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Experimental and Model-Based Characterization of a Xanthan Gum Solution as a Blood-Mimicking Fluid at Body Temperature

Orhan YILDIRIM[1*],

[1*] Atatürk University Faculty of Engineering, Department of Mechanical Engineering
25030, Erzurum/TÜRKİYE
ORCID No: 0000-0001-8780-1297, e-mail: orhan.yildirim@atauni.edu.tr

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Abstract

In biomedical engineering, reliable blood-mimicking fluids that accurately replicate the thermophysical properties of human blood are essential for in vitro flow experiments and Computational Fluid Dynamics simulations, particularly those involving heat transfer mechanisms. This study experimentally characterizes the temperature-dependent viscosity and density of non-Newtonian dilute Xanthan gum aqueous solutions (0.06% and 0.12% w/w) across a clinically relevant range of 15°C to 40°C. Measurements were performed using a Rudolph Research Analytical density meter, and the data were modeled using a physiological reference-based exponential decay function for viscosity and a Boussinesq-based linear equation of state for density. The findings revealed that the 0.12% (w/w) solution exhibited high conformity to healthy adult human blood rheology, yielding a dynamic viscosity of 3.78 mPa·s at the physiological temperature of 37°C. The proposed viscosity model, anchored at 37°C, operated with 0% error at the reference point, although deviations up to 19.15% were observed at the lower thermal boundary due to hysteresis. Thermodynamic analysis indicated a flow activation energy of 18.76 kJ mol^{-1}, reflecting stable, plasma-like flow characteristics. Crucially, the calculated Prandtl numbers for the 0.12% solution ranged from 24.43 to 45.64, closely aligning with human blood values. This confirms that momentum transfer is more dominant than thermal diffusion and demonstrates that the thermophysical data obtained using the proposed formulation provide a comprehensive basis for future CFD and PIV studies involving convection-limited haemodynamic applications and requiring precise thermo-rheological coupling.

Keywords: Blood-mimicking fluids, Xanthan gum, Thermo-rheological characterization, Hemodynamic simulation

Vücut Sıcaklığında Kanı Taklit Eden Sıvı Olarak Ksantan Sakızı Çözeltisinin Deneysel ve Model Tabanlı Karakterizasyonu

Özet

Biyomedikal mühendisliğinde, insan kanının termofiziksel özelliklerini doğru bir şekilde taklit eden güvenilir kan benzeri sıvılar, özellikle ısı transfer mekanizmalarını içeren in vitro akış deneyleri ve Hesaplamalı Akışkanlar Dinamiği simülasyonları için çok önemlidir. Bu çalışma, klinik olarak ilgili 15°C ila 40°C aralığında, Newton olmayan seyreltik ksantan zamkı sulu çözeltilerinin (ağırlıkça %0.06 ve %0.12) sıcaklığa bağlı viskozitesini ve yoğunluğunu deneysel olarak karakterize etmektedir. Ölçümler, Rudolph Research Analytical yoğunluk ölçer kullanılarak gerçekleştirilmiş ve veriler, viskozite için fizyolojik referans tabanlı üstel bozunma fonksiyonu ve yoğunluk için Boussinesq tabanlı doğrusal durum denklemi kullanılarak modellenmiştir. Bulgular, %0.12 (a/a) çözeltinin sağlıklı yetişkin insan kan reolojisine yüksek uyum gösterdiğini ve 37°C fizyolojik sıcaklıkta 3.78 mPa·s dinamik viskozite verdiğini ortaya koydu. 37°C'de sabitlenen önerilen viskozite modeli, referans noktasında %0 hata ile çalıştı, ancak histerezis nedeniyle alt termal sınırda %19.15'e varan sapmalar gözlemlendi. Termodinamik analiz, 18.76 kJ mol^{-1}'lik bir akış aktivasyon enerjisi gösterdi ve bu da kararlı, plazma benzeri akış özelliklerini yansıtıyordu. Önemli olarak, %0.12'lik çözelti için hesaplanan Prandtl sayıları 24.43 ile 45.64 arasında değişmekte olup, insan kanı değerleriyle büyük ölçüde uyumludur. Bu, momentum transferinin termal difüzyona göre daha baskın olduğunu doğrulamakta ve önerilen formülasyon ile elde edilen termo-fiziksel verilerin, konveksiyon sınırlı hemodinamik uygulamalar ve hassas termo-reolojik kuplaj gerektiren gelecekteki CFD ve PIV çalışmaları için kapsamlı bir temel oluşturduğunu göstermektedir.

Anahtar Kelimeler: Kan benzeri sıvılar, Ksantan zamkı, Termoreolojik karakterizasyon, Hemodinamik simülasyon

1. INTRODUCTION

Blood-mimicking fluids (BMFs) are central to biomedical engineering experiments where reproducible, observable, and safe surrogates for human blood are required for cardiovascular research and medical device testing. In vitro flow simulators and compliant-phantom experiments use BMFs to reproduce physiological flow rates, pressures, and shear conditions while enabling visualization techniques that are impractical in vivo. Key experimental contexts include bench studies of pulsatile aortic flow, device flow characterization, and flow-visualization measurements such as particle image velocimetry (PIV), where matching rheological response is necessary for subsequent studies aiming to capture realistic velocity and shear-stress distributions [1, 2]. The development and validation of accurate blood analogs are essential for advancing our understanding of hemodynamics, optimizing medical device design, and improving computational fluid dynamics (CFD) simulations.

Human blood exhibits complex non-Newtonian behavior dominated by shear-thinning and viscoelastic features that significantly influence velocity profiles, shear stresses, and flow separation in cardiovascular geometries. Experimental and modeling studies emphasize the importance of reproducing shear-rate–dependent viscosity to capture differences between Newtonian and non-Newtonian flows in stenoses, compliant vessels, and pulsatile conditions [2, 3]. At physiological temperature (37°C), healthy adult human blood typically exhibits a viscosity in the range of 3.0–4.0 mPa·s and a density of approximately 1050–1060 kg/m^3. These rheological properties are critical benchmarks for the development of realistic blood-mimicking fluids.

The literature has relied on several families of BMF formulations, each with trade-offs between rheology, optical properties, and thermophysical stability. Glycerol–water mixtures have been widely used as Newtonian analogs due to their simple control of kinematic viscosity and density, and their compatibility with refractive-index adjustments for optical diagnostics [4]. However, these formulations lack the shear-thinning behavior required to reproduce non-Newtonian hemodynamics observed in actual blood flow [4]. Polymer-based solutions, particularly those containing xanthan gum (XG), have emerged as superior alternatives because they reproduce shear-thinning and some viscoelastic effects, making them suitable for PIV and compliant-phantom studies that aim to emulate non-Newtonian blood behavior [2, 5]. Nevertheless, the rheology of these solutions is sensitive to additives and refractive-index (RI) agents, and concentration and temperature effects require careful characterization [3, 5]. RI-matched salt or urea solutions with polymers permit optical index matching for PIV and laser Doppler velocimetry (LDV) while tuning density and viscosity to match test-section materials [6]. However, salt and RI agents can substantially alter viscosity and reduce shear-thinning when combined with polymers, complicating rheological fidelity [3].

Xanthan gum is widely used in blood analog formulations because small additions confer pronounced shear-thinning and measurable viscoelasticity, which improve agreement with blood-like velocity profiles, recirculation lengths, and wall-shear distributions in model geometries. Multiple experimental works report that XG-based fluids prolong flow stabilization and alter turbulent and transitional responses compared with Newtonian analogs, demonstrating their value in cardiovascular hemodynamics research [2, 5]. Reported experimental uses of XG span PIV studies, ventricular-assist device investigations, microchannel pulsatile experiments, and compliant-phantom flow visualization; investigators tailor XG concentration to reproduce target rheological behavior for each application [1, 5, 7]. Temperature-dependent formulations have been proposed, and recent work has derived relations linking XG concentration and body temperature for narrow temperature bands, reporting concentration ranges on the order of a few hundred parts per million for specific target viscosities [8]. Despite wide use, the literature cautions that additives used for optical matching or density adjustment can modify XG rheology and that published concentration ranges and temperature correlations vary by study and intended application [3, 8].

Although XG-based analogs are established for reproducing shear-thinning hemodynamics in PIV and phantom experiments, the supplied literature indicates incomplete coverage of precise thermophysical datasets and validated predictive models spanning broader laboratory temperature ranges and targeted concentrations. In particular, adjustments for optical or density matching have been shown to affect viscosity and shear-thinning, underscoring the need for rigorous thermorheological characterization and empirical models tailored to specific XG concentrations and temperature bands [3, 8]. Furthermore, most existing studies focus on narrow temperature ranges or specific experimental conditions, limiting the generalizability and applicability of their findings to diverse research scenarios.

While the use of Xanthan gum as a blood analog is documented in the literature, there is a lack of validated, temperature-dependent mathematical models that span the full clinical range from ambient laboratory conditions to physiological body temperature. Most existing studies focus on narrow temperature bands or specific experimental conditions, limiting the generalizability of their findings. This study fills this gap by providing not only experimental datasets but also a calibrated exponential decay constant ($b = 0.025$) and comprehensive thermodynamic parameters, such as Prandtl numbers and flow activation energy. These outputs are specifically designed to serve as high-fidelity input parameters for future PIV and CFD investigations requiring precise thermo-rheological coupling.

In the literature, xanthan gum solutions are widely utilized as blood-mimicking fluids (BMFs). Specifically, concentrations between 0.05% and 0.15% have been reported to best replicate the shear-thinning characteristics and physiological viscosity levels of human blood. This study focuses on two critical points within this range to model the specific impact of temperature on these properties. This study aims to address these gaps by providing a comprehensive experimental and model-based characterization of dilute xanthan gum aqueous solutions as blood-mimicking fluids across a wide temperature range. Specifically, the objectives of this study are to: (1) perform experimental thermophysical characterization of 0.06% and 0.12%

(w/w) xanthan gum aqueous solutions over the temperature range of 15°C to 40°C, encompassing both ambient laboratory conditions and physiological body temperature; (2) develop and evaluate predictive mathematical models for temperature-dependent dynamic viscosity using exponential decay functions and for density using linear equations of state based on the Boussinesq approximation; and (3) validate the proposed models against experimental measurements at the physiological temperature of 37°C to provide accurate thermophysical parameters intended for use in in vitro hemodynamics, PIV, CFD simulations, and heat transfer studies. While this study focuses on thermorheological characterization, the resulting datasets and correlations are specifically designed to serve as input parameters for future PIV and CFD investigations. By providing reproducible, temperature-resolved property datasets for commonly used XG concentrations and validated mathematical models, this work provides a reliable thermophysical foundation for improved experimental–numerical interoperability in cardiovascular research and offers a practical reference for researchers designing blood analog experiments.

2. MATERIALS AND METHODS

In this study, Xanthan gum (XG) aqueous solutions were prepared to investigate blood-analog fluid behavior. The test fluids consisted of dilute solutions containing 0.06% and 0.12% (w/w) Xanthan gum dissolved in distilled water. The solutions were prepared by gradually adding XG powder to deionized water under constant stirring at room temperature (21 °C) using a magnetic stirrer. To ensure complete hydration and homogeneity, the mixture was stirred continuously for 90 minutes. Subsequently, the solutions were left to rest for 5 days at room temperature to eliminate entrapped air bubbles and stabilize the rheological structure. Prior to measurements, the solutions were homogenized again using a magnetic stirrer.

Figure 1. Experimental setup for thermophysical characterization: (a) Rudolph Research Analytical Density Meter for high-precision density readings, and (b) Anton Paar SVM 2001 viscometer used for temperature-dependent dynamic viscosity measurements

The thermophysical properties of the prepared xanthan gum solutions were characterized using specialized instrumentation. Density and viscosity measurements were performed using a Rudolph Research Analytical Density Meter and an Anton Paar SVM 2001 viscometer, respectively (Figure 1). These devices were selected for their high precision and integrated temperature control systems, ensuring data consistency across the 15°C to 40°C range. Estimating parameters for temperature–viscosity models is achieved either through direct calculation using a few specific data points or by regression analysis using multiple measurements. The measurement procedure was carefully standardized to ensure high fidelity and repeatability. For density measurements, approximately 5 mL of the sample was injected into the Rudolph Research Analytical Density Meter using a gastight syringe to eliminate the formation of micro-bubbles within the oscillating U-tube cell. For viscosity characterization, the Anton Paar SVM 2001 utilized its integrated Peltier thermostatting system to maintain temperature stability within ±0.03°C. Before recording any data, a 10-minute waiting period was observed at each thermal setpoint (15°C and 37°C) to allow the xanthan gum solutions to reach complete thermal equilibrium. To minimize experimental error, each test was performed in triplicate, and the arithmetic mean of these runs was used for subsequent mathematical modeling and thermodynamic analysis.

The mathematical model was specifically calibrated using 15°C and 37°C as they represent the operational extremes of most *in vitro* hemodynamic experiments ranging from cold-start laboratory conditions to regulated physiological states. While the model uses these anchor points, the monotonic nature of xanthan gum's thermal thinning ensures that the exponential decay function (Eq. 1) remains physically consistent between these boundaries. The high conformity observed near the 37°C reference point validates the model for its intended use in cardiovascular simulations, where precise property estimation at body temperature is paramount. Future studies may incorporate additional intermediate points to further refine the curve-fitting at sub-physiological temperatures where structural hysteresis is more pronounced.

These mathematical procedures apply to both Newtonian fluids and non-Newtonian fluids (provided the latter are measured at constant shear rates). While the models focus on dynamic viscosity, they are also applicable to kinematic viscosity since density changes are minimal compared to viscosity shifts; however, these models generally fail near boiling or freezing points, or at temperatures high enough to cause chemical changes [9]. All experimental measurements were conducted at two distinct temperatures: 15 °C and 37 °C. The kinematic viscosity was calculated by dividing the dynamic viscosity by the corresponding density (ρ), as shown in Table 1.

Table 1. Experimental thermophysical properties of the working fluids at 15°C and 37°C.

Temperature	**Fluid Concentration**	**Dynamic Viscosity (Pa·s)**	**Density (kg/m^3)**	**Kinematic Viscosity (m^2/s)**
15 °C	0.06% (w/w) XG	0.004056	998.6	4.062 ×10-6
	0.12% (w/w) XG	0.005497	999.9	5.498 ×10-6
37 °C	0.06% (w/w) XG	0.002090	995.3	2.100 ×10-6
	0.12% (w/w) XG	0.003779	995.6	3.796 ×10-6

The xanthan gum concentrations of 0.06% and 0.12% (w/w) were specifically selected to represent the rheological spectrum of human blood. The 0.12% concentration exhibits a dynamic viscosity of approximately 3.78 mPa·s at a physiological temperature of 37°C, which closely aligns with the average blood viscosity of a healthy adult (typically ranging from 3.0 to 4.0 mPa·s). The 0.12% concentration serves as a baseline for normal physiological conditions, while the 0.06% concentration was chosen to represent low-hematocrit (anemic) blood conditions and to investigate the transition threshold between Newtonian and non-Newtonian (shear-thinning) behavior. To analyze the thermorheological behavior of the solutions, the temperature dependence of viscosity and density was modeled using empirical correlations calibrated with the experimental data [9].

For dynamic viscosity, an exponential decay model was applied, as polymer solutions typically exhibit Arrhenius-type behavior where viscosity decreases exponentially with increasing temperature. For density, a linear equation of state based on the Boussinesq approximation was used to describe the thermal expansion. The mathematical models and their governing equations are presented in Table 2. The model parameters (constant b and thermal expansion coefficient α) were determined by curve fitting the experimental data relative to the physiological reference temperature (T_0 = 37°C).

Table 2. Mathematical models used for the temperature-dependent thermophysical properties.

Property	**Model Name**	**Equation**	**Parameters**
Dynamic Viscosity [9, 10]	Exponential Decay	$\mu(T) = \mu_0 e^{-b[T-T_0]}$ (1)	μ_0: Ref. Viscosity@37°C b: Decay constant (0.025)
Density [11]	Linear (Boussinesq)	$\rho = \rho_0[1 - \alpha(T - T_0)]$ (2)	ρ_0: Ref. Density@37°C α: Thermal exp. coeff.

2.1. Determination of Thermodynamic and Dimensionless Parameters

To elucidate the physical mechanisms governing the thermal thinning behavior and to evaluate the heat transfer characteristics of the blood-mimicking fluids, thermodynamic and dimensionless parameters were calculated based on the experimental viscosity data.

Flow Activation Energy (E_a):

The flow activation energy (Eq.3), representing the energy barrier for molecular motion, was determined using the linearized Arrhenius equation:

$$\ln(\mu) = \ln(A) + \frac{E_a}{R}\left(\frac{1}{T}\right) \quad (3)$$

where μ is the dynamic viscosity (Pa·s), A is the pre-exponential factor, R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature (K). E_a was calculated from the slope of the natural logarithm of viscosity versus the reciprocal of absolute temperature (1/T).

Prandtl Number (Pr):

The Prandtl number (Eq.4), a dimensionless parameter representing the ratio of momentum diffusivity to thermal diffusivity, was calculated to assess the relative dominance of viscous effects over thermal conduction. The calculation was performed using the following relation:

$$Pr = \frac{c_P \mu}{k} \quad (4)$$

Given the dilute nature of the xanthan gum solutions (>99% water content), the thermal properties were assumed to be dominated by the solvent. Therefore, the specific heat capacity (Cp) and thermal conductivity (k) of water were taken as constant values of 4180 J/kg·K and 0.6 W/m·K, respectively, for the calculation range.

2.2 Uncertainty Analysis

The experimental uncertainties were estimated using the rigorous Kline and McClintock[12] method, which is a standard approach for calculating the propagation of errors in single-sample experiments. This method accounts for the combined effects of multiple independent variables specifically instrument accuracy, temperature stability, and measurement repeatability on the final calculated values of density and viscosity. Based on the manufacturer's specifications for the Rudolph Research Analytical Density Meter and Anton Paar SVM 2001, along with the observed temperature stability of ±0.03°C, a comprehensive error propagation analysis was performed. The results indicate that the maximum combined relative uncertainty for dynamic viscosity is 1.2% and for density is 0.05%. These values confirm that the experimental data are highly reliable and suitable for high-precision applications such as CFD simulations and PIV measurements.

3. RESULTS AND DISCUSSION

This section presents the experimental characterization and mathematical modeling of the thermophysical properties of dilute xanthan gum aqueous solutions (0.06% and 0.12% w/w), focusing on the temperature-dependent variations of dynamic viscosity and density to evaluate their suitability as blood-mimicking fluids.

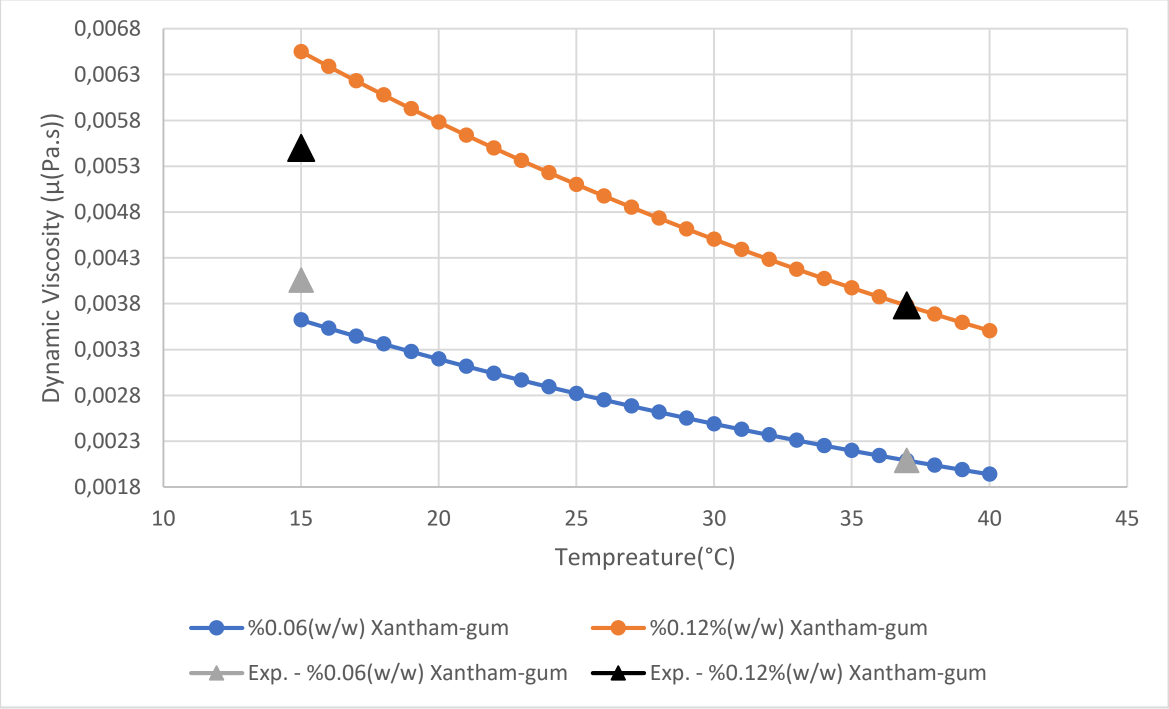

Figure 2. Temperature-dependent dynamic viscosity profiles of Xanthan gum aqueous solutions and comparison of the exponential model with experimental data for 0.06% and 0.12% (w/w)

Figure 2 shows the temperature-dependent dynamic viscosity of 0.06% and 0.12% (w/w) xanthan gum aqueous solutions over the range of 15–40 °C, together with the corresponding exponential model fits. For both concentrations, viscosity decreased continuously and monotonically with increasing temperature, which is characteristic of polymer solutions and consistent with thermally activated flow behavior [13–15]. Across the entire temperature range, the 0.12% (w/w) solution exhibited higher viscosity than the 0.06% (w/w) solution. This concentration-dependent behavior reflects the increase in intermolecular interactions and hydrodynamic resistance with increasing polymer content [13, 16]. The approximately constant viscosity difference between the two concentrations indicates that, within the studied range, temperature and concentration effects are largely independent.

At the physiological temperature of 37 °C, the 0.12% (w/w) xanthan gum solution exhibited a dynamic viscosity of 3.78 mPa·s, which lies within the typical viscosity range of healthy adult human blood (3.0–4.0 mPa·s). This close agreement confirms the suitability of this formulation as a blood-mimicking fluid for hemodynamic applications [5]. The model (Eq. 1) was calibrated at 37 °C, yielding zero error at this reference point and high accuracy in the physiologically relevant range of 30–40 °C. The largest relative deviation (19.15%) was observed at the lowest temperature (15 °C), while deviations remained below 5% near body temperature. The larger discrepancies at low temperature are attributed to enhanced structural effects and possible thermal hysteresis in xanthan gum solutions, which are not fully captured by a simple two-parameter exponential model [16]. Nevertheless, the model performs reliably near physiological temperature, where biomedical applications are typically conducted.

In summary, the experimental results and the exponential model demonstrate that a 0.12% (w/w) xanthan gum solution provides a blood-like viscosity at 37 °C and that the proposed temperature-dependent formulation offers a practical and accurate tool for hemodynamic experiments and CFD simulations within the physiological temperature range.

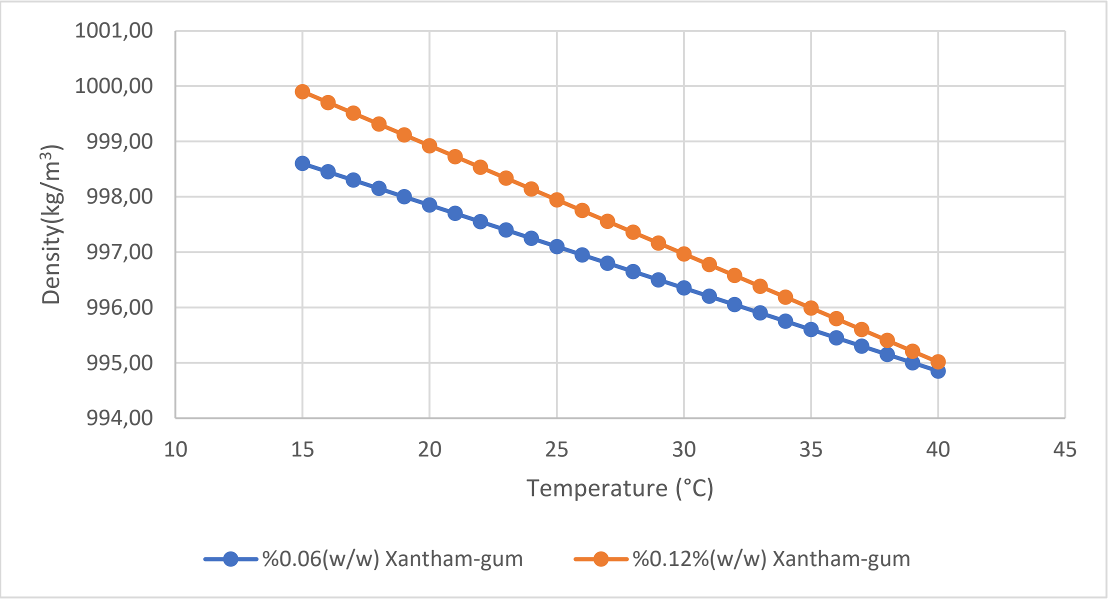

Figure 3. Temperature-dependent density variations of the working fluids and the linear decay trend obtained using the Boussinesq approximation.

Figure 3 illustrates the temperature-dependent density variations of the 0.06% and 0.12% (w/w) xanthan gum solutions over the range of 15–40 °C. For both solutions, density decreased linearly with increasing temperature. Similar linear trends have been reported in previous experimental studies on dilute xanthan gum solutions [17]. This behavior is attributed to thermal expansion, whereby an increase in temperature enhances molecular kinetic energy, leading to greater intermolecular spacing and an increase in specific volume. In dilute xanthan gum solutions, the thermal response of density is primarily governed by the solvent (water), while the contribution of the polymer remains secondary, as widely reported in the literature [18, 19].

Throughout the investigated temperature range, the 0.12% (w/w) solution exhibited higher density values than the 0.06% (w/w) solution due to its higher polysaccharide content. However, the nearly parallel density–temperature slopes observed for both solutions indicate that the thermal expansion behavior is largely independent of xanthan gum concentration, which is consistent with previously reported findings [17]. For numerical modeling, the Boussinesq approximation was employed. The total density variation remained below 0.5% over the investigated temperature range, supporting the validity of this assumption. Although the magnitude of density variation is small, accurate determination of the thermal expansion coefficient is essential for reliable estimation of the Grashof and Rayleigh numbers in natural convection simulations, as emphasized in prior studies [20].

To quantify this behavior for numerical modeling, the Boussinesq approximation was applied. This approach assumes that density variations are negligible except when they give rise to buoyancy forces. The linear equation of state derived from the experimental data is expressed as Eq. 2. The calculated coefficients were $1.507 \times 10^{-4}\ K^{-1}$ for the 0.06% solution and $1.963 \times 10^{-4}\ K^{-1}$ for the 0.12% solution. Although the total density variation over the tested range (15–40°C) was relatively small (<0.5%), accurate characterization of α is essential for the correct calculation of the Grashof number (Gr) and Rayleigh number (Ra) in future heat transfer simulations.

3.1. Thermodynamic and Heat Transfer Analysis

To further elucidate the molecular mechanism of thermal thinning and evaluate heat transfer potential, thermodynamic parameters were analyzed. First, the flow activation energy (Ea) was estimated using the linearized Arrhenius relationship ($\ln \mu$ vs. $1/T$), a method widely applied for temperature-dependent viscosity analysis of polymeric and blood-analog fluids [5]. The activation energy was calculated as $18.76\ kJ\ mol^{-1}$ for the xanthan gum solutions. This value, being slightly higher than that of pure water ($\approx 16.5\ kJ\ mol^{-1}$), reflects the additional energy barrier required to disentangle the semi-rigid xanthan chains and disrupt weak polymer–solvent associations, as previously reported for xanthan-based non-Newtonian fluids [8].

The magnitude of Ea indicates that while the fluid exhibits structural viscosity due to the presence of the polysaccharide network, its thermal sensitivity is largely governed by the aqueous solvent characteristics. Similar solvent-dominated thermal behavior has been observed in xanthan gum blood analogs, where temperature effects primarily influence viscosity through water-mediated molecular mobility rather than polymer phase. From a hemodynamic perspective, this activation energy level suggests that the blood analog maintains stable flow characteristics comparable to plasma, without undergoing drastic structural transformations such as gelation within the physiological temperature range, consistent with previous blood analog validation studies [21].

Furthermore, the dimensionless Prandtl number (Pr), representing the ratio of momentum diffusivity to thermal diffusivity, was calculated assuming that the thermal properties of the solvent dominate ($Cp \approx 4180\ J\ kg^{-1}\ K^{-1}$, $k \approx 0.6\ W\ m^{-1}\ K^{-1}$), an assumption commonly adopted for dilute xanthan gum solutions. The calculated Pr values ranged from 13.51 to 25.24 for the 0.06 % solution and 24.43 to 45.64 for the 0.12 % solution across the tested temperature range. These values are significantly higher than that of pure water ($Pr \approx 7$) and closely comparable to reported Prandtl numbers for human blood (Pr ≈ 20–25), confirming the suitability of xanthan gum solutions as thermal–hydrodynamic blood analogs. High Prandtl numbers indicate that momentum transfer dominates over thermal diffusion, resulting in a thermal boundary layer that is considerably thinner than the hydrodynamic boundary layer. This behavior has also been reported for non-Newtonian blood analog fluids and real blood flow, where heat transfer is predominantly convection-limited. Consequently, efficient heat transfer in such fluids strongly depends on flow-induced mixing mechanisms, emphasizing the importance of shear rate distribution and flow geometry in hemodynamic thermal applications.

3.2. Validation as a Blood Analog for Hemodynamic Applications

The 0.12% (w/w) xanthan gum solution demonstrated excellent suitability as a blood-mimicking fluid based on its viscosity match with healthy adult human blood at physiological temperature. Xanthan solutions are widely recognized and used as blood analogs because their shear-thinning rheology and tunable viscosity make them adaptable to mimic bulk blood behavior across a range of flow conditions [5]. Published blood-analog formulations have demonstrated that xanthan concentration can be systematically correlated with target temperatures to obtain physiologically relevant viscosities, and the present study contributes to this body of knowledge by providing precise temperature-resolved data and a validated predictive model.

For hemodynamic applications, it is recommended to validate both the zero-shear or low-shear viscosity at 37°C and the complete shear-thinning curve across the relevant shear-rate range (typically 1–1000 s^{-1} for arterial and venous flow). Documentation of model residuals and uncertainty bounds is also important so that CFD validations and PIV comparisons include appropriate error estimates and sensitivity analyses. The exponential model developed in this study provides a robust foundation for such applications, particularly for experiments conducted near physiological temperature where model accuracy is highest.

In conclusion, the experimental characterization and exponential modeling of temperature-dependent viscosity for 0.06% and 0.12% xanthan gum solutions presented in this study provide valuable data and predictive tools for researchers in biomedical engineering, cardiovascular research, and medical device testing. The validated model enables accurate interpolation of viscosity across the physiologically relevant temperature range and supports the use of xanthan gum solutions as reliable blood-mimicking fluids in in vitro experiments and computational simulations.

Table 3. Comparative properties of human blood and common blood-mimicking fluids (BMFs).

Fluid Type	**Rheological Behavior**	**Density ρ [kg/m³]**	**Viscosity μ [mPa·s] @ 37°C***	**Prandtl Number (Pr)****	**References**
Human blood	Non-Newtonian	1050–1060	3.0–4.0	20–25	[22–25]
Water-glycerol - XG	Newtonian	~1040–1100	3.0–5.0	20–30	[22, 23, 26, 27]
XG-water-glycerol (typical)	Non-Newtonian	≈1000–1060	3.0–5.0	20–40	[5, 8, 28, 29]
Dextran/$CaCl_2$ BMF	Non-Newtonian	≈1040–1060	~3.0–5.0	20–30	[23, 30, 31]

Fluid Type	**Rheological Behavior**	**Density ρ $[kg/m^3]$**	**Viscosity μ [mPa·s] @ 37°C***	**Prandtl Number (Pr)****	**References**
CMC (1%, example)	Non-Newtonian	~1000	~3.0	20–30	[32]
CMC based neurovascular analogue (1 wt%)	Non-Newtonian, shear-thinning	1000	3.0 (37 °C, CW conditions)	≈19–22	[32]
Alginate-microsphere two-phase BMF	Non-Newtonian, shear-thinning (particulate)	≈1000–1050	3.7–4.6 (37 °C, high shear)	≈23–30	[33, 34]
0.12% XG (Proposed)	Non-Newtonian	995.6	3.78	24.43–45.64	This Study

*Viscosity values refer to high shear rate plateau (≈100–1000 s^{-1}), where blood behaves quasi Newtonian.

**Pr calculated using cp≈4180 J kg^{-1} K^{-1} and k≈0.6 W m^{-1} K^{-1} as commonly assumed for aqueous BMFs.

***Estimated 37 °C values obtained by applying typical temperature viscosity correction for aqueous solutions based on reported room temperature data [32, 33, 35–37]

Table 3 provides a comprehensive comparison between the proposed 0.12% XG solution and established blood-mimicking fluids (BMFs) found in the literature. While density and viscosity values for several non-Newtonian analogs (such as CMC and Dextran-based solutions) align with human blood, the explicit determination of the Prandtl number in this study represents a distinct scientific contribution. Most existing literature focuses on purely rheological matching, often omitting dimensionless parameters critical for heat transfer. By aligning both the dynamic viscosity (3.78 mPa·s) and the Prandtl number (24.43–45.64) with physiological targets, the proposed formulation ensures a reliable baseline for cardiovascular research involving coupled thermal and momentum transport mechanisms.

4. CONCLUSION

This study presented a detailed experimental characterization of the thermophysical properties of Xanthan gum (XG) aqueous solutions to evaluate their suitability as blood analog fluids. The temperature-dependent rheological behavior and density variations were analyzed for 0.06% and 0.12% (w/w) concentrations within the thermal range of 15°C to 40°C. The novelty of this research lies in the integration of experimental thermo-physical characterization with ready-to-implement mathematical models. By anchoring the viscosity model at the physiological reference of 37°C and providing a validated decay constant, this work offers a standardized thermophysical foundation for researchers to ensure interoperability between experimental measurements and numerical simulations. The selected concentrations were specifically justified by their alignment with healthy adult blood viscosity (0.12%) and the representation of the Newtonian to non-Newtonian transition threshold (0.06%). The major conclusions drawn from this research are summarized as follows:

- Blood Analog Suitability: The 0.12% (w/w) Xanthan gum solution demonstrated rheological properties highly comparable to healthy human blood. Specifically, its dynamic viscosity at the physiological temperature of 37°C was measured as approx. 3.78 mPa·s, falling within the standard range of human blood viscosity (3.0–4.0 mPa·s).
- Mathematical Modeling: The temperature dependence of dynamic viscosity was successfully modeled using an exponential decay function (Eq. 2) with a decay constant

of b=0.025. Similarly, the density variation was accurately described by a linear equation of state based on the Boussinesq approximation.

- Model Accuracy and Validation: The proposed viscosity model was calibrated at the physiological reference temperature (37°C), achieving 0% error at this critical point. Quantitative error analysis against experimental data at the lower thermal boundary (15°C) revealed a maximum deviation of 19.15%. This confirms that the model provides a highly accurate representation of the fluid's behavior under physiological conditions, while remaining within acceptable uncertainty limits for broader thermal ranges.
- Thermodynamic analysis revealed a flow activation energy of 18.76 kJ mol^{-1}, indicating stable plasma-like flow characteristics without abrupt structural phase transitions. Furthermore, the calculated Prandtl numbers (ranging from 24.43 to 45.64 for the 0.12% solution) closely align with human blood values ($Pr \approx 20–25$), confirming that momentum transfer dominates over thermal diffusion and demonstrating the fluid's suitability for convection-limited hemodynamic heat transfer applications
- Thermophysical Parameters: The thermal expansion coefficients were determined experimentally, providing essential data for future computational simulations involving buoyancy-driven flows or natural convection.
- The derived mathematical models and the specific decay constant (b = 0.025) are formulated to be directly compatible with Computational Fluid Dynamics (CFD) codes. By integrating these parameters into temperature-coupled solvers via User-Defined Functions (UDF), researchers can significantly improve the accuracy of hemodynamic simulations involving thermal gradients, such as hyperthermia treatments or blood-warming procedures

Recommendations for Future Work; Based on the characterization results, the following recommendations are proposed:

- CFD Implementation: The derived mathematical models and the decay constant (b=0.025) can be implemented into Computational Fluid Dynamics (CFD) codes to improve the accuracy of hemodynamic simulations involving heat transfer (e.g., hyperthermia treatments or blood warming devices).
- Experimental Utilization: The 0.12% XG solution is recommended for use in Particle Image Velocimetry (PIV) and flow visualization studies where a transparent, non-Newtonian blood analog is required without the optical complications of real blood.
- Shear Rate Analysis: While this study focused on temperature dependence, future characterization should comprehensively map the viscosity changes over a wider range of shear rates to fully capture the non-Newtonian flow behavior in complex geometries.

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