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Investigation on the Impact of Nickel and Silica Nanoparticles on B20 Fuel Mixtures with Biodiesel to Improve Combustion Efficiency and Reduce Emissions

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Abstract

The radiation, flame temperature, and emissions characteristics of an oil furnace powered by biodiesel mix fuel including energetic and non-energetic nanoparticles (NPs) in suspension were examined in this work using a comparative experimental technique. While silica (SiO_2) was selected for its non-energetic characteristics, nickel NPs were used as energetic NPs. A homogeneous mixture of NPs was added to the B20 blend fuel at a concentration of 520 ppm in a diluted form. A further step involved heating the fuels in an oil burner. Temperature, brightness, and total radiation profiles, as well as nitrogen oxides (NO_x) and carbon monoxide (CO) emissions were recorded from the flame. Evidence suggests that the two NPs accelerate the rate of fuel droplet evaporation and shift the upstream flame temperature peak. Furthermore, in biodiesel mixed fuel, the energetic nickel NPs raise the peak flame temperature while the non-energetic silica NPs lower it. Furthermore, both NPs enhance the nucleation and growth of intermediate soot particles. Fuels containing suspended particles enhance flame emissivity and increase the fraction of intermediate soot particles. Total flame radiation, infrared radiation, and visible light are all intensified. It is possible to raise the average flame radiative flux by 30% and 15% by adding energetic nickel NPs and non-energetic silica NPs to nano biodiesel blend fuel, respectively. Using non-energetic silica NPs reduces NO_x emissions by 12% while adding energetic nickel NPs to B20 gasoline decreases them by 14%.

Keywords

Biodiesel, Silica, Efficiency, Combustion, Emissions, Temperature

Introduction

Renewable, sustainable, and alternative fuels are in high demand due to rising energy demands, environmental concerns, and the depletion of fossil fuel supplies [1]. Because of their accessibility and ease of manufacture from renewable resources, biodiesel fuels have garnered a lot of interest as a potential replacement for liquid fossil fuels [2, 3]. Biodiesel fuels are environmentally friendly and may be blended with diesel for use in systems that burn liquid fossil fuels [4]. One of the possible raw materials for biodiesel is palm oil, which is extracted from palm trees. Unlike other vegetable oils, palm oil grows year after year [5, 6]. Future combustion systems can take use of these advantages using palm oil biodiesel [7]. Combustion systems that combine palm oil with other liquid fuels have been the subject of extensive and influential research on combustion and emission properties [8, 9].

Thermodynamic characteristics, catalytic activity, and a high area/volume ratio have made NPs prominent players in thermal engineering as of late [10]. An innovative and advantageous way to improve the thermophysical, reaction rate, ignition properties, combustion efficiency, emissions, and heat transfer characteristics of hydrocarbon liquid fuels is to include nanoscale additives into these fuels. Researchers examined diesel fuel's ignition potential when mixed with NPs of different metal oxides [11]. In comparison to pure diesel fuel, fuel containing 0.05% (wt) of SiO_2 and Si_3O_4 NPs of metal oxides exhibited a greater ignition probability. In a similar vein, authors [12] found that adding a few silica NPs to diesel fuel increases the likelihood of igniting. Authors [13] investigated to learn how acetylene black and multi-walled carbon nanotubes affected the burning characteristics of crude oil droplets. They showed that the combustion rate was increased by 39.8% with 0.8% acetylene black and by 31.4% with multi-walled carbon nanotubes. According to their findings [14, 15], once the liquid fuel was completely used up, the majority of the clumped particles in dense nano-suspensions were burned. Additionally, it was pointed out that this agglomeration might not be burned if the energy supplied by the droplet combustion is inadequate. When studying diluted solutions, they found that the particles and droplets burned at the same time. Diesel nano-fuel containing copper oxide (CuO) and SiO_2 nanoparticles was studied by authors [16] for its efficiency and NO_x emission in a diesel engine. NPs additions of CuO and SiO_2 were also discovered to lower NO_x emissions and brake-specific fuel consumption. The impact of canola biodiesel combined with silica NPs on diesel engine emissions and performance was studied [17, 18].

From combustion point of view, metal NPs can be separated into two groups. One is energetic NPs, and the other is inert or non-energetic. The metal NPs with low melting point can melt, react, and release energy in the flame. These are called energetic metal NPs. Examples are aluminum, boron, and nickel. Unlike energetic NPs, inert or non-energetic NPs only change the thermophysical properties of fuel droplets and participate in heat transfer mechanisms of flame just by absorbing and scattering heat energy. The presented literature review indicates that in spite of a number of investigations performed in this domain, there has been no systematic investigation on the impact of energetic and inert NPs on radiation and emissions of diesel and biodiesel fuel flames. So, the main purpose of this study is to compare and contrast the effects of using a nano biodiesel mix fuel—which contains both energetic and non-energetic metal NPs floating in the fuel—on the flame temperature, radiation characteristics, and NO_x emissions of an oil burner.

Experimentation

The methodology to synthesize and prepare stable B20 blend fuel (80% diesel + 20% biodiesel), the devices employed in this work, procedure of the experiments, and the uncertainty analysis are the same as those of the former work and were discussed in detail there. The B20 mix fuel is thought to benefit from the addition of SiO_2, a non-energetic NPs, and silica NPs, which are very active with an extremely low [O] level and may even burn themselves. The physical characteristics of NPs are listed in table 1.

Table 1: Physical characteristics of nickel and silica NPs.

Item	Specifications	
Chemical name	Silica (SiO_2)	Nickel (Ni)
NPs density	2.2 - 2.6 g/cm^3	8.9 g/cm^3
Average particle size diameter	85 nm	40 - 50 nm
Purity	95+%	99.95+%
Appearance	Colorless to white powder or crystals	Silvery-white with a slight golden hue

Furthermore, the oxide layer in SiO_2 NPs is sufficiently thermal resistant and the NPs' melting point is adequately high to prevent ignition of the NPs. To prepare the energetic and non-energetic nano biodiesel blend fuels, Si and SiO_2 NPs are combined with blended fuel by shaking. The concentrations of both Si and SiO_2 NPs are 520 ppm, which is classified as a dilute NPs concentration.

Even though the agglomeration of the particles is negligible in dilute concentrations, sonication and surfactants addition are applied. This is a well-known method that can reduce the coagulation of NPs in the fuels. In the method, 40 ml of span 80 (as surfactant) is added to each suspension and mixed for 25 min. Finally, nanoparticles are dispersed in the fuel using a supersonic homogenizer (185 W) (Figure 1).

Results and Discussion

Figure 2 explains the impact of energetic and non-energetic NPs on flame temperature. It shows that the peak flame temperature is raised by nano biodiesel mix fuel containing energetic nickel NPs and lowered by non-energetic silica NPs. Furthermore, both NPs displace the peak of flame temperature. The dimension of the fuel droplets is significantly larger than that of the NPs. Hence, there are a large number of NPs inside each droplet of nano biodiesel blend fuel. In most cases, NPs improve fuel droplet thermal properties, such as their absorption coefficient and thermal conductivity. So, fuel droplets made of nano biodiesel mix are able to absorb heat more quickly than fuel droplets made of B20. As a result, the fuel droplets evaporate more quickly, which speeds up their mixing with oxidizing air and causes the flame's peak temperature to shift upstream. Comparing to the small low density white-colored SiO_2 NPs, the big dense, black-colored nickel NPs can absorb higher amounts of heat energy from the flame reaction zone which accelerates the evaporation and mixing rate of nickel nano biodiesel blend fuel droplets. Consequently, the maximum flame temperature in the case of nickel nano biodiesel blend fuel is fairly closer to the upstream region.

Synchronous combustion of liquid droplets and NPs defines the burning process for diluted suspensions [19, 20]. During combustion of the nano-fuel droplets, energetic nickel NPs melt, ignite, and burn. The energy density of energetic metal NPs is considerably higher than that of liquid fuels.

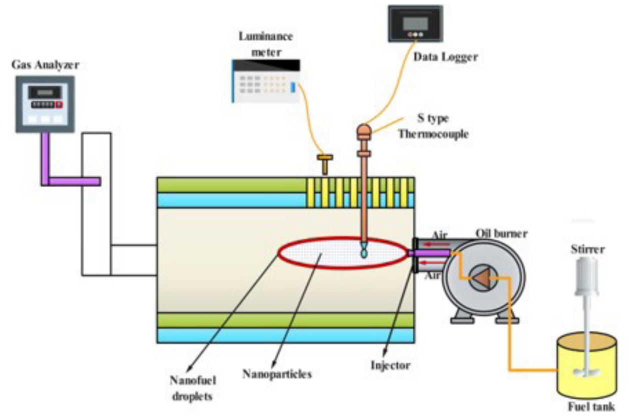

Figure 1: Schematic view of experimental set up.

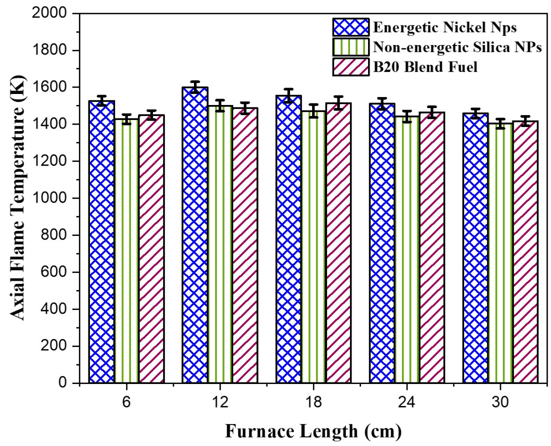

Figure 2: Effect of energetic and non-energetic NPs on flame temperature.

Therefore, the combustion of energetic nickel NPs releases a substantial amount of energy that leads to an increase in the flame temperature of 5.4%. Unlike energetic nickel NPs, inert or non-energetic and noncombustible SiO_2 NPs can only participate in heat transfer mechanisms of flame by scattering and absorbing heat energy. Although the absorption of heat by SiO_2 NPs enhances the nano biodiesel blend fuel droplets evaporation and mixing rate (this can raise the flame temperature), the contribution from heat scattering is higher for SiO_2 NPs comparing to their heat absorption. This contributes to accelerating heat transfer and reducing the temperature of non-energetic SiO_2 blended oil flame.

The flame radiation heat flux for nickel and silica NPs blend fuel, as well as B20 blended fuel, is compared in figure 3. The flame radiation is clearly enhanced when energetic nickel NPs and non-energetic SiO_2 NPs are added to B20 mixed fuel. Adding energetic nickel NPs to a nano biodiesel mix fuel increases the average flame radiation heat flow by 30% and non-energetic SiO_2 NPs by 15%. A number of factors influence the radiation flow, including emissivity and temperature. Figure 3 shows that dynamic nickel NPs raise the flame temperature while non-dynamic SiO_2 NPs lower it. Therefore, unlike energetic nickel nano biodiesel blend fuel, the flame temperature in the case of non-energetic SiO_2 nano biodiesel blend fuel tends to reduce the flame radiative heat flux. The

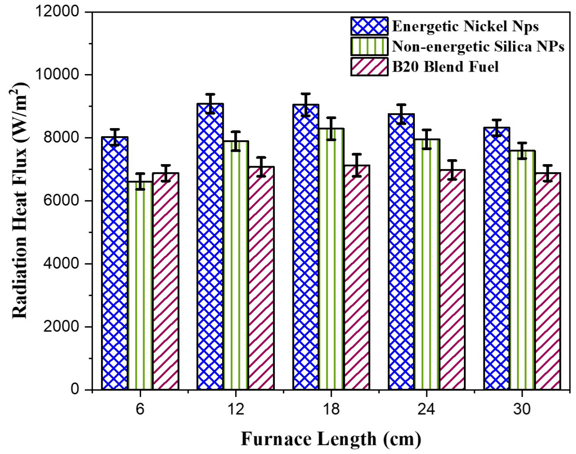

Figure 3: Effect of nickel and silica NPs on B20 blend fuel fire contamination heat flux.

flame emissivity coefficient is another element that affects the radiative heat flux. Compared to the gaseous products of combustion which have small emissivity coefficient and poor radiation, metal NPs including Si and SiO_2 NPs have higher emissivity coefficients that enhance flame radiation. Furthermore, NPs have a higher area/volume ratio (larger specific surface area) which makes an appropriate base for the nucleation of intermediate soot particles. NPs of Si and SiO_2 enhance the nucleation and surface development of soot particles, leading to a higher concentration of intermediate soot particles in the flame reaction zone as a highly emissive material. In order to test this theory, a chemiluminescence-based qualitative distribution of intermediate soot particle (ISP) concentrations was defined. According to the chemiluminescence approach, the yellow color of the flame is due to burning of soot particles called luminosity. Thus, the luminosity of the flame is proportional to the concentration of ISP. In figure 4, the luminosity measurement of flame is shown for silica and nickel NPs blend fuel and B20 blended fuel. It is quite obvious that both nano biodiesel blend fuel flames are more luminous than B20 blended fuel flames. Hence, compared to B20 blend fuel, nano fuel flames have a higher concentration of ISP which enhances the total flame emissivity coefficient and radiation. In addition, the energetic nickel nano biodiesel blend fuel flame is significantly more luminous than the non-energetic SiO_2 nano biodiesel blend fuel flame.

The average size of nickel NPs is smaller than that of non-energetic SiO_2 NPs. Therefore, compared to SiO_2 NPs, nickel NPs have a higher specific surface area that strengthens the intermediate soot particles nucleation rate. Energetic and overactive nickel NPs would create a layer of soot particles. This layer that has been formed over the top of nickel NPs then burns rapidly and causes it to generate an extremely luminous flame. High energy density of energetic nickel NPs and oxygen atoms in the chemical structure of B20 blend fuel leads to more complete combustion, which increases the flame temperature and decreases the CO emission. However, for SiO_2 nano biodiesel blend fuel, SiO_2 NPs which are coated by soot particles can soak up heat from the flame and lessen the flame temperature and because they are incombustible particles, the soot particles formed on their surfaces do not burn completely which results in an upsurge in the CO emission (Figure 5).

The soot particles emit mostly in the near infrared band, which is distinct from other types of flames. Compared to B20 fuel, the red tone color in the flame images attributed to both nano biodiesel blend fuel, which occurs due to the soot particles, is wider. This confirms that NPs improve ISP concentration. Additionally, the active nickel flame emits more infrared light than the inert SiO_2 nano biodiesel mix fuel flame.

Figure 6 shows the NO_x emission for energetic nickel NPs and non-energetic SiO_2 NPs. Based on figure 6, both energetic and non-energetic NPs reduce NO_x emission from B20 fuel. The reduction of NO_x emission due to the addition of nickel NPs is as high as 14% whereas NO_x reduction for non-energetic SiO_2 NPs can go up to 12%. Thermal nitric oxide (NO) and fuel NO are general mechanisms of NO_x formation in liquid fossil fuel with nitrogen components in chemical structures. Thermal NO_x formation mechanism severely accelerates at high temperatures (beyond 1700 K). Nevertheless, figure 2 shows that for all cases flame temperature is significantly lower than the critical temperature. So, it can be concluded that the rate of thermal NO_x formation is lower.

Flame temperature is a parameter that can strengthen the rate of fuel NO formation. Based on the results shown in figure 2, energetic nickel NPs raise the flame temperature which increases the rate of NO formation. However, the results illustrated in figure 6 show a drop up to 14% in NO_x emission when the energetic nickel NPs are added to B20 fuel. Therefore, some other factors contribute to overcoming the temperature raise factor and lead to reducing NO_x emission that are outlined in the following.

Based on the results shown in figure 3, both nano biodiesel blend fuels (in particular energetic nickel nano biodiesel blend fuel) help in enhancing flame radiation heat transfer. So, compared to B20 blended fuel flames, flames made of nano biodiesel mix fuel release more combustion heat, and they do so more quickly. Hence, flame hotspot zones, which are major NO_x generators, do not materialize [21, 22]. Furthermore, high-temperature NPs serve as energy transporters following the evaporation of fuel droplets containing nano biodiesel blends. Because of this, the temperature gradient between the flame and the hot spot shrinks, and the amount of nitric oxide produced decreases. Finally, as mentioned earlier in figure 4 to figure 6, both nano biodiesel blend fuels increase the concentration of ISP which strengthen NO reduction through carbon (soot)–NO reaction and CO–NO reaction.

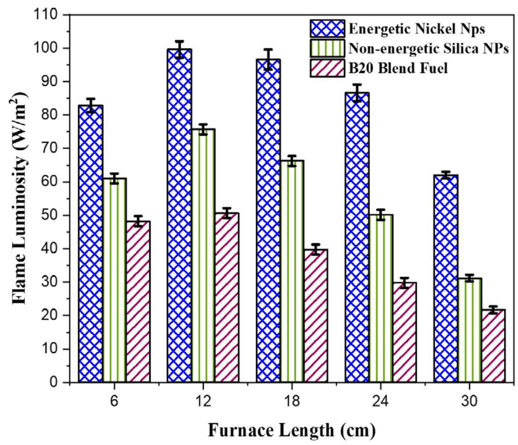

Figure 4: Comparison of flame luminosity for energetic nickel nano-fuel, non-energetic silica nano-fuel, and B20 blend fuel.

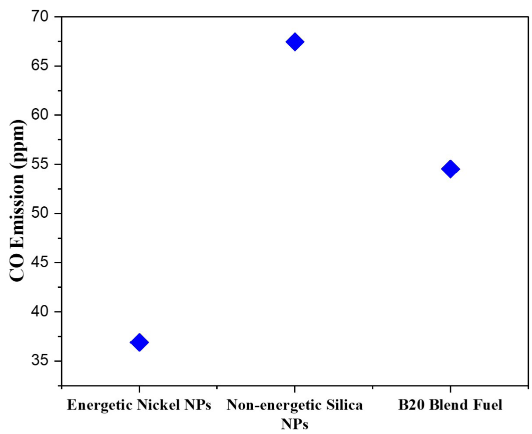

Figure 5: CO emission for energetic nickel nano-fuel, non-energetic silica nano-fuel, and B20 blend fuel.

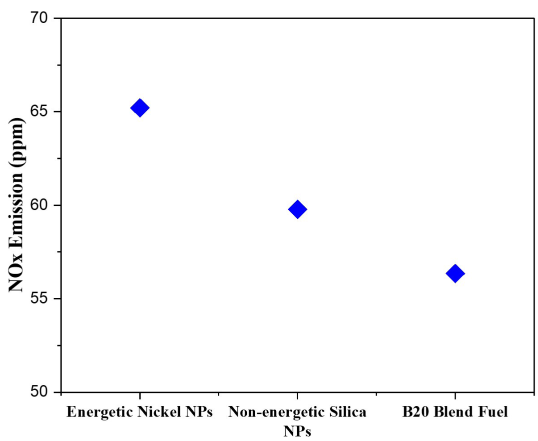

Figure 6: Comparison of NO_x emission for energetic nickel nano-fuel, non-energetic silica nano-fuel, and B20 blend fuel.

Conclusions

An oil burner that runs on a nano biodiesel mix fuel that included both energetic and non-energetic silica NPs suspended in it was studied for its flame temperature, radiation behavior, and NO_x emissions. Here are the key points from the study:

- NPs, whether energetic or non-energetic, increase the rate of fuel evaporation and move the flame's temperature peak further upstream.
- Compared to the small low density SiO_2 NPs, the high dense, black-colored nickel NPs absorb higher amount of heat energy from the flame reaction zone, which accelerates the evaporation and mixing rate of nickel

nano biodiesel blend fuel droplets. Consequently, the maximum flame temperature of nickel nano fuel is closer to the upstream region.

- The combustion of energetic nickel NPs releases a considerable amount of energy which increases the flame temperature up to 5.2%. While energetic nickel NPs contribute to flame heat transfer mechanisms through absorption and scattering, inert SiO_2 NPs do not contribute to these processes and are noncombustible. Nano biodiesel blend fuel droplets evaporate and mix more quickly when SiO_2 NPs absorb heat; this might lead to a higher flame temperature; nevertheless, SiO_2 NPs' contribution from heat scattering is more than their heat absorption. This increases the flame heat transfer and reduces the SiO_2 NPs blend fuel fire temperature.
- Fuel B20 can have its flame radiation enhanced by adding energetic nickel NPs and non-energetic SiO_2 NPs. Adding energetic nickel NPs to nano biodiesel mix fuel may increase the average flame radiative flux by 30% and non-energetic SiO_2 NPs by 15%.
- Compared to B20 blended fuel, using energetic nickel nano biodiesel blend fuel reduces NO_x emissions by 14% and non-energetic silica nano biodiesel blend fuel by 12%.

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None.

Conflict of Interest

None.

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