery where gradual thickening under shear helps in enhancing load-bearing capacity and reducing wear over time.

Cementitious Materials: Cement slurries used in construction benefit from rheopectic behavior, as their viscosity increases over time during application, ensuring greater stability and strength in final structures.

Suspensions in Chemical Processing: In chemical processing, rheopectic fluids stabilize suspensions, preventing sedimentation and ensuring uniform distribution of materials during prolonged operations.

2.6 Second grade Fluid

In this paper we study one of the most important non-Newtonian fluid classifications at the elementary-grade levels, namely second-grade fluids of the differential type (these are often referred to as second-grade fluids). These are fluids that are not Newtonian, meaning stress is not a function of the rate of strain (as it is for Newtonian fluids, such as water and most gases, where stress is proportional to the rate of strain - this is captured by the first Rivlin–Ericksen tensor). In addition to the first Rivlin–Ericksen tensor, second-grade fluids include higher-order kinematic variables which account for elastic and memory effects of the fluid. The resulting constitutive equation is solvable and predicts normal stress differences and viscoelastic effects, described by the Navier–Stokes equation.

The mathematical model of a second-grade fluid is generally expressed as:

$$\mathbf{T} = -p\mathbf{I} + \mu\mathbf{A}_1 + \alpha_1\mathbf{A}_2 + \alpha_2\mathbf{A}_1^2 \tag{2}$$

where $\mathbf{T}$ denotes the Cauchy stress tensor, p represents pressure, μ is the dynamic viscosity, and α_1, α_2 are material moduli associated with elastic effects. The inclusion of these additional terms makes the governing equations highly nonlinear and more suitable for describing real fluids with complex rheological properties.

Second-grade fluids are equivalent to both viscous and elastic media and therefore suitable for a wide variety of fluid dynamics and rheology problems. Second-grade fluids model a wide variety of physical situations of interest in engineering, including polymer processing, lubrication, pipeline flow of petroleum products, coating, blood flow, and food processing. Such fluids exhibit effects not present in Newtonian fluids such as the rod climbing phenomenon and die swell observed when flowing through a contrite die. In fluid mechanics a wide variety of interesting problems can be solved using the second-grade fluid model. These include boundary-layer flow, heat/mass transfer, MHD flow, flow through porous media, and stretching sheet problems. The second-grade fluid model is advantageous over more complex models for viscoelastic fluids because it yields analytical and/or easily solvable solutions which include nearly all of the characteristics of non-Newtonian fluids. Second-grade fluid models also include many classes of physical fluids of interest to engineers. The second–grade fluid is a well-known model in rheology and computational fluid dynamics. Although it is not realistic enough to be state–of–the–art, it is physically realistic yet mathematically tractable, which is why it continues to be of considerable significance.

Applications:

Second-grade fluids are applied in many practical problems in applications where highly viscous liquids are moved slowly (e.g. pasty food products, oils, polymers, lubricants). They model second-degree fluids, i.e. highly viscous fluids. This class of fluids is non-Newtonian and may also show viscous-elastic properties. In contrast to purely viscous fluids, they are also capable of storing stress over time and releasing it afterwards. This property is also often referred to as "memory" and is the reason for the term "membrane fluids". The second-grade fluid model is very frequently used in the polymer industry to calculate the flow of plastic masses (plasticizers, resins, adhesives, synthetic fibers) during plastic molding. Especially in plastic molding processes using the method of extrusion molding and coating processes, this model shows its benefits. In lubrication engineering, special importance is attached to the higher shear rate range. This is why the second-grade fluid model is particularly suited for calculating lubricant behavior. In petroleum engineering, second-grade fluids are used to calculate the flow of crude oil and drilling fluids through permeable rocks (porous media) and through pipelines. Second-grade fluid models or models of fluid fluids are currently widely used in biomechanics and biomedical engineering to model blood flow and other naturally occurring fluids in arteries, capillaries and other blood vessels including elastic effects. In food processing and related industries, second-grade fluid models are used to model a wide variety of non-Newtonian foods such as ketchup, syrups, honey and dairy products. At the second-grade level, models of fluid fluids that include both the velocity of the fluid and its rate of change as necessary variables are employed.

The study of second-grade fluids has gained significant attention in applied mathematics and computational fluid dynamics. Many fluid dynamics problems have been studied in this class of fluids such as boundary layers, stretching or shrinking sheets, rotating, magnetohydrodynamics, mixed convection of heat and mass transfer and heat transfer over various surfaces including solar collectors, nuclear reactors, chemical, geophysics and environmental applications. In the field of engineering, problems such as flow of viscoelastic fluid past moving surface, over rotating or oscillating disks and pumping of mud and ground water through porous media are modeled using second-grade fluid. The model is also used for lava flow model. These fluids are less complex than general highly non-Newtonian, viscoelastic fluids, but are sufficiently simple for most practical purposes. Consequently, they represent a simple yet powerful model for theoretical development, numerical solution, and experimental verification in rheology and fluid dynamics for second-grade fluids involving second- and zero-order time derivatives. The research relevant to second-grade fluids involves students at the second-grade of undergraduate studies and is carried out by academician and practitioners at various levels of studies.

2.7 Third grade fluid

Advanced non-Newtonian fluid models for describing highly non-linear viscoelastic behaviour of complex fluids are called third-grade fluids. In contrast to Newtonian and second-grade fluids, third-grade fluids include third-order terms in the constitutive equation. This class of fluids can describe more complex rheological behaviour such as shear-thinning or shear-thickening, strain hardening, and other non-linear normal stress differences. In contrast to second-grade fluids, the resulting constitutive relations of third-grade fluids include higher-order Rivlin-Ericksen tensors and non-linear products of these tensors. This article presents third-grade fluids - named in reference to third-grade students - by discussing some basic aspects of these fluids and first results on free damping for spherical drops.

A general constitutive equation for a third-grade fluid is given by:

$$\mathbf{T} = -p\mathbf{I} + \mu\mathbf{A}_1 + \alpha_1\mathbf{A}_2 + \alpha_2\mathbf{A}_1^2 + \beta_1\mathbf{A}_3 + \beta_2(\mathbf{A}_1\mathbf{A}_2 + \mathbf{A}_2\mathbf{A}_1) + \beta_3(\mathrm{tr}\mathbf{A}_1^2)\mathbf{A}_1 \tag{3}$$

where the coefficients β_1, β_2, and β_3 characterize higher-order nonlinear material responses. These additional nonlinear contributions make the model highly suitable for describing fluids with complex deformation histories and strong elastic properties.

Third-grade fluids have physical significance as models for several real fluids which exhibit large non-Newtonian effects. These include polymer melts, lubricating greases, non-Newtonian paints, some biological media (e.g., synovial joint fluid), and other highly viscous manufacturing materials. Third-grade fluids are of interest in heat and mass transfer, boundary layer flows, peristaltic flows, MHD third-grade fluid, and chemically reactive third-grade fluid. When the nonlinear effects of stress are significant, third-grade fluids give more accurate predictions than second-grade fluids, which in turn give more accurate predictions than Newtonian fluids. Solutions of third-grade fluid models are significantly more complex than those of second-grade fluid models.

Various solution methods have been used to determine these more complex solutions, including both analytical and semi-analytical and numerical methods. In literature, for solving and approximating many mathematical models, numerous numerical methods such as perturbation methods, homotopy analysis method, Adomian decomposition method, finite difference methods, spectral methods, and some neural-network-based methods etc have been developed and implemented. Third-grade fluid models have numerous real applications in the modern physics and engineering such as polymeric fluids, non-Newtonian liquids and pastes, biological media etc, and they have remained as an important area of research in modern fluid dynamics and continuum mechanics with the capability to simulate more realistic rheological behaviors.

Applications:

Third-grade fluids or polymeric fluids of differential type are significant for modern engineering, industrial and applied sciences since they can precisely describe the highly non-linear viscoelastic behavior of some complex liquids. These models can exactly describe the elastic effects, shear-thinning or -thickening and the non-linear stress–strain relationship of certain complex liquids and therefore cannot be described by Newtonian fluid or second-grade fluid. Third-grade fluid models have found many practical applications in polymer and plastic manufacturing and processing industries, elastic and non-Newtonian lubrication, petroleum industry, bio- and medical engineering, etc., since molten polymers, rubber compounds, adhesives, and other synthetic products, high performance lubricants and greases and heavy crude oils, drilling muds and other complex hydrocarbons, blood and other biological fluids are subjected to large deformation and non-linear rheological behaviors in these fields.

Heavy crude oils are very dilute solutions of asphaltene molecules dispersed in an aromatic oil solvent. They exhibit non-Newtonian flow behavior, especially at high shear rates. Drilling muds are colloidal mixtures of water, clay particles, and other additives. They are used in oil wells to carry cuttings to the surface. The transport of these complex fluids through porous media and pipes is another field of application for third-grade fluid models. Third-grade fluid theory can be used to model a number of important biological fluids such as normal blood flow, as well as some abnormal flow conditions like cancerous blood. In addition, third-grade fluid models are used in many industrial applications, such as in the processing of paints, cosmetics, food pastes and industrial suspensions. Non-Newtonian effects in such flows can have significant effects on processing and end product quality. Fluids of third-grade in third-grade class are much more difficult to solve even than the higher-order nonlinear terms are included in the constitutive equation of third-grade class fluids. However, for such equations many methods have been established to solve them either analytically or numerically, such as homotopy methods, spectral methods, finite element methods, and even some new methods of machine learning. Therefore, solutions for third-grade fluids are very meaningful both theoretically and applications. For third-grade fluids of the third grade in the third grade these aspects have been investigated in a class of third-grade fluids.

2.8 Fourth grade fluid

Fourth-grade fluids are new generation of advanced non-Newtonian fluid models of differential type of viscoelastic fluid of continuum mechanics and rheology. They are considered as a model for description of higher complexity of flow phenomena in contrast to Newtonian, second- and third-grade fluids. The stress in fourth-grade fluid depends on the rate of deformation, and, in addition, includes higher-order nonlinear functions of deformation history and of elastic properties of fluid. In this respect, the constitutive equation of fourth-grade fluid includes higher-order Rivlin–Ericksen tensors and their nonlinear interactions. As a result, fourth-grade fluids exhibit strong viscoelasticity, nonlinear normal stress differences, both shear-thinning and shear-thickening, strain hardening, and memory effects. They are capable of describing strongly nonlinear behavior of real fluids and materials, especially in case of large deformations. The fourth-grade fluid models for fourth-grade fluids are much more complicated than the lower-grade models since the stress tensor includes not only the fourth-order kinematic terms, and therefore the corresponding fluid models are Navier-Stokes like and solvable using the standard tools of continuum mechanics, but it also includes more non-linear material parameters characterizing the elastic and viscosity properties of the fluid. The governing equations for flow of fourth-grade fluids are strongly coupled, nonlinear and very difficult to solve exactly.

Fourth-grade fluids have important applications in various branches of engineering and industrial sciences. Fourth-grade fluid model represents advanced complex fluid and also some complex materials, such as polymeric melts and solutions, and synthetic resin. The other applications of fourth-grade fluid model are liquid crystalline fluids, biological and biomimetic fluids and molecules, molten plastics, lubricant and industrial suspensions. In various papers, flow of fourth-grade fluid through parallel plates, square and circular ducts, over stretching surfaces, from sphere and cylinder, over nonlinear stretching surfaces, due to the motion of infinite continuous plane caused by radial contraction or expansion, are investigated. Oscillations of nanofluids, peristaltic flow, MHD, couple stress and third-grade fluids flow of fourth-grade fluids through porous medium, and heat transfer of rotating flow of fourth-grade fluid through micro-porous tube, over horizontal plate in rotating system, heat and mass transfer over radially and axially moving cylinders, stretching and shrinking sheet, are studied. Some papers deal with flow of fourth-grade fluids with heat absorption or release.

Non-Darcy natural convection, mixed convection and heat and mass transfer of flows, and Soret and Dufour effects in free convection and mixed convection of heat and mass transfer for various types of fluids are presented. Thermocapillary instabilities in a heated fluid layer and buoyancy driven flow of fourth-grade fluids in a porous medium are considered. Capillary-driven flows of fourth-grade fluid are also studied. Convection and boiling of dielectric working fluids at engineering relevant conditions for geothermal applications are presented. In addition, convective heat and mass transfer in suspended nanofluids and in micro-channels, instabilities of stratified systems, liquid and gas film evolution, thin film heat and mass transfer, and transient heat and mass transfer are discussed. Mixing of laminar fluids and film condensation of various types of fluids are also investigated. Heat and mass transfer of flow of fourth-grade fluid with change of physical properties through infinite parallel plates, over vertical or inverted vertical continuous surfaces, from vertical or horizontal cylinders, from spheres, and over stretching surfaces, are presented.

Change of temperature and change of solute concentration of third- and fourth-grade fluids flowing through porous flexible tube, channel or annulus, and over horizontal or inclined plates, are studied. Forced convection and change of solute concentration of fourth-grade fluid from concentric or eccentric rotating cylinders, and change of solute concentration of fourth-grade fluids along vertical or inclined surfaces in presence of natural and mixed convection, are presented. Combined heat and mass transfer of third- and fourth-grade fluids for various geometrical configurations, i.e., from vertical plate, from horizontal plate, from horizontal circular cylinder, from hemisphere, and from vertical circular cylinder, are discussed. Although these models are mathematically quite advanced for a 4th grade class, they do provide more realistic physical models and predictions for non-linear rheological behavior, and could be a great topic for a study on advanced fluid mechanics and computational rheology.

Applications:

Fourth-grade fluids, or extended power law fluids, are important in a wide variety of fields in engineering and science. They can serve as advanced engineering fluids and materials and can also be used as idealized models of complex industrial fluids and materials. Within the scope of fourth-grade fluids, fourth-grade fluids are important fourth-grade fluids because they can exhibit significantly more realistic fourth-grade fluid behavior than lower grade fluids. The fourth-grade fluids can exhibit strong elastic effects, large elastic deformation, memory effects, and nonlinear stress–strain relationships, and, therefore, they are important fourth-grade fluids.

Applications of fourth-grade fluids include the polymer and plastics industry where highly viscous melts, resins, rubber compounds, adhesives, and other industrial materials exhibit complex rheological behavior during processing, such as extrusion, injection molding, stretching, and coating. In lubrication engineering, fourth-grade fluid models are important for the study of advanced lubricants and greases that are non-Newtonian. The use of non-Newtonian lubricants can significantly improve lubricant performance under high shear rates, high pressure, and high-temperature conditions. In petroleum engineering, fourth-grade fluid models are commonly used to study transport of heavy crude oil, drilling muds, and other non-Newtonian fluids and hydrocarbons through porous media (reservoir rock) and through long-distance pipelines. Viscoelastic fourth-grade fluids represent many important biological materials and complex biological fluids which exhibit remarkable viscoelastic effects and strong nonlinearity. For many industrial fourth-grade fluids, such as high-tension food and cosmetic materials (creams and gels, syrups and pastes, emulsions etc.), the study of highly nonlinear fluid flow is of great practical significance and applications. These studies have significant theoretical value, great applicability for numerical and experimental simulation and thus can have wide applications in many branches of industry.

Fluid models of fourth-grade (heat-contractive, micro-rotational, bulk-rotational, and/or magnetic field coupled) fluids are important in various areas of fluid dynamics and applied mathematics. Many features of transport phenomena are studied by using these types of fluids. Heat and mass transfer, MHD flows and heat transfer, Newtonian and non-Newtonian flow through porous media, mixed convection and double diffusion, non-linear rotating and non-uniform heat and mass transfer are some of the phenomena studied. Stretching or shrinking surfaces, peristaltic flow, and heat and mass transfer from rotating surfaces are other applications of these models. The solutions obtained by using these types of fluids are important in many heat and mass transfer devices such as heat exchangers, energy storage systems, solar energy systems, geothermal energy systems, cooling systems, chemical and electrochemical reactors, pumps (biomedical and industrial), and aerospace applications. In environmental and geophysical flows, mudflow, lava flow, sediment transport, and many other highly viscous geologic materials are simulated by using fourth-grade fluid models. A large number of problems of these types of fluids are solved by using homotopy methods, spectral methods, finite element method, finite difference method, differential quadrature method and artificial intelligence solutions. A fourth-grade fluid is used in this study because it can closely approximate real nonlinear fluid by simulating its behavior using both theoretical solutions and computational simulations. In modern day continuum mechanics and fluid engineering, such a fluid is very useful in industrial applications and optimization studies.

3. Mathematical Models of Non-Newtonian Fluids

Several models describe the behavior of non-Newtonian fluids, including:

- **Power-Law Model:** The power-law model is one of the simplest mathematical models to describe non-Newtonian fluid behavior. It expresses the relationship between shear stress and shear rate as:

$$\tau = K(\gamma^{\cdot})^{\mathrm{n}}$$

where K is the flow consistency index, and n is the flow behavior index. When $n < 1$, the fluid is shear-thinning (viscosity decreases with increasing shear rate). When $n > 1$, the fluid is shear-thickening (viscosity increases with increasing shear rate). This model is widely used because of its simplicity, though it does not account for yield stress.

- **Bingham Plastic Model:** The Bingham plastic model describes fluids that behave as solids at low stress levels but flow like a viscous fluid once a critical stress (yield stress) is exceeded. The relationship is given by:

$$\tau = \tau_0 + \mu p\dot{\gamma} \tag{4}$$

where μp is the plastic viscosity. Below the yield stress, the fluid behaves as a rigid body. This model is commonly applied to drilling muds, sludges, and toothpaste.

- **Herschel-Bulkley Model:** The Herschel-Bulkley model is a generalization of both the Bingham plastic and power-law models. It accounts for yield stress as well as shear-thinning or shear-thickening behavior. The model is expressed as:

$$\tau = \tau_0 + K(\dot{\gamma})^{\mathrm{n}} \tag{5}$$

where τ_0 is the yield stress, K is the consistency index, and n is the flow behavior index. This model is versatile and used for complex fluids such as suspensions, emulsions, and foams.

4. Industrial and Engineering Applications

Non-Newtonian fluids play a pivotal role in various industries due to their unique flow characteristics. Their ability to respond differently under stress or shear rates makes them essential in the following sectors:

Food Processing: Non-Newtonian fluids are extensively used in food processing to improve the texture, stability, and shelf life of products. Sauces, dressings, and dairy products often exhibit shear-thinning behavior, allowing them to remain thick and stable during storage but flow easily when poured or spread. This property enhances consumer experience by ensuring smooth application and prevents phase separation during processing.

Pharmaceuticals: In pharmaceuticals, non-Newtonian fluids are crucial for controlled drug delivery and formulation. Many gels, creams, and suspensions display thixotropic behavior, which allows for ease of application and stability during storage. This ensures accurate dosing and efficient absorption. Additionally, non-Newtonian fluids are used in the development of biocompatible gels and injectable solutions that require specific flow properties under varying shear conditions.

Petroleum Engineering: Non-Newtonian fluids play a vital role in petroleum engineering, particularly in drilling fluids and enhanced oil recovery processes. Drilling muds often exhibit thixotropic and shear-thinning properties, allowing them to flow easily during drilling operations but solidify when at rest to prevent borehole collapse. This ensures greater efficiency and safety in oil extraction processes.

Biomedical Engineering: Understanding the non-Newtonian behavior of blood and biological fluids is essential for biomedical engineering. Non-Newtonian models help simulate blood flow through arteries, veins, and medical devices, leading to improved designs for prosthetic heart valves, stents, and artificial organs. This enhances the accuracy of diagnostic tools and the effectiveness of medical treatments.

3D Printing: Non-Newtonian fluids are key to advancing 3D printing technology by improving the flow and layer formation of printing materials. Shear-thinning fluids are commonly used in printing inks and polymer-based resins, ensuring smooth extrusion and precise deposition of layers. This leads to higher-quality prints with greater structural integrity and intricate designs.

Construction: In the construction industry, non-Newtonian fluids are employed in the development of self-healing concrete, cement slurries, and grout materials. These fluids exhibit rheopectic or thixotropic properties, allowing them to flow easily during application but solidify over time to provide strength and durability. This improves the longevity of structures and reduces maintenance costs.

5. Experimental Methods

Characterizing non-Newtonian fluids involves rheometry, viscometry, and imaging techniques to measure viscosity, elasticity, and time-dependent properties. Instruments such as rotational rheometers and capillary viscometers are widely used. Additionally, advanced computational fluid dynamics (CFD) techniques and particle image velocimetry (PIV) enhance the understanding of fluid behavior at microscopic levels.

6. Conclusion

Non-Newtonian fluids exhibit diverse and complex behaviors crucial to many scientific and industrial applications. Understanding their properties and classifications helps in optimizing processes, designing better products, and developing innovative solutions across various sectors. Ongoing research continues to explore the intricate nature of these fluids, expanding their applicability in emerging technologies and interdisciplinary fields such as bioprinting, microfluidics, and nanotechnology.

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