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An Experimental Evaluation of Thermal Conductivity of Colloidal Suspension of Carbon-Rich Fly Ash Microparticles and Diamond-Nano Powder (DNP) in Jet-A Fuel

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Abstract
This study investigates the enhancement of thermal conductivity in Jet-A fuel by dispersing carbon-based micro/nano materials, specifically Carbon Fly Ash (CFA) and Diamond Nano Powder (DNP). CFA, derived from heavy fuel oil combustion and rich in unburned carbon and inorganic oxides, possesses a porous structure, while DNP is renowned for its high thermal conductivity. Both materials were introduced into Jet-A fuel to assess their impact on heat transfer properties. Colloidal suspensions were stabilized using a two-step process involving surfactant addition and sonication, with stability lasting between 20 to 60 minutes, depending on particle concentration. Thermal conductivity measurements under controlled heat flux conditions revealed that a 2% DNP concentration increased thermal conductivity by 2%, whereas a 3% CFA concentration resulted in an 8% improvement comparable to activated carbon nanoparticles. The significant enhancement by CFA is attributed to its porous structure and trace iron content, making it a promising additive for fuel performance improvements. This study highlights the potential of CFA and DNP to enhance thermal properties in Jet-A fuel, while also identifying the challenges in colloidal stability, particularly for DNP.

***Keywords*:** Carbon Fly Ash (CFA), Diamond Nano Powder (DNP), Thermal conductivity, Jet-A fuel, Colloidal suspension Stability

1. Introduction

During the combustion of heavy fuel or crude oil in boilers, intense heat and oxidation deplete the fuel, while impurities like sulfur, vanadium, and nickel undergo chemical transformations to form ash particulates [1]. About 3 kg of ash is produced per kiloliter of heavy fuel oil, with 90% being fly ash, which is collected by electrostatic precipitators or cyclones for disposal or reuse. Heavy Carbon Oil Fly Ash (CFA) mainly contains SiO_2, Fe_2O_3, Al_2O_3, and 70–80% unburned carbon [2]. Salah et al. [3] highlighted HOFA's unique porous structure, suggesting applications in cement and concrete for sustainable construction. Studies show that incorporating CFA into epoxy resin enhances tensile strength and affects thermal conductivity and diffusivity [4]. CFA also functions as an anti-corrosion agent for steel coatings, a lubricant additive in base oils [10], and is used in alkali metal ion batteries and water treatment. The incorporation of micro- and nano-sized particles into liquid fuels has been extensively researched, demonstrating enhancements in properties such as thermal conductivity [5]. The inclusion of carbon materials, whether in nano or micron dimensions, has been shown to improve optical properties and combustion rates. For instance, Ghamari and Ratner's experimental studies have demonstrated enhanced combustion rates for graphene nanoplatelets (GNP), multi-walled carbon nanotubes (MWCNT), and activated carbon particles in jet fuel [6]. Moreover, Aboalhamayie et al. have investigated the increased evaporation rates in Jet-A fuel, attributed to the enhanced thermal conductivity from added carbon nanomaterials [7]. Notably, the carbon content in the residue of heavy oil combustion, referred to as rich carbon fly ash, is analogous to that found in activated carbon nanomaterials used in previous studies such as [6,7]. Diamond Nano Powder (DNP), renowned for their high thermal conductivity [8], serve as a comparative benchmark for heavy oil fly ash, especially since previous research has examined CNP, GNP, and MWCNT in Jet-A fuel [6-9]. These intriguing parallels necessitate a comprehensive examination of CFA's potential, particularly its influence on key research parameters such as thermal conductivity [10]. Nanodiamonds have the potential for diverse applications, including the ability to exfoliate and convert graphite layers entirely into carbon composite spheres (CCSs) [11,12].

2. Methods

2.1. Sample preparation

Two different types of carbon-based materials were used to prepare Micro/Nano fuel samples at different concentrations: Carbon Fly Ash (CFA), also known as Heavy Oil Fly Ash (HOFA), that was directly collected from the electrostatic precipitator (ESP) of the Rabigh IPP power plant, located in Rabigh on the coast of the Red Sea in western Saudi Arabia, and Diamond Nanopowder (DNP), that were purchased from Nanostructured and Amorphous Materials Inc (Product ID 1321JGY). The elemental composition of CFA is documented in ref. [3].

Table 1: Physical properties of carbon nanoparticles (SSA: specific surface area)

Particle Type	CFA	DNP
Size (µm and nm)	30 µm	3–10 nm
True Density (g/cm^3)	1.07	3.05–3.30
SSA (m^2/g)	1.8	~280

The dimension and morphology of micro and nanoparticles can affect the way they promote heat transfer mechanisms through colloidal fuels. For instance, particles with a larger specific surface area (SSA) are expected to be more efficient in transferring heat within the liquid fuel. Figure 1 shows the morphology and microscopic structure of (a) DNP and (b) CFA.

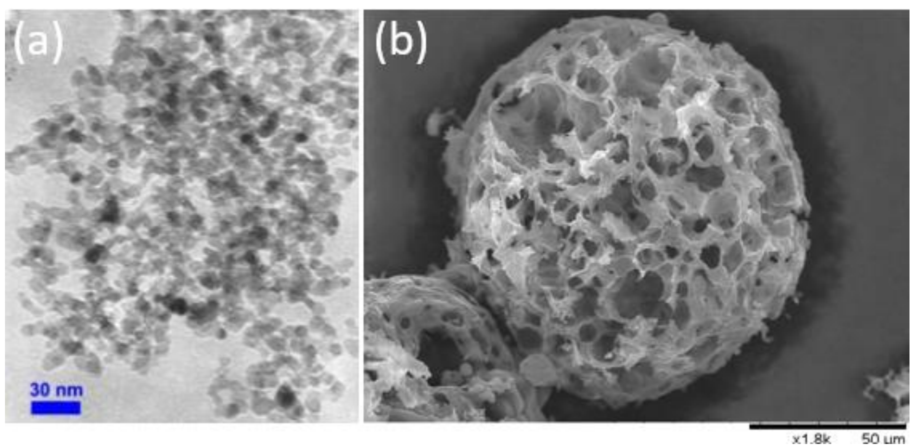

Fig. 1: (SEM) images at various magnifications:
(a) Diamond Nano Powder (DNP) and (b) carbon rich fly ash (CFA).

For successful experimental research on Micro/Nano fuels, preparing a stable colloidal suspension of micro and nanoparticles in the fuel is crucial. Stability must be maintained for at least 25 minutes to ensure accurate measurements of thermophysical properties in particular thermal conductivity which may take up to 20 minutes. To prevent particle agglomeration, a hybrid two-step method combining surfactant addition and sonication was used. A 3% (by weight) Span 80 surfactant solution in Jet-A fuel was prepared using magnetic stirring for 30 minutes. Then, particles were added and stirred for an additional 10 minutes until a homogeneous mixture formed. Samples were sonicated in an ultrasonic bath (Elmasonic S10H) at 30% power for 45 minutes, yielding colloids that remained stable for at least 20 minutes. Two tactics were applied the first one is by experimental apparatus to evaluate the stability and the second approach by the visual inspection and using flash light. Figure 2-(A) shows the experimental apparatus designed in the lab comprises an infrared (IR) laser, an IR receiver (detector), thermocouple amplifier attached with thermocouple type-K, and a microcontroller. Both the IR laser and IR receiver are powered by 3 volts. The setup is configured so that the sample is positioned centrally between the IR laser and the laser receiver. When the system is powered on, the IR laser emits a beam in a parallel direction, directly facing the IR receiver on the opposite side. As the colloidal suspension in the fuel sample begins to settle, and the medium becomes sufficiently clear, the IR laser beam passes through the glass laboratory setup. This unobstructed passage of the beam is detected by the IR receiver, which registers it as a '1.' In the absence of any laser detection or when the beam is blocked by suspended particles or any other source, the receiver continues to register '0,' indicating a clear detection or no interference in the laser's path. It worth mention that thermocouple type-K been immersed in the sample in the far left to detect if there is any increase in the temperature due to the laser radiation which is been reading as same the room temperature based on the accuracy of the interpretation of the thermocouple amplifier. Nevertheless, four laser and laser receiver provided to detect if there's any separation phase occurred in the middle of the sample or in the bottom since it is powerful methodology to understand how the stability may last for each colloidal suspension when it is been examined particularly in thermal conductivity apparatus. Stability varied by concentration: 0.25-0.5% suspensions of carbon fly ash (CFA) and Diamond Nano Powder (DNP) remained stable for up to an hour as shows in Figure 2-(B) for .15% CFA, while higher concentrations showed reduced stability (e.g., 38 minutes at 2% DNP) in Figure 3. Due to their high surface area, DNP are more prone to agglomeration, which affects suspension stability. Ensuring stability for at least 20 minutes is essential to prevent phase separation and ensure reliable measurements as summarized in Figure 3 represents variation of time stability in minutes of jet-A fuel +CFA and jet-A fuel +DNP with bar errors for at least 3 experiments for repeatability and quality of the suspension at different particle concentrations.

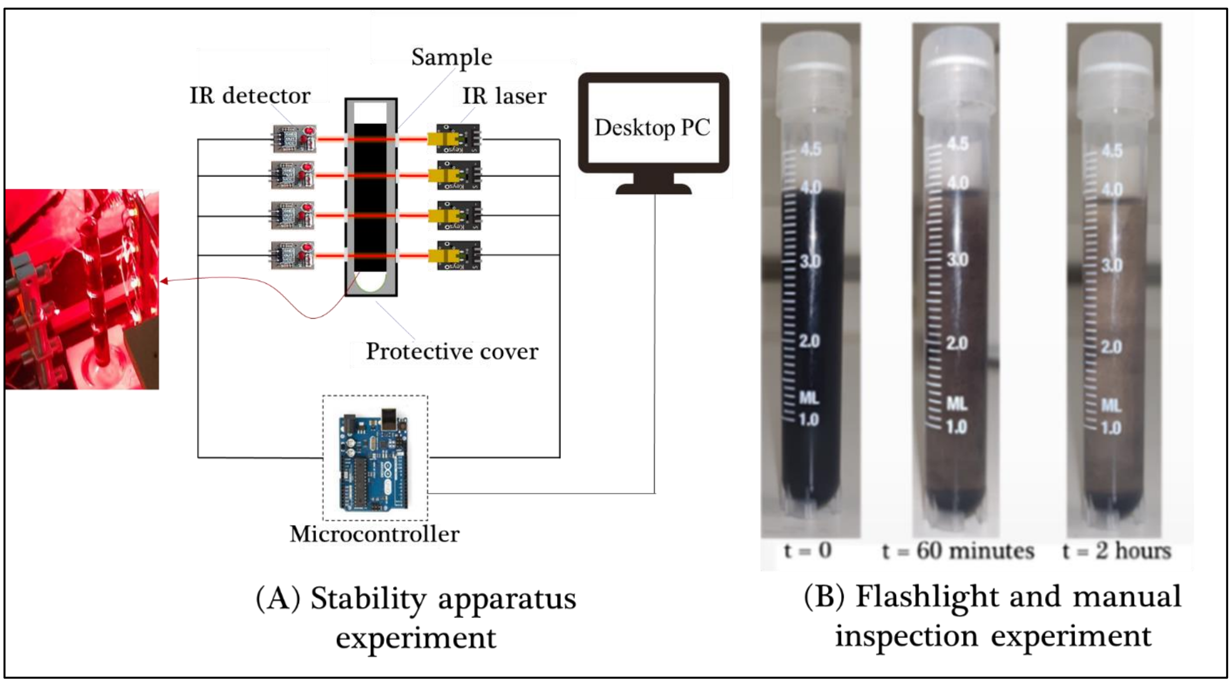

Fig. 2: (A) Schematic of stability of colloidal suspension apparatus
(B) Stability of .15% CFA in Jet-A fuel

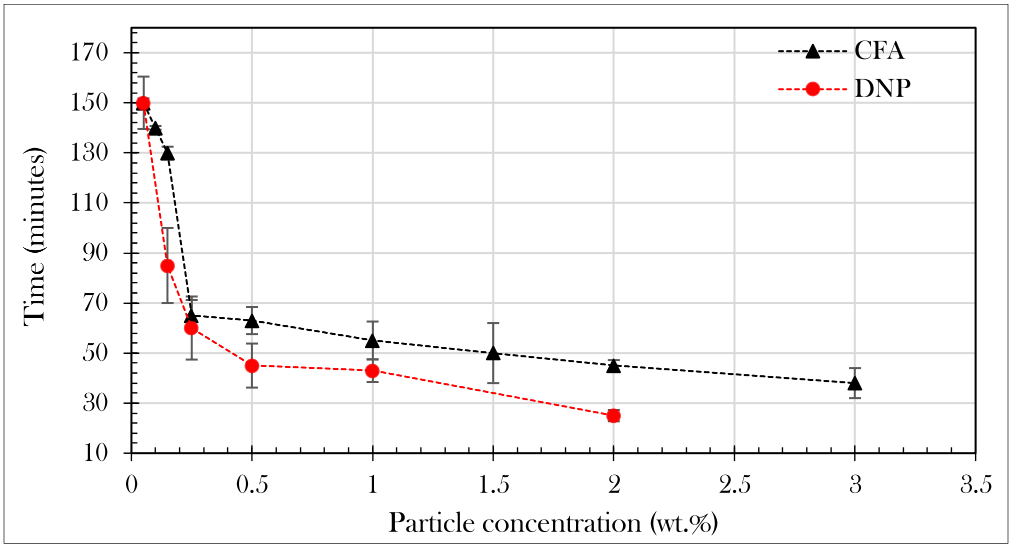

Fig. 3: Variation of time stability in minutes of jet-A fuel +CFA and jet-A fuel +DNP with bar errors at different particle concentrations

2.2 Thermal conductivity measurement

The determination of thermal conductivity in Micro/Nano fuel was conducted utilizing the Hilton Ltd H470 represented in Figure 4, employing a well-defined experimental setup: A thin radial layer of the Nano fuel sample (Δx = 0.325 mm) was subjected to controlled heating via a known resistance (R) provided by a heating element. This element was connected to a transformer, facilitating the adjustment of voltage (V) in volts to ensure a constant heat rate (V^2/R). To maintain thermal equilibrium and dissipate excess heat, a continuous flow of cold water at a rate of 3 liters per minute circulated through a cooling jacket surrounding the fuel sample. To measure the temperature difference (ΔT) across the thin Nano fuel layer with precision, two Type-K thermocouples were meticulously employed. The determination of thermal conductivity (k) for the Nano fuel sample was accomplished by rigorously applying Fourier's law of heat conduction, which asserts that by Equation (1), where A denotes the cylindrical surface area exposed to the heat rate ($Q^{\cdot}$) known as heat flux, liquid thickness (Δx), and temperature gradient (ΔT). The evaluation of thermal conductivity involved an in-depth examination of Nano fuel samples incorporating micro-particles derived from heavy oil-rich fly ash, with concentrations spanning from negligible levels up to 1%. These concentration levels were systematically measured at intervals of 0.05%, 0.1%, 0.15%, 0.25%, 0.5%, 1%,1.5%, 2%, and 3%. For each concentration, a trio of distinct heat fluxes was meticulously administered, with voltage settings set at 100, 120, and 140 V, all meticulously tailored to the liquid samples. Temperature measurements were conducted with precision on both sides of the liquid sheet, and the mean temperature of the fuel sample was accurately recorded once thermal equilibrium had been satisfactorily reached.

$$Q^{\cdot} = k \cdot A \cdot (\Delta x/\Delta T) \quad (1)$$

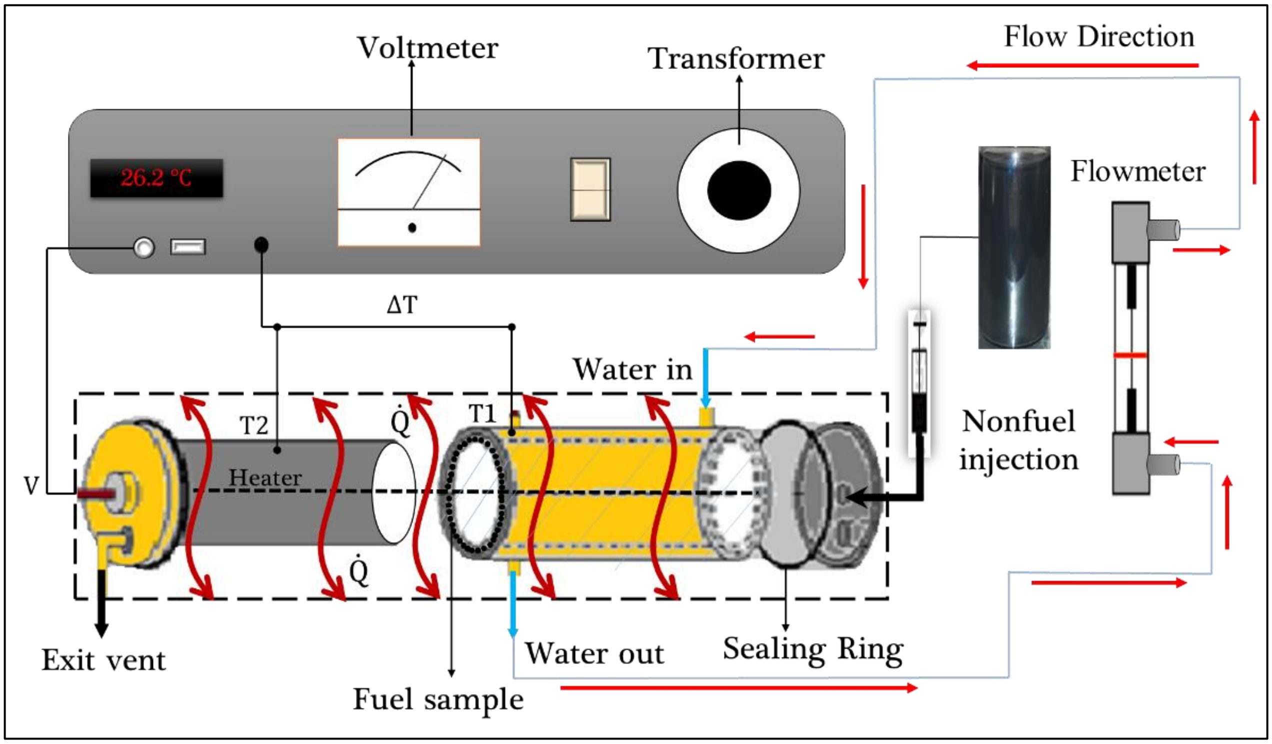

Fig. 4: Schematic of thermal conductivity apparatus device

3. Result and Discussion

3.1. Thermal conductivity of suspended CFA and DNP in Jet-A fuel

The application of three distinct heat rates to each sample, accompanied by temperature monitoring until thermal equilibrium was reached, revealed only minor fluctuations in thermal conductivity across varying particle concentrations. As illustrated in Figure 5, the thermal conductivity of both CFA and DNP increases with temperature, albeit modestly, due to the small temperature differentials involved. The average thermal conductivity for each concentration is presented in Figure 6, which also depicts the variation in thermal conductivity as a function of particle concentration. Both CFA and DNP substantially enhance the thermal conductivity of Jet-A fuel.

For carbon fly ash (CFA), the baseline thermal conductivity of Jet-A fuel at 0 wt.% is 0.995 W/m·°C. When 0.05 wt.% CFA is added, thermal conductivity increases by 3.006%, reaching 1.024 W/m·°C. At 0.1 wt.%, the thermal conductivity decreases slightly by 1.606%, bringing it to 1.011 W/m·°C. However, as the concentration increases, CFA's porous structure begins to exert a more pronounced influence. At 0.15 wt.% CFA, thermal conductivity rises significantly by 6.589%, reaching 1.060 W/m·°C. At 0.25 wt.%, there is another slight decrease of 1.606%, with thermal conductivity returning to 1.011 W/m·°C. Further increases in CFA concentration to 0.5 wt.% and 1 wt.% lead to small decreases in thermal conductivity by 1.302% and 0.466%, respectively. However, at 1.5 wt.%, thermal conductivity increases by 3.512%, reaching 1.029 W/m·°C. Finally, at 2 wt.% and 3 wt.% CFA, the thermal conductivity increases by 2.097% and 8.385%, reaching 1.078 W/m·°C at the highest concentration. These improvements highlight the advantageous effect of CFA's porous morphology, which promotes better heat dissipation and enhances thermal conductivity, particularly at higher concentrations, similar to the effects observed with activated carbon nanoparticles in Jet-A fuel [7]. This enhancement is partially attributed to the presence of trace iron content within CFA [3].

In contrast, for diamond nanopowder (DNP), the baseline thermal conductivity of Jet-A fuel also starts at 0.995 W/m·°C. However, when 0.05 wt.% DNP is introduced, the thermal conductivity decreases by 1.572%, falling to 0.979 W/m·°C. At 0.15 wt.%, a slight rise of 0.672% occurs, bringing the conductivity to 1.001 W/m·°C. At 0.25 wt.% DNP, there is a marginal increase of 0.501%, with thermal conductivity hovering near 1.000 W/m·°C. Subsequent increases in DNP concentration at 0.5 wt.% and 1 wt.% lead to minor variations, with a 0.944% increase at 0.5 wt.% and a small decrease of 0.468% at 1 wt.%. Finally, at 2 wt.% DNP, the thermal conductivity increases by 2.023%, reaching 1.015 W/m·°C. While DNP exhibits slight improvements at higher concentrations, CFA demonstrates superior performance due to its porous structure, which facilitates more efficient heat transfer. The consistent increases in thermal conductivity at higher CFA concentrations indicate that its porous morphology significantly enhances heat transfer, making CFA a more effective additive for improving the thermal properties of Jet-A fuel. This enhanced performance of CFA over DNP is clearly depicted in Figure 6, where CFA's improvements are more pronounced across all particle concentrations.

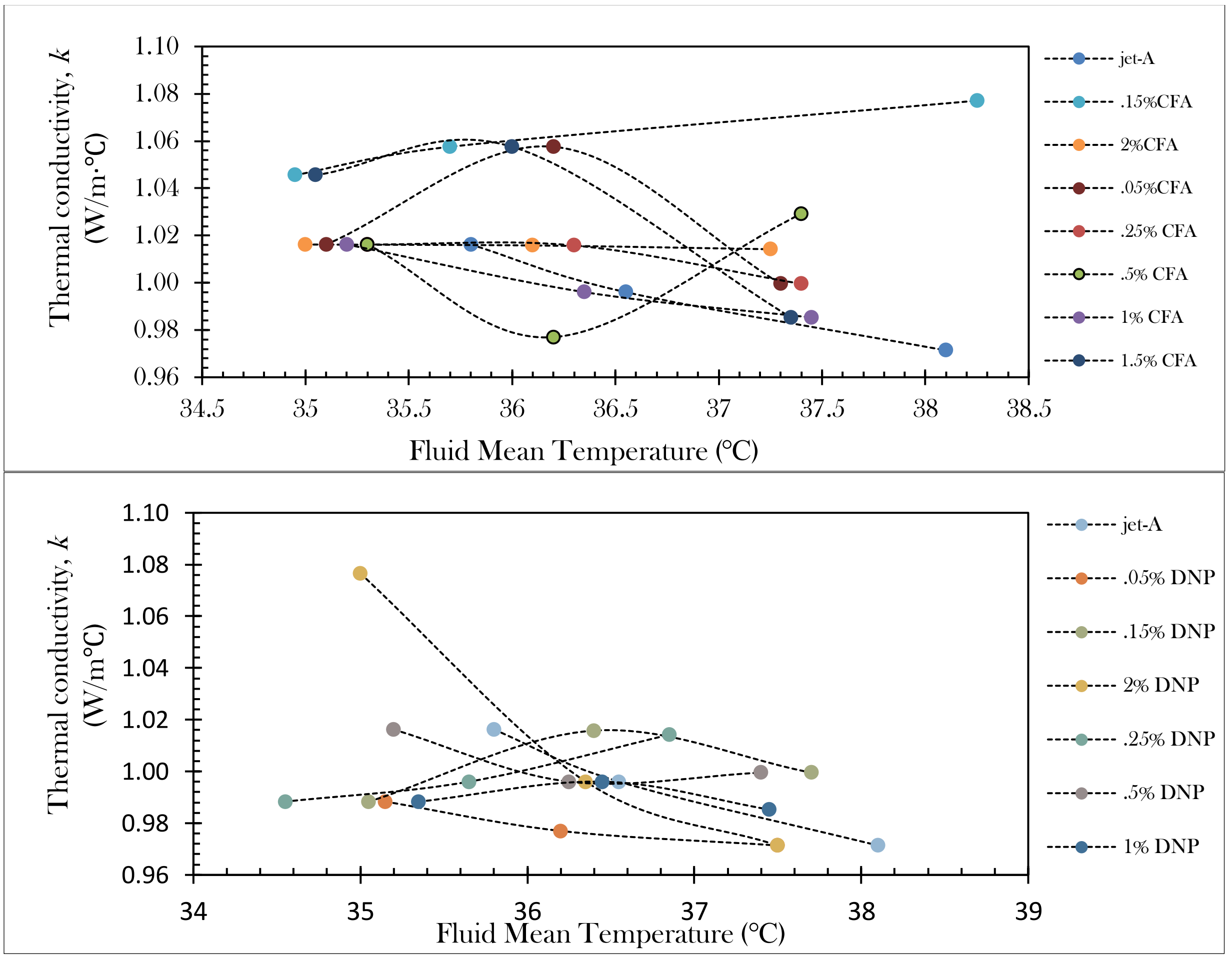

Fig. 5: Variation of thermal conductivity of Jet-A+CFA at different mass concentration
as a function of fluid mean temperature

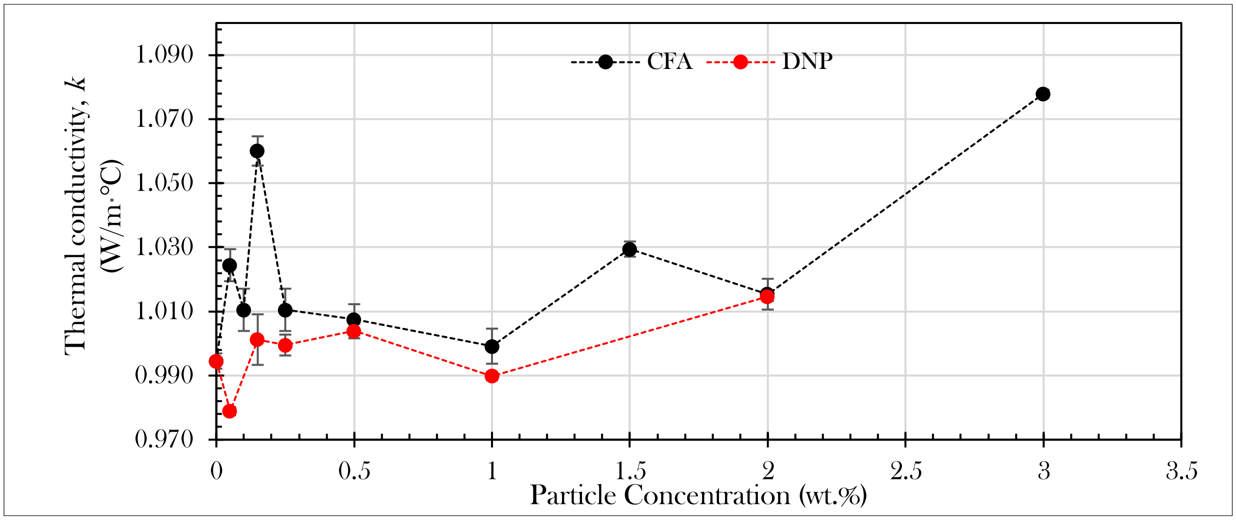

Fig. 6: Variation of thermal conductivity of jet-A fuel +CFA and jet-A fuel +DNP with bar errors at different concentration

4. Conclusions

This study highlights the potential of Carbon Fly Ash (CFA) and Diamond Nano Powder (DNP) in enhancing the thermal conductivity and stability (sedimentation) characteristics of Jet-A fuel. The key findings are as follows:

1- Thermal Conductivity Enhancement: A 2% concentration of DNP in Jet-A fuel increased thermal conductivity by 2%. A 3% concentration of CFA resulted in an 8% improvement, attributed to its porous structure and iron content, positioning it as a competitive alternative to activated carbon particles.

2- Stability Considerations: The morphological structure of DNP was found to cause rapid agglomeration, leading to a shorter stability time compared to CFA. This underscores the need for further investigation to optimize the use of DNP in practical applications.

To complete the study and enhance understanding, the following recommendations are proposed:

a- Viscosity and Surface Tension Analysis: Investigating the viscosity and surface tension properties of both DNP and CFA suspensions would provide valuable insights into their behavior in Jet-A fuel.

b- Evaporation/Combustion Rate Study: Applying the droplet suspension technique to assess the evaporation and combustion rates of the suspensions will help clarify the impact of morphological structure on performance.

c- Residue Analysis: Performing SEM and EDS analyses on the combustion and evaporation residues will shed light on the effects of DNP and CFA on residue formation, enhancing understanding of their behavior during combustion.

These recommendations will provide a more comprehensive understanding of how DNP and CFA influence fuel performance, particularly in terms of stability and combustion characteristics.

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