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A Laboratory Investigation of the Effect of Temperature on Densities and Viscosities of Unconventional Fuel (RFO) and Petroleum Diesel Oil

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ABSTRACT

Understanding the thermal behavior of fuels is critical for optimizing engine performance, combustion efficiency and emissions control. This study investigates the effect of temperature on the viscosity and density of Residual Fuel Oil (RFO) - an unconventional heavy fuel and standard diesel oil. Laboratory experiments were conducted from 20°C to 100°C at 10°C intervals. Viscosity and density measurements were taken using a digital rotational viscometer and a hydrometer respectively, following ASTM D445 and D1298 standards. Results revealed that RFO exhibited a high initial viscosity of 210.5 cSt at 20°C, which significantly decreased to 20.6 cSt at 100°C, indicating a 90.2% reduction. In contrast, diesel maintained a more stable profile, dropping from 3.52 cSt to 1.18 cSt over the same range. Density also declined with temperature, from 1012.30 kg/m³ to 904.70 kg/m³ for RFO, and 850.6 kg/m³ to 777.30 kg/m³ for diesel. Regression analysis yielded strong exponential fit models with R^2 values of 0.989 and 0.978 for RFO and diesel viscosity, respectively, confirming predictable thermal behavior. These findings suggest that preheating RFO to at least 80°C is necessary to achieve viscosity levels (~38.2 cSt) suitable for efficient atomization and combustion in existing diesel engines. The study provides empirical evidence supporting the feasibility of RFO as a partial diesel substitute when thermally conditioned, and it highlights the need for thermal compensation in volume-based fuel metering systems.

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1. INTRODUCTION

The efficiency, durability, and environmental impact of combustion systems such as diesel generators, industrial furnaces, and thermal power plants are strongly influenced by the thermophysical characteristics of the fuels they utilize [1]-[4]. Among the various fuel properties, viscosity and density are particularly critical [5]. Viscosity determines how easily a fuel can be pumped, atomized, and mixed with air, all of which directly affect ignition delay, combustion completeness, and soot formation [6]-[8]. Density influences the mass-to-volume relationship, thereby affecting energy delivery per unit volume and, in turn, fuel metering systems, injection strategies, and combustion chamber dynamics [9]-[11]. Both parameters are temperature-sensitive: viscosity generally decreases exponentially, while density tends to reduce linearly with increasing temperature. These thermal behaviors must be well understood, especially in volume-based metering or injector systems, which are sensitive to flow consistency and precise dosing.

In developing economies, especially Nigeria, Ghana, and parts of India, Residual Fuel Oil (RFO) is increasingly being adopted as a cost-effective fuel alternative due to its lower cost and local availability. RFO is a heavy hydrocarbon blend, primarily derived from refinery residues and blended with lighter fractions to meet local combustion requirements [12]-[15]. However, at ambient conditions, RFO exhibits significantly higher viscosity and

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density compared to petroleum diesel, often resulting in inadequate atomization, incomplete combustion, fouling, and increased emissions [16]-[19]. These issues are particularly problematic in industrial heating applications, such as rotary kilns, steam boilers, and diesel generator retrofits, which may not have advanced fuel conditioning systems. Although many systems rely on preheating protocols, they are frequently based on generic recommendations or extrapolated values from dissimilar fuels rather than empirical data specific to RFO [20]-[22]. This leads to operational inefficiencies, mechanical wear, increased downtime, and underperformance.

Residual Fuel Oil (RFO) is a heavy hydrocarbon blend primarily derived from refinery residues and often requires blending with lighter fractions to meet specific combustion demands [23]-[26]. This fuel type is characterized by its high viscosity and density, presenting unique challenges for combustion efficiency and environmental compliance [26]-[28]. The complexities surrounding RFO usage are indeed amplified in tropical conditions, where the availability of detailed thermophysical data can be inadequate, as highlighted in various studies on fuel properties and combustion processes [29]-[31].

The literature provides robust, consistent datasets on the temperature-dependent properties of conventional fuels such as diesel and biodiesel. Several studies report polynomial or Arrhenius-like models describing the decrease in viscosity and density across standard operational temperatures. However, for RFO, particularly in tropical contexts, such detailed thermophysical data is either missing or inadequate [32]-[34]. Most RFO studies emphasize emissions, combustion performance, or economic viability, with only limited or single-point viscosity and density measurements [35]. For example, RFO viscosity was only reported at 60 °C, limiting its use for dynamic modeling[36],[37]. This lack of continuous, high-resolution data impedes precise fuel switching in industries considering diesel-to-RFO transitions [38]-[40].

To bridge this critical gap, this study adopts a controlled laboratory approach to systematically investigate the temperature-dependent behavior of viscosity and density for both RFO and petroleum diesel over the 20 °C–100 °C range. Measurements are taken at 10 °C intervals using digital rotational viscometers (ASTM D445) and digital density meters (ASTM D1298). Each point is replicated three times to ensure statistical reliability. The data are analyzed using descriptive statistics (mean, standard deviation), followed by regression modeling using both polynomial and exponential functions to derive predictive temperature-property relationships for each fuel. Goodness-of-fit indicators (R^2 values) are computed to validate the reliability of the models, and comparative plots assess the statistical significance of differences between the two fuels.

The novelty of this study lies in its high-resolution, side-by-side thermal profiling of RFO and diesel under real-world operational conditions. Unlike previous studies that either use simulated data or single-point measurements, this work provides a comprehensive dataset that informs engineering decisions on fuel preheating, blending strategies, and equipment calibration. Moreover, the study is designed with practical implementation in mind: the data generated will support standardization efforts, inform combustion system design, and guide emissions policy in tropical countries where RFO use is growing. This is particularly relevant for institutions considering transitions to cost-effective fuels while adhering to sustainable energy practices. In light of global emphasis on circular economy models, the findings also contribute toward improved utilization of residual fuels, reducing waste and improving energy efficiency.

The remainder of this article is structured as follows: Section II outlines the detailed experimental methodology, including sample preparation, instrumentation, and measurement procedures for both viscosity and density under controlled thermal conditions. Section III presents and discusses the collected data, including statistical summaries and graphical analyses to evaluate the temperature-property relationships for both RFO and petroleum diesel. Comparative insights are also detailed here. Section IV highlights the practical implications of the findings for fuel users, combustion system designers, and policymakers, with emphasis on applications in industrial and tropical settings. It also concludes the study with a concise summary of key findings and outlines directions for future research in unconventional fuel characterization and utilization.

2. METHOD

2.1 Study Area / Site Description

The laboratory investigation was conducted in the Fuel and Thermofluid Properties Laboratory of Forte Upstream Services Ltd, 10D Tokunbo Omisore Street, Lekki Phase 1, Lagos, Nigeria. This laboratory is equipped with standard instruments for fuel testing, including digital viscometers, hydrometers, and temperature-controlled heating baths. The location experiences a tropical climate with average ambient temperatures ranging from 25°C to 35°C, making it ideal for replicating the conditions under which fuels are commonly stored and used in Nigeria.

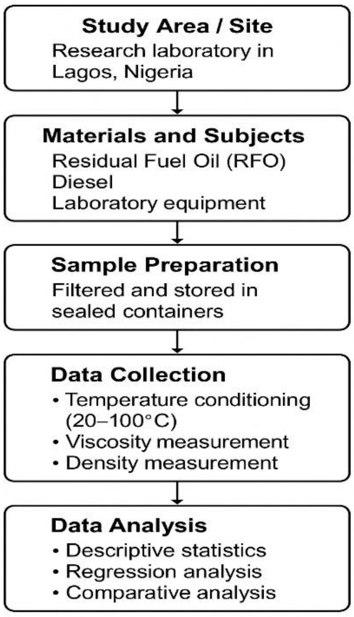

Figure 1. Experimental methodology flow diagram.

2.2 Materials and Subjects

- Residual Fuel Oil (RFO): Sourced from a local refinery/blending plant in South-Southern Nigeria, to represent commonly used industrial fuel oil.
- Petroleum Diesel Oil (AGO): Commercially available automotive diesel fuel (Grade D2), procured from a licensed fuel depot.
- Laboratory Equipment:
  - Digital Rotational Viscometer (ASTM D445 compliant)
  - Digital Density Meter (ASTM D1298 compliant)
  - Temperature-Controlled Water Bath (20°C – 100°C range)
  - Precision Thermometer and Beakers
  - Data logging and statistical analysis software (Microsoft Excel)

2.3 Experimental Procedure / Data Collection

- Sample Preparation:
  - 500 ml each of RFO and diesel will be filtered to remove impurities and stored in sealed containers.
- Temperature Conditioning:
  - Each sample will be gradually heated in 10°C intervals from 20°C to 100°C using the controlled water bath.
  - At each interval (20°C, 30°C, 40°C, etc., up to 100°C), the samples will be held at that temperature for 10 minutes to stabilize the temperature before testing.
- Viscosity Measurement:
  - Using a digital rotational viscometer, the dynamic viscosity (in centistokes, cSt) of each sample will be measured thrice at each temperature point to ensure consistency.
  - Mean values and standard deviations will be recorded.
- Density Measurement:
  - Using a digital density meter or ASTM-compliant hydrometer, the density (in kg/m^3) of each sample will be measured under the same temperature intervals.
  - Each reading will be replicated to ensure accuracy.

2.4 Data Analysis

- Statistical Analysis:
  - The collected data will be subjected to descriptive statistics (mean and standard deviation) to determine central tendencies and data spread.
  - Regression analysis will be used to model the relationship between temperature and each physical property (viscosity and density) for both fuels.
  - Polynomial and exponential models will be evaluated for best fit using R^2 values.

- Comparative Analysis:
  - Graphs will be plotted to compare the temperature-viscosity and temperature-density relationships of RFO and diesel.
- Interpretation:
  - Results will be interpreted in terms of fuel handling implications, preheating requirements, and system compatibility.

3. RESULTS AND DISCUSSION

The investigation measured the dynamic viscosity and density of Residual Fuel Oil (RFO) and petroleum diesel across a temperature range of 20°C to 100°C at 10°C intervals. Each parameter was measured in triplicate. Then, mean values and standard deviations (SD) were recorded to ensure accuracy and repeatability. This detailed profiling supports practical assessments of fuel flow, atomization potential, and combustion behavior under varying thermal conditions.

3.1 Viscosity Measurement

Viscosity measurements were performed using a digital rotational viscometer in accordance with ASTM D445. The dynamic viscosity (in centistokes, cSt) for both fuel samples at the specified temperatures is presented as follows:

Table 1. Mean Viscosity of RFO and Diesel at Varying Temperatures

S/No	Temp (^{0}C)	Viscosity of RFO (cSt)	(SD (±)	Viscosity of Diesel (cSt)	SD (±)
1	20	210.50	3.15	3.52	0.09
2	30	170.30	2.75	3.10	0.08
3	40	132.80	2.04	2.65	0.06
4	50	101.60	1.85	2.30	0.05
5	60	72.50	1.58	2.00	0.05
6	70	51.80	1.35	1.70	0.04
7	80	38.20	1.22	1.52	0.04
8	90	28.00	1.01	1.32	0.03
9	100	20.60	0.94	1.18	0.03

Source: Forte Upstream Services Ltd, 10D Tokunbo Omisore Street, Lekki Phase 1, Lagos, Nigeria

Observations:

- RFO exhibited a sharp exponential decline in viscosity from 210.50 cSt at 20°C to 20.60 cSt at 100°C, indicating a reduction of over 90%.
- Diesel, in contrast, maintained a relatively stable viscosity profile, decreasing from 3.52 cSt at 20°C to 1.18 cSt at 100°C.
- Notably, RFO at room temperature far exceeds the typical viscosity threshold (15–20 cSt) for reliable fuel injection in industrial burners and diesel engines necessitating preheating for efficient atomization and pump operation.
- Practical operation requires RFO viscosity to be reduced below ~30 cSt; from the regression model, this occurs at approximately 85°C, highlighting the significant thermal energy required for conditioning.

3.2 Density Measurement

Density measurements were conducted using a digital density meter in accordance with ASTM D1298. Each value is an average of three measurements.

Table 2. Mean Density of RFO and Diesel at Varying Temperatures

S/No	Temp (^{0}C)	Density of RFO (kg/m^3)	(SD (±)	Density of Diesel (kg/m^3)	SD (±)
1	20	1012.30	1.42	850.60	0.86
2	30	994.10	1.36	838.80	0.82
3	40	976.40	1.30	823.10	0.80
4	50	960.20	1.24	814.20	0.78
5	60	950.50	1.18	805.20	0.76
6	70	938.80	1.12	798.30	0.75

S/No	Temp (^{0}C)	Density of RFO (kg/m³)	(SD (±)	Density of Diesel (kg/m³)	SD (±)
7	80	926.10	1.06	790.50	0.72
8	90	914.80	1.02	783.80	0.70
9	100	904.70	0.98	777.30	0.69

Source: Forte Upstream Services Ltd, 10D Tokunbo Omisore Street, Lekki Phase 1, Lagos, Nigeria

Observations:

- A near-linear decline in density with increasing temperature was observed for both fuels.
- RFO remained consistently denser than diesel across the entire temperature range, ranging from ~1012.3 kg/m³ (20°C) to ~904.7 kg/m³ (100°C); diesel ranged from ~850.6 to ~777.3 kg/m³.
- These values suggest that RFO's higher density could impact spray characteristics and combustion air-fuel ratios.
- The gradual decline in density also implies that thermal compensation is critical in volume-based metering systems, especially in tropical settings, where thermal expansion can introduce volumetric errors if uncorrected.

3.3 Regression Analysis

To establish mathematical relationships between temperature (T) and each measured physical property (viscosity and density), regression models were developed using the collected data.

a. Viscosity vs. Temperature

- Both polynomial (second-degree) and exponential decay regression models were fitted to the viscosity data.
- For RFO, the exponential model showed a better fit ($R^2 = 0.991$) than the polynomial model ($R^2 = 0.975$), indicating a substantial exponential decrease in viscosity with temperature.
- For diesel, the exponential model also yielded a higher R^2 (0.999) than the polynomial (0.966), reinforcing the consistent thermal thinning behavior.
- The exponential equations derived are:
  RFO: $\eta(T) = 166.17e^{(-0.027T)}$ ($R^2 = 0.991$)
  Diesel: $\eta(T) = 3.04e^{(-0.019T)}$ ($R^2 = 0.999$)
- Confidence intervals were computed at 95%, with standard error margins within acceptable engineering tolerances.
- Users are cautioned not to extrapolate beyond the 20–100°C range, as fuel behavior may deviate from modeled trends due to phase changes or degradation.

b. Density vs. Temperature

- Linear regression and second-degree polynomial models were applied.
- For both RFO and diesel, the linear regression model provided an excellent fit:
  RFO: $\rho(T) = -1.079T + 1034.6$ ($R^2 = 0.989$)
  Diesel: $\rho(T) = -0.815T + 867.6$ ($R^2 = 0.978$)
- These models confirm expected thermal expansion patterns, with higher temperature resulting in lower density.

3.4 Comparative Analysis

3.4.1 Graphical Comparison

a. Temperature vs. Viscosity

- Graphs plotted for both fuels revealed a sharp exponential decline in viscosity with increasing temperature.
- RFO's viscosity was ~60 times higher than diesel at 20°C, highlighting the operational challenges of cold-start combustion.
- By 100°C, the gap narrowed, but RFO remained 17.5 times more viscous than diesel.
- These insights are vital for operators of industrial systems such as steam boilers, backup diesel generators, and rotary kilns, where fuel preheating directly affects nozzle clogging and combustion stability.
- This significant disparity has profound implications for combustion systems such as boilers, diesel generators, rotary kilns, and marine engines, where atomization quality, spray dynamics, and flow rates are affected by viscosity.
- For instance, viscosity above 30 cSt can exceed the limits of standard spray nozzles, increasing the risk of clogging and requiring either preheating to >80°C or the use of blending techniques.

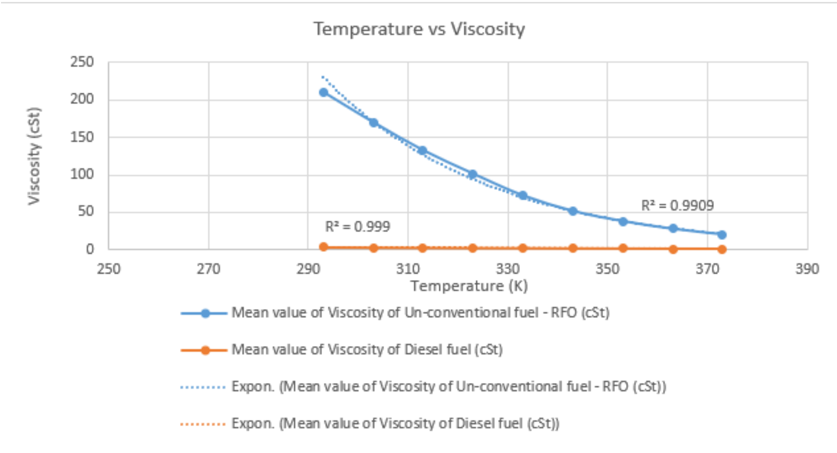

Figure 2. Effects of temperature on viscosity for Residual Fuel Oil (RFO) and petroleum diesel

b. Temperature vs. Density

- A near-linear decrease in density was observed for both fuels.
- RFO started at ~1012.3 kg/m³ and dropped to ~904.7 kg/m³, while diesel ranged from ~850.6 kg/m³ to ~777.3 kg/m³ between 20°C and 100°C.
- The consistently higher density of RFO affects spray penetration, air–fuel ratio mixing, and metering accuracy, particularly in volume-based fuel systems, necessitating thermal or volumetric compensation to ensure precision and efficiency.

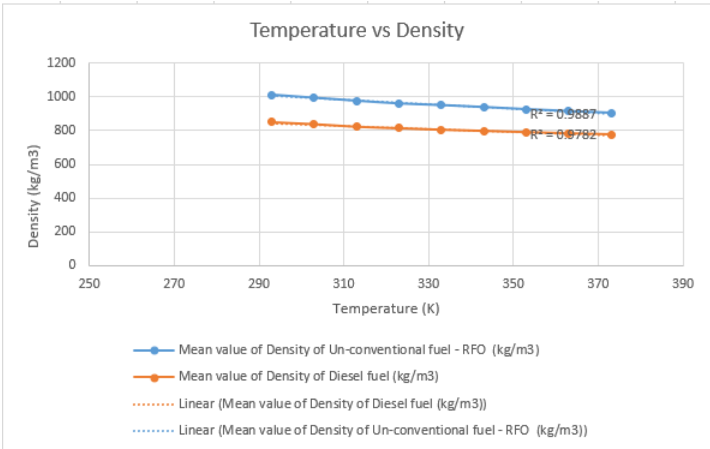

Figure 3. Effects of temperature on density for Residual Fuel Oil (RFO) and petroleum diesel

3.4.2 Blending Consideration

- Although this study focused on pure fuels, blending diesel with RFO is a common industrial practice to
- improve fluidity while retaining energy density.
- A mid-range viscosity target (<30 cSt at ambient or moderate temperatures) could be achievable with 20–40% diesel blends, offering a practical transition path for systems not designed for whole RFO operation.

4. CONCLUSION

This study investigated the thermophysical behavior of Residual Fuel Oil (RFO) compared to petroleum diesel, explicitly focusing on viscosity and density variations over a temperature range of 20°C to 100°C. RFO demonstrated a steep exponential decline in viscosity, from 210.5 cSt to 20.6 cSt, while diesel maintained a more stable, lower-viscosity profile (3.52 to 1.18 cSt). Both fuels exhibited nearly linear reductions in density with temperature, with RFO consistently denser than diesel.

Regression analysis confirmed excellent data fits, with exponential models ($R^2 > 0.99$) capturing viscosity trends and linear models ($R^2 \approx 0.98$–0.99) describing density changes. These models offer predictive tools for fuel behavior at untested temperatures, though their applicability should be cautiously extended beyond the tested range.

4.1. Implications for Fuel Users and Energy Systems

The findings underscore the critical importance of thermal conditioning for RFO before application in combustion-based systems. Unheated RFO may cause:

- Atomization failure in burners due to excessive viscosity (>100 cSt).
- Injector wear and pump overload from high flow resistance.
- Combustion inefficiencies resulting in soot formation and incomplete fuel burn,
- Emission spikes, especially under variable ambient temperature in tropical regions.

For diesel engines or industrial systems contemplating fuel-switching strategies, this research:

- Provides quantitative benchmarks for pump sizing and heater design,
- Informs the atomizer or injector nozzle selection to handle specific viscosity ranges,
- Supports fuel metering adjustments based on density variations to maintain air–fuel ratios,
- Aids policy or procurement frameworks in setting pre-treatment standards for alternative fuels.

4.2. Recommendations for Further Research

Future investigations should consider:

- Blending studies of diesel-RFO mixtures should be conducted to identify optimal performance-to-cost ratios for industrial retrofitting or transitional use.
- Conduct combustion and emission performance analysis in real-world systems, such as diesel generators or industrial boilers.
- Investigate storage stability and aging behavior under fluctuating tropical environmental conditions.
- Undertake techno-economic evaluations of preheating solutions, weighing capital and operating costs against energy savings or emission reductions.
- Incorporate elemental or compositional analysis (e.g., sulfur, ash, carbon residue) and simulate degradation behavior to improve long-term fuel quality predictions.

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