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A Review on the Applications of the Kuang-Luo Fluid model in Arterial Blood Flow with Stenosis

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ABSTRACT: This work investigates the impact of blood flow parameters within a stenosed artery featuring an irregular shape and multiple constrictions. The findings indicate that the flow characteristics are notably influenced by the non-Newtonian (K-L) fluid. We observed that stenosis significantly affects the flow pattern, with the flow becoming more complex as the stenosis increases. This review examines the behaviour of blood flow in arteries affected by stenosis through the lens of the Kuang-Luo (K-L) non-Newtonian fluid model. The K-L model, recognized for capturing both yield-stress and shear-thinning characteristics, provides a more realistic description of blood rheology than traditional models such as Casson or Herschel-Bulkley. By analyzing previous mathematical and computational studies, the review highlights how the K-L model improves predictions of velocity distribution, flow resistance, wall shear stress, and diffusion processes in narrowed arteries with varying geometries. The findings show that stenosis severity, yield stress, and plasma viscosity significantly influence flow behaviour, with the K-L model offering enhanced sensitivity to these parameters due to its extended rheological structure. Overall, the review demonstrates that the K-L model serves as a powerful tool for understanding hemodynamic changes in diseased arteries and can support more accurate assessment of cardiovascular risks.

I. INTRODUCTION

Non-Newtonian fluids can behave in many ways — some become thinner when moved (like blood), others become thicker (like cornstarch and water), and some even act partly like solids — scientists can't describe all of them using one single formula. So, different mathematical models (like the Casson, Carreau, or Kuang-Luo models) were created to describe each type of behaviour more accurately [14].

Arteries are responsible for transporting oxygenated blood from the heart to various parts of the body, including the lungs, brain, and peripheral tissues. However, in many cases, the normal blood flow through arteries can be obstructed due to the buildup of fatty deposits, known as plaques, on the arterial walls. This narrowing of the arterial lumen leads to a condition called atherosclerosis or stenosis. Over time, the stenotic region becomes more rigid and constricted, significantly restricting the flow of oxygen-rich blood to vital organs and tissues [17]. Blood is a complex biological fluid that can behave as both a Newtonian and a non-Newtonian fluid, depending on how fast it flows. In large arteries, where the shear rate (the rate at which blood layers move past each other) is high usually above 100 s^{-1} then blood shows Newtonian behaviour, meaning its viscosity remains almost constant. However, in smaller blood vessels such as arterioles, narrow arteries, and capillaries, where the shear rate drops below 10 s^{-1} , blood exhibits non-Newtonian properties, and its viscosity changes with flow conditions. This non-Newtonian nature is important to consider when studying cardiovascular diseases, which are among the leading causes of death worldwide. Conditions such as heart attack, stroke, ischemia, and angina pectoris often result from atherosclerosis, a disease characterized by the buildup of fatty substances, cholesterol, calcium, and fibrin on the inner walls of arteries. This buildup forms stenosis, a narrowing of the blood vessel that restricts blood flow and increases pressure on the heart. The geometry of stenosis can be symmetrical or asymmetrical, both of which disturb the normal flow of blood [2].

Instead of studying each cell one by one, scientists often treat blood as a smooth, continuous fluid. For this reason, many mathematical models have been developed to describe how blood flows.

Some earlier models that were widely used are the Casson model [5, 23] and the Carreau-Yasuda model [4, 10, 24]. Researchers such as Ashrafizadeh and Bakhshaei and Boyd et al. used these models to study blood flow in simple shapes like straight tubes, and they checked that the results matched with known mathematical solutions [1]. Later,

these ideas were expanded to study blood flow in more complicated blood vessels and to include more detailed fluid behaviour. Newer models include Casson [5], Herschel–Bulkley [9], Kuang–Luo [12], and bi-viscosity models. These more advanced models have been used by researchers such as Liu and Sriyab [22], and Bali & Gupta [2], [3] to better understand how blood flows in realistic and complex situations (for example, where vessels are not straight or blood behaves differently at different points) [8].

To better understand how blood behaves in such narrowed arteries, researchers use mathematical fluid models, such as the Kuang–Luo (K–L) fluid model [12], which accurately describes the non-Newtonian and shear-thinning behaviour of blood. This model helps in studying how blood flow, pressure, and wall shear stress are affected in diseased arteries and in predicting the potential risks associated with cardiovascular disorders [2].

The Kuang–Luo (K–L) fluid model[12] is a mathematical way to describe how blood flows, especially since blood doesn't behave like ordinary fluids such as water.

It was developed by Luo and Kuang as an improved version of the Casson model [17]. The Casson model [5] already accounts for some of blood's special properties, but the K–L model goes further - it includes three important factors:

1. Yield stress – the minimum force needed before blood starts to flow.
2. Plasma viscosity – how thick or sticky the liquid part of the blood is.
3. Chemical variables – factors related to the chemical composition of blood that affects its flow.

Because of these extra details, the K–L model gives a more accurate picture of blood's behaviour, especially how it becomes thinner (less viscous) when it flows faster - a property called shear-thinning [12]. Experiments by Zhang and Kuang showed that the K–L model matches real blood behaviour in both humans and animals better than some other model [25]. Many researchers have since used the K–L model to study how blood moves through arteries that have stenosis (narrowing) and to understand how this affects blood flow and pressure.

Researchers have found that the Kuang–Luo (K–L) model gives one of the most accurate descriptions. Zhang and Kuang suggested that this model fits real blood behaviour better than many others [25]. Ashrafizaadeh and Bakhshaei used the K–L model in their computersimulations of blood flow using a technique called the Lattice Boltzmann (LB) method [1]. They compared the K–L model with two other well-known non-Newtonian models, the Casson model [5] and the Carreau–Yasuda model [4], and showed that the K–L model provided reliable and realistic results. Later, Sriyab studied how blood flows through narrow arteries that have mild, bell-shaped stenosis (a smooth narrowing). Using the K–L model, he derived formulas for flow rate, skin friction, and resistance to blood flow. His research explained how different factors such as the shape of the narrowing and fluid properties affect how easily blood moves through a narrowed artery [2].

In recent years, a growing number of researchers have concentrated on understanding the complex rheological behaviour of blood by employing non-Newtonian fluid models such as the Kuang–Luo (K–L) [12], power-law, Herschel–Bulkley [9], and Casson [5] models. These models have greatly contributed to advancements in cardiovascular flow analysis, particularly in studying how blood behaves in arteries affected by stenosis or other abnormalities. Among these, the K–L fluid model has emerged as a more refined approach because it can capture both the yield stress of red blood cell suspensions and the viscous contribution of plasma, allowing for a more realistic representation of blood's dual-phase nature.

Building on the foundational work of Sriyab, Bali and Gupta extended the analysis of blood flow in non-symmetrical stenosed arteries by employing the K–L model. Their study demonstrated that the additional plasma-viscosity parameter in the K–L formulation enables more accurate prediction of velocity and wall shear stress in constricted arteries compared with traditional Casson and Herschel–Bulkley models. Unlike these older models which depend mainly on a single rheological parameter such as yield stress or power-law index - the K–L model introduces an extra degree of freedom to describe how plasma and red blood cells interact under varying flow conditions [2].

Further investigations by Kumar and colleagues explored blood motion through porous and two-layered elastic arteries using viscoelastic non-Newtonian formulations. Their work analyzed how the presence of stenosis influences the propagation of pressure waves and the filtration velocity of interstitial or tissue fluids across arterial wall [11].

Similarly, Shah developed a three-layer arterial model by treating blood as a Casson or Bingham plastic fluid, providing insights into the mechanical interactions among multiple arterial layers during constricted flow [19].

Other researchers have examined the impact of stenosis geometry on flow dynamics. Owaisit and Sriyab compared two distinct stenosis shapes - bell-type and cosine-type - and observed minor but notable differences in flow behaviour depending on the shape and severity of the narrowing [15]. Nadeem and co-authors expanded this approach by testing four different stenosis forms, including triangular, trapezoidal, overlapping (W-shaped), and composite geometries, within arteries of elliptical cross-sections. Their findings highlighted the significant influence of geometry on velocity distribution and wall shear forces [13].

The work of Ponalagusamy and Manchi further refined blood flow modelling by introducing a two-fluid framework that considered the plasma layer as Newtonian and the core region as Kuang–Luo non-Newtonian fluid [18]. Through this approach, they obtained analytical expressions for velocity profiles corresponding to six types of mild stenosis - symmetric, triangular, trapezoidal, elliptical, bell-shaped, and composite. Their results confirmed that incorporating the K–L model improved the accuracy of simulated flow fields, particularly near arterial walls where plasma effects are dominant. Finally, Singh and Kumar studied blood flow through inclined arteries with multiple stenosis under the assumption of Newtonian fluid behaviour, providing a comparative baseline for later non-Newtonian analyses [11].

In summary, these studies collectively demonstrate that the Kuang–Luo fluid model provides a more comprehensive framework for representing real blood rheology compared with older non-Newtonian models. By accounting for both yield stress and plasma viscosity, it effectively captures the layered and shear-dependent nature of blood flow. Consequently, this model enhances the precision of hemodynamic simulations, particularly in predicting wall shear stress, pressure distribution, and velocity profiles in stenosed arteries. Its parameters are vital for understanding the onset and progression of cardiovascular diseases such as atherosclerosis [21].

II. KUANG-LUO MODEL FORMULATION

Understanding the Equation

$$\delta = \eta_1 \dot{\gamma} + \eta_2 \sqrt{\dot{\gamma}} + \delta_Y \quad (1)$$

where:

δ - The shear stress (how much force per area the fluid experiences while flowing)

$\dot{\gamma}$ - The shear rate (how fast the fluid layers move past each other)

η_1 , η_2 are the constants that describe how the fluid's viscosity changes with flow

δ_Y - The yield stress - the minimum stress needed to make the fluid start moving

When blood is still, it doesn't start flowing until a certain minimum force (yield stress) is applied. Once it starts moving, its thickness (viscosity) depends on how fast it flows - it gets thinner at higher speeds (shear-thinning behaviour). The two parts, η_1 and η_2 describe these changing flow behaviour — one part for normal flow, and one part for when the fluid thins out more quickly.

So, the Kuang–Luo model combines:

1. The idea of yield stress (like a paste that needs a push to start moving), and
2. Shear-thinning (like honey becoming thinner when stirred faster).

The apparent viscosity equation is:

$$\mu_{app} = \eta_1 + \frac{\eta_1}{\sqrt{\dot{\gamma}}} + \frac{\delta_Y}{\dot{\gamma}} \quad (2)$$

This just rearranges things to show how thick the fluid appears to be at different flow speeds. At low flow speeds, the yield stress term $\frac{\delta_Y}{\dot{\gamma}}$ dominates—the blood feels thick.

At high flow speeds, the viscosity decreases because the term $\sqrt{\dot{\gamma}}$ increases -the blood feels thinner [8].

The Kuang–Luo (K–L) model can behave like different well-known fluid models depending on how its parameters are chosen. For example, if the yield stress and one viscosity term are set to zero, the model behaves like a shear-thinning power-law fluid; if other parameters are adjusted; it acts like a Bingham fluid, which needs a minimum force to start flowing. However, the original K–L model has a mathematical problem at zero shear rate because the viscosity becomes extremely large, and this also creates regions where the fluid behaves like a solid rather than a liquid. To handle this issue in simulations, researchers use a “regularization” technique similar to the method introduced by Papanastasiou for Bingham fluids which smooths out the sharp jumps and prevents infinite viscosity [16]. This leads to a modified, regularized version of the K–L model that is easier and more stable to use in numerical calculations.

The regularized K–L model can then be defined as;

$$\mu_{app} = \eta_1 + \left[\frac{\eta_2}{\sqrt{\dot{\gamma}}} + \frac{\delta\gamma}{\dot{\gamma}} \right] (1 - e^{-m\dot{\gamma}}) \quad (3)$$

where m is the regularization parameter.

Regularizing the K–L model has two important effects. First, the exponential term smoothes out the parts of the equation that would normally blow up when the shear rate becomes zero. This means the viscosity no longer becomes infinite at rest; it stays at a manageable, finite value. Second, because the model is now smooth everywhere, the fluid never becomes perfectly solid in any region. In other words, it does not create a true unyielding zone. But if the regularization parameter m is chosen to be large enough, the model still produces a region where the flow is extremely slow and behaves almost like a solid, closely imitating a real unyielding zone without causing numerical problems [7].

III. APPLICATIONS IN STENOSED ARTERIES

The current mathematical formulation provides a robust framework for analyzing the Kuang–Luo (K–L) non-Newtonian fluid model when subjected to the influence of an electric field. This model has been particularly effective in describing the behaviour of blood flow, both in healthy arteries and those affected by stenosis (narrowing due to plaque or other obstructions). Its application helps capture the complex rheological properties of blood and how external electric forces modify flow patterns and shear stresses within the vascular system [20]. The study presents an enhanced formulation of blood rheology by employing the Kuang–Luo (K–L) model [12], which serves as a refined extension of the classical Casson model. While the Casson model [5, 23] captures yield-stress behaviour, it contains relatively few parameters and therefore offers a limited representation of how blood responds to varying shear rates. The K–L model, on the other hand, incorporates additional rheological parameters that allow it to describe both yield stress and shear-thinning effects more accurately. Because of this enriched structure, the K–L model can reflect subtle variations in blood viscosity and deformation, making it more suitable for analyzing complex arterial environments, especially those affected by stenosis.

Using this improved model, the authors derive analytical expressions for key flow variables. By applying physically relevant boundary conditions—such as no-slip at the arterial wall and symmetry at the centre-line—they obtain solutions for the axial velocity profile, the volumetric flow rate, and the longitudinal effective diffusion coefficient. These solutions provide insight into how stenosis severity, yield stress, and shear-thinning behaviour collectively influence blood movement.

The results are then evaluated through graphical representations, which illustrate how changes in the model parameters modify the flow characteristics. Trends in velocity, wall shear stress, and mass transport behaviour are discussed to highlight the advantages of the K–L model over simpler non-Newtonian descriptions. Overall, the analysis demonstrates that the added rheological detail of the K–L model yields a more realistic and thorough understanding of blood flow in stenosed arteries [3].

IV. NUMERICAL SIMULATIONS OF RESULTS

The objective of our study is to discuss the effects of various parameters on the physiologically important flow quantities such as flow rate, skin friction, and resistance of blood flow.

4.1 BLOOD FLOW RATE

In a stenosed artery, resistance to flow is already high due to the reduced cross-sectional area. When the yield stress of the blood increases, the fluid requires a higher minimum stress to start flowing, this naturally reduces the flow rate. However, in the Kuang–Luo (K-L) model, this reduction is relatively small because the model treats blood as a combination of yield-stress behaviour and shear-thinning effects. As a result, the influence of yield stress on overall flow remains moderate [12].

A more pronounced effect arises from the plasma viscosity coefficient in the K-L model. Plasma is the base fluid in which blood cells are suspended, so an increase in its viscosity makes the entire mixture more resistant to deformation. Because of this, the flow rate drops sharply when plasma viscosity becomes higher. This shows that in the K-L approach, viscosity of the continuous phase plays a dominant role in determining how easily blood can move through a stenosed artery.

The trend regarding yield stress is consistent across the Casson [5], Herschel–Bulkley [9], and K-L models [12]. In all three, an increase in yield stress leads to a reduction in blood flow rate, since greater stress is required to initiate motion. The key difference is that in the K-L formulation, plasma viscosity contributes to an additional and stronger influence. Therefore, both yield stress and plasma viscosity determine the blood flow behaviour, but the plasma viscosity coefficient has a much more significant impact on the flow reduction in narrow or stenosed arteries.

4.2 THE SKIN FRICTION

4.2.1 The Effect of Stenosis on Skin Friction. In the Kuang–Luo (K-L) model, stenosis has a direct influence on the skin friction, which represents the tangential stress acting along the arterial wall. As the length of the stenosis increases, the narrowing persists over a larger portion of the artery, causing the fluid to experience greater resistance. This elevated resistance increases the velocity gradients near the wall, leading to an overall rise in skin friction. Similarly, an increase in yield stress makes the blood behave more like a fluid that requires higher force to start deforming, which again contributes to stronger shear forces at the wall and therefore higher skin friction.

However, the effect of plasma viscosity in the K-L model is the opposite. When the plasma viscosity coefficient becomes larger, the fluid behaves more smoothly and tends to form a thicker, more uniform velocity profile. This reduces sharp velocity gradients near the wall, causing skin friction to decrease. In this sense, plasma viscosity acts as a stabilizing factor that lowers the wall shear compared to the effects of stenosis length or yield stress.

When comparing the K-L model with other non-Newtonian blood models such as the Casson [5] and Herschel–Bulkley [9] models, similar trends appear regarding the role of stenosis length. In the Casson model, increasing the length of the stenosed region produces a strong increase in skin friction, much like what is observed in the K-L model. The influence of yield stress, however, behaves differently in these classical models: in both the Casson and Herschel–Bulkley models, higher yield stress leads to only a slight decrease in skin friction. This difference highlights how the K-L model captures additional rheological effects - such as the role of plasma viscosity - while still agreeing with the Casson model concerning the impact of stenosis length on skin friction.

4.2.2 The Effect of Non-Newtonian Behaviour on Skin Friction. In the Kuang–Luo (K-L) model, the non-Newtonian characteristics of blood have a noticeable impact on the skin friction. As the length of the stenosis increases, the constricted region extends over a larger arterial segment, forcing the blood to accelerate and creating sharper velocity gradients near the arterial wall. These intensified gradients lead to a significant rise in skin friction. This behaviour reflects the sensitivity of the K-L model to geometric changes in the artery, showing that a longer stenosis produces stronger shear forces on the vessel wall.

Another important influence in the K-L model is the plasma viscosity coefficient. When the plasma viscosity increases, the blood behaves more uniformly, and the velocity profile becomes smoother across the artery. This reduces the

steepness of the velocity gradient close to the wall, causing skin friction to decrease. Hence, the plasma viscosity coefficient not only affects the flow characteristics but also plays a key role in determining the shear stress distribution in non-Newtonian blood flow.

When comparing these observations with the Casson [5] and Herschel–Bulkley [9] models, similar and contrasting trends emerge. The Casson model predicts a strong increase in skin friction with increasing stenosis length, which matches the behavior of the K-L model. However, this trend is not fully consistent with the Herschel–Bulkley model, indicating that different non-Newtonian formulations respond differently to geometric constriction. Overall, the K-L model stands out because it accounts for both stenosis length and plasma viscosity, making it more responsive to the combined rheological and structural factors that influence skin friction in non-Newtonian blood flow.

4.3 THE RESISTANCE OF BLOOD FLOW

4.3.1 The Effect of Stenosis on the Resistance of Blood Flow. In the Kuang–Luo (K-L) model, the resistance to blood flow is influenced by both the rheological properties of blood and the geometry of the stenosed artery. When the plasma viscosity coefficient increases, the fluid becomes thicker and more resistant to motion, causing the overall flow resistance to rise. A similar effect occurs when the yield stress increases since a higher yield stress requires a greater force to initiate flow; the artery experiences more opposition to movement, which leads to higher resistance. Interestingly, the K-L model also predicts that resistance decreases when the length of the stenosis increases. This counter-intuitive behavior arises from how the K-L formulation redistributes shear and velocity gradients along the extended narrowed region, allowing part of the flow to adjust in a way that reduces overall resistance.

When the K-L model is compared with the Casson model, some similarities emerge. In the Casson formulation, the resistance to blood flow increases when either the stenosis length or yield stress increases. This trend agrees with the yield-stress effect seen in the K-L model, though the behavior regarding stenosis length differs. The Casson model predicts a direct increase in resistance with longer stenosis, whereas the K-L model allows the resistance to decline due to its more complex representation of shear-dependent viscosity.

Additionally, the increase in plasma viscosity has only a modest effect on resistance in the K-L model. The rise is present but relatively small compared to the influence of yield stress. This suggests that, while both rheological factors shape the flow behavior, yield stress plays a more dominant role in determining resistance in this model. Overall, the K-L approach provides a more nuanced understanding by incorporating how both plasma viscosity and yield stress interact with arterial narrowing to determine flow resistance.

4.3.2 The Effect of Non-Newtonian Blood Behavior on the Resistance of Blood Flow. In the Kuang–Luo (K-L) model, the non-Newtonian nature of blood strongly affects how resistance behaves inside a stenosed artery. One key observation is that the model predicts a reduction in the resistance coefficient when the yield stress increases. This means that when blood requires higher stress to start flowing, the K-L model surprisingly shows a drop in flow resistance. However, this trend does not hold when the stenosis becomes longer. As the length of the narrowed section increases, the resistance rises sharply because the fluid must travel through a more restricted passage for a longer distance.

The Casson model [5] shows the opposite pattern for yield stress. In this model, higher yield stress leads to a noticeable increase in flow resistance. This is expected because a fluid needing more stress to begin motion naturally faces greater resistance in a constricted artery. At the same time, the Casson model indicates that resistance decreases with an increase in stenosis length, which contrasts with the K-L model's prediction.

Because of these differences, the influence of non-Newtonian behavior on flow resistance varies between the two models. The K-L model suggests a decreasing trend with yield stress, whereas the Casson model predicts the opposite. Additionally, within the K-L framework, resistance is reduced when plasma viscosity increases—an effect not seen in the Casson model. In summary, plasma viscosity plays an important role in shaping flow resistance in the K-L non-Newtonian formulation, highlighting those different non-Newtonian models can produce distinctly different physical predictions [22].

V. RESULTS AND DISCUSSION

The primary aim of the present study is to understand how the presence of stenosis alters the natural pattern of blood flow inside an artery. Stenosis, which creates a narrowing in the vessel, disrupts the smooth movement of blood and produces complex flow features such as accelerated velocity near the throat of the narrowing and reduced flow downstream. By analyzing these changes, the study seeks to identify how different levels of constriction influence overall hemodynamics and how these changes may contribute to the progression of cardiovascular disease.

Another major objective is to examine how the non-Newtonian nature of blood influences flow behavior under stenotic conditions. Blood does not behave like a simple Newtonian fluid because its viscosity changes depending on the shear rate. Factors such as yield stress, the thickness of the plasma layer near the arterial wall, and the viscoplastic properties of the core region all contribute to this non-Newtonian behavior. Understanding how these characteristics interact with stenosis provides deeper insight into how blood responds to varying physiological and pathological conditions.

The study also focuses on key physiological quantities—including velocity distribution, plug-flow radius, volumetric flow rate, wall shear stress, and overall flow resistance. Each of these variables plays an important role in determining how efficiently blood is transported through the artery. Variations in yield stress or plasma viscosity can significantly modify the velocity profile and the size of the central plug-flow region, while porosity or permeability of the arterial wall can further influence resistance to flow. By analyzing these parameters together, the study aims to present a comprehensive picture of how multiple fluid and vessel characteristics shape the behaviour of blood in a stenosed artery.

Ultimately, the objective is to capture the combined effects of stenosis geometry, non-Newtonian rheology, and vessel-wall properties on critical hemodynamic indicators. Such analysis not only deepens theoretical understanding but also supports improved clinical interpretation of arterial diseases by highlighting how subtle changes in blood properties or vessel structure can significantly affect flow behaviour.

VI. CONCLUSION

The collective research discussed in this review makes it clear that the Kuang–Luo (K–L) fluid model provides a superior framework for studying blood flow in stenosed arteries. Unlike earlier non-Newtonian formulations, the K–L model incorporates both yield stress and plasma viscosity, enabling it to represent the layered and shear-dependent nature of blood more effectively. This broader rheological foundation allows the model to capture subtle variations in flow behavior, especially in arteries with complex or severe stenosis.

Studies using the K–L model consistently show improved predictions of velocity profiles, wall shear stress, flow resistance, and mass transport when compared with simpler models such as the Casson or Herschel–Bulkley models. The model's ability to reflect the influence of plasma viscosity – an aspect often overlooked in other formulations—further enhances its relevance for physiological applications. Additionally, numerical simulations reveal that the K–L model provides meaningful insights into how stenosis geometry, length, and severity shape hemodynamic patterns, which are essential indicators in the progression of cardiovascular diseases.

In summary, the K–L model stands out as a robust and versatile tool for analyzing blood flow in narrowed arteries. Its detailed representation of blood rheology makes it especially valuable for understanding pathological flow conditions and for supporting future work in diagnosis, treatment planning, and biomedical engineering.

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