Performance and Combustion Characteristics of Diesel Blended with Ceria Nano-additives

Akshat Jain, Umesh Saini, Anirudha Ambekar, Thaseem Thajudeen
School of Mechanical Sciences, Indian Institute of Technology Goa
Ponda, Goa, India

1 Introduction

The impact of air pollution through particulate and gaseous emissions from internal combustion (IC) engines on human health is a major concern worldwide. Although battery-operated electric vehicles and hydrogen engines are promising technologies, they may not be viable in the short term. More practical and immediate mitigation tactics include enforcing stringent emission standards [1], using after-treatment techniques, and improving engine technology. Blending nanoparticles in liquid fuels is known to have numerous advantageous characteristics. Multiple studies have been reported exploring nanoparticle blended fossil fuels to improve the combustion, performance, and emission characteristics of automobile engines [2–5]. Recently, such studies have also been extended to diesel-biodiesel blends.[6–8]. In addition to direct engine studies, a fundamental understanding of how the nano-additives alter the characteristics of the base fuels is often sought through droplet combustion and evaporation studies [9–12].

The efficacy of nano-additives in the fuel depends significantly on how well they remain dispersed in the base fuel. The nanoparticles in a suspension typically exist as aggregated particles with a tendency for further increase in size through different aggregation mechanisms and subsequent adherence. Aggregation of the particles aids in the gravitational settling of the additives, nullifying the benefits of the nano-additives. Therefore, the stability of the nano-additives in the base fuel plays a vital role in enhancing the effect of nano-fuels. Reduction in the particle size and prevention of aggregation can be expected to improve the stability of the particles in the nano-fuel.

Despite several studies related to this topic, the optimal method for obtaining a stable nano-fuel suspension, the mechanism through which nano-additives increase the performance characteristics, the effect of the particle size distribution, and the morphology of the nano-additives have not yet been completely understood. In this study, we have investigated the benefits of using ball-milled ceria (CeO_2) nanoparticles as an additive in diesel fuel. Ball milling of CeO_2 is expected to improve stability through a reduction in the size of the dispersed nanoparticles. In addition to ball milling, Span80 was used as a surfactant, and bath sonication was performed to improve stability. The effect of CeO_2 as an additive is investigated by measuring the performance and emission characteristics of a single-cylinder compression ignition engine and through droplet combustion studies.

Correspondence to: anirudha@iitgoa.ac.in

2 Experimental Study

The experimental study consisted of preparing nano-fuel samples, testing the stability of the nano-fuel, engine performance tests with the nano-fuel, and droplet combustion study. For the preparation of nanofuel, CeO_2 nanoparticles with an average particle size of less than 25 nm were blended with diesel fuel in specific weight ratios. CeO_2 nanoparticles were ball-milled, and Span80 was used as the surfactant for increased steric stabilization. CeO_2–laden diesel was ball milled using a mini planetary ball mill, with two mini jars purchased from Insmart Systems. The nanofuel samples were also bath sonicated to increase their stability. In the current study, two samples were prepared, consisting of 100 ppm CeO_2 and 0.02% Span80 by mass blended with diesel. The first sample, 'Ce100 BS', was bath sonicated without using ball milling, while the second sample, ' Ce100 BM-BS', was processed using ball-milling and bath sonication.

To study the stability of nanofuel samples, dynamic light scattering (DLS) was carried out to measure the size distribution of the nanoparticles. DLS was carried out using Zetasizer ZS-90 from Malvern Panalytical. In DLS measurements, the diffusion coefficents of the dispersed nanoparticles are measured, which are then converted to obtain an apparent hydrodynamic diameter. The engine experiments were performed on a variable compression ratio (VCR) engine in the CRDI mode for compression ratio (CR) 20 at an engine speed of 1100 RPM. VCR engine is a single-cylinder, 4-stroke, water-cooled, multi-fuel engine with a displacement of 553 cm^3 and rated power output of 5 HP. The engine was connected to a data acquisition system (DAQ) along with various sensors and thermocouples to record the data at different-different crank angles (θ) and brake power (BP). The droplet combustion study was carried out with droplets suspended at the closed end of a glass capillary. The droplets were ignited using a pilot flame that was extinguished once the droplet was ignited. The combustion process was recorded using a DSLR camera with a micro 60 mm lens. A white LED lamp was utilized as the backlight to obtain shadowgraphs of the burning droplet. The recorded video yielded frames showing droplet combustion at various stages. All experimental measurements were repeated thrice and the uncertainty in the measured values was quantified through the relative standard deviations from the average values.

3 Results and Discussion

After the successful preparation of the nanofuel samples, the experimental studies were carried out further to study the performance characteristics of the engine and droplet evaporation characteristics of the nanofuel. Figure 1 shows the DLS measurement of CeO_2 nanoparticle size dispersed in the nanofuel sample prepared at the beginning and after 1 day. The effect of ball milling in the reduction of the size of the nanoparticle dispersion is quite evident from the plots, with significant shifts in the peak value as well as concentraton of larger particles.

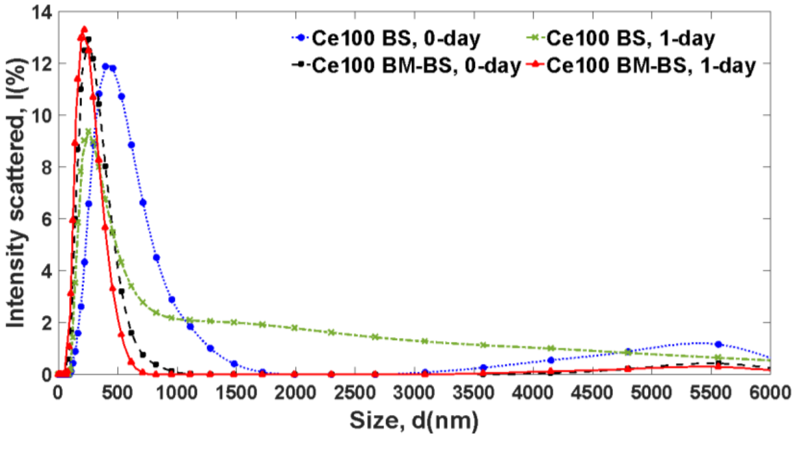

Figure 1: Size analysis of 100 ppm CeO_2 nanofuel sample using DLS

The maximum decrease in brake-specific fuel consumption (BSFC) of the engine for 'Ce100 BS' and 'Ce100 BM-BS' is 9.4% and 14.6%, respectively, as shown in Figure 2. The brake thermal efficiency (BTE) of the engine was measured with the addition of the different fuel samples, and the results are summarized in Figure 3. The measurement uncertainty for the BSFC and BTE values at 75% loading condition are shown in Table 1. The uncertaintaines at other loading conditions were found to be of the same order and included in the Fig. 2 and 3 as error bars.

Table 1: The measurement uncertainty at 75% load in the case of three fuel samples

Engine Parameters	σ_{rel} (%) Diesel	σ_{rel} (%) Ce100 BS	σ_{rel} (%)Ce100 BM-BS
BSFC (kg/kWh)	1.82	1.42	1.61
BTE (%)	1.78	1.07	1.39

The results show the impact of nanofuel in the enhancement of BTE. The percentage improvement in the BTE for 'Ce100 BS' and 'Ce100 BM-BS' nanofuel samples is 4.1% – 9.4% and 11.7% – 15.5%, respectively, when the load on the engine varies between 0–100%. The improved performance could be linked to the rate at which the overall combustion process progresses in the nano-additive blended fuels case. Factors such as droplet breakup, ignition delay, and rate of combustion reaction would play a significant role in this case. These aspects must be elucidated through an investigation into the fundamental combustion characteristics of the nanofuels. Our initial studies in this direction are described in the following paragraphs.

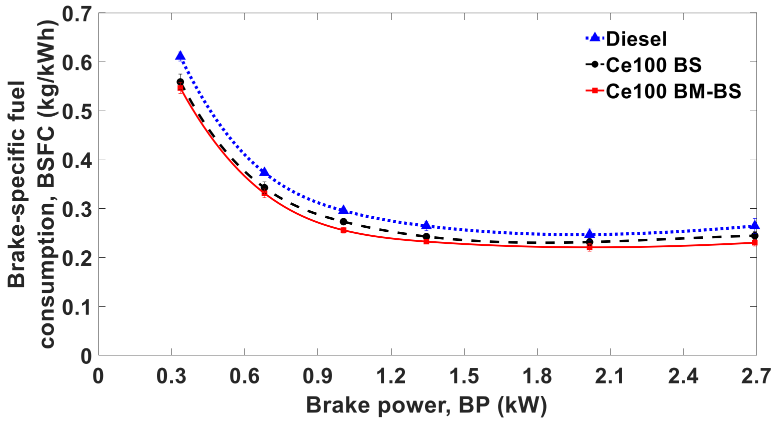

Figure 2: Brake-specific fuel consumption (BSFC) of the VCR engine (@ 1100 RPM, CR=20).

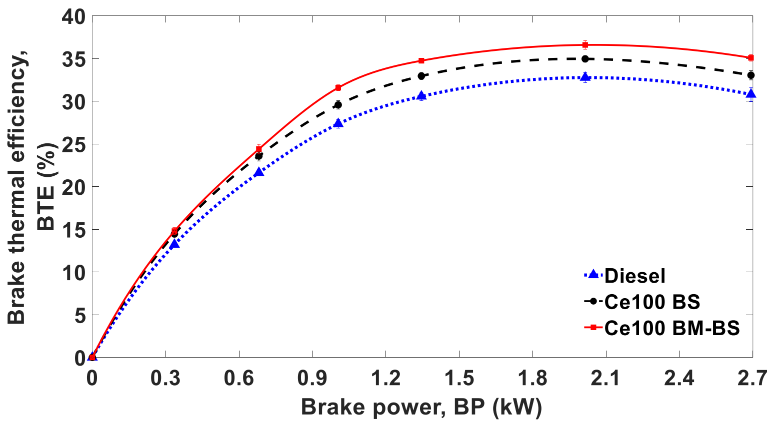

Figure 3: Brake thermal efficiency (BTE) of the VCR engine (@ 1100 RPM, CR=20).

Droplet combustion studies were carried out with the nano-additive blended fuel samples, and results were compared with the characteristics of base diesel fuel. The phenomenon of micro-explosion was observed, as seen in the selected frames in Figure 4. A dramatic change in the apparent droplet diameter was observed just before micro-explosions, which was linked to the formation of bubbles within the liquid droplet.

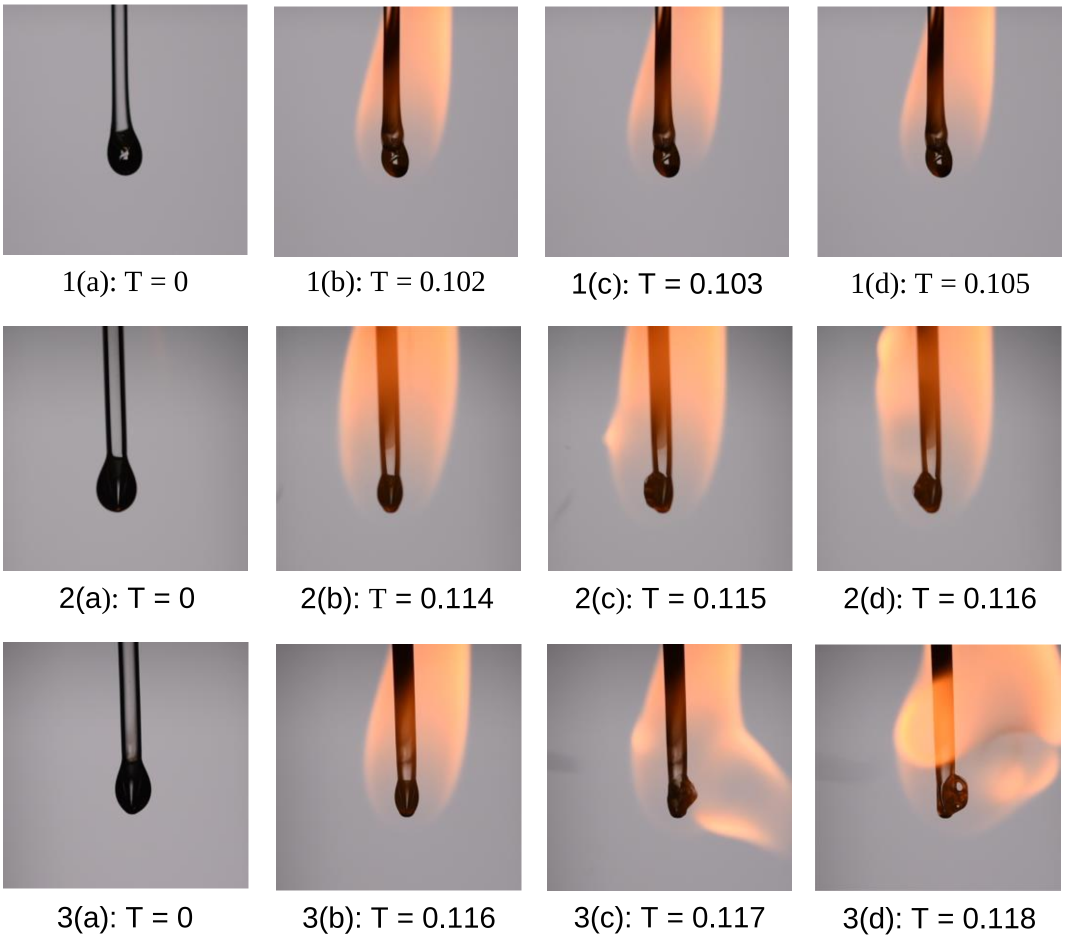

Figure 4: Droplet evaporation images for the following fuel samples: (1) Diesel, (2) Ce100 BS, and (3) Ce100 BM-BS; the event of micro-explosion in case of nanofuel [$T = t/D_o^2$, 't' is in seconds, ' D_o' is in mm, and 'T' is in sec/mm^2]

The effective diameter of the droplet was extracted from a sequence of images obtained from ignition to extinction of the droplet. The square of the nondimensionalized instantaneous diameter was plotted against the normalized time, as shown in Figure 5. It was observed that all fuels followed the classical D^2-law of droplet combustion during the stable combustion phase. The outlier points in Figure 5 in the case of nanofuel samples, depict bubble formation and micro-explosions. The slope of the D^2 plots in Figure 5 can be observed to be significantly steeper for nanofuel samples compared to the neat diesel fuel. The slope indicates the droplet burning rate constant, and a higher value could indicate an intrinsically higher burning rate of the nanofuels. The overall combustion could also be accelerated due to the apparent micro-explosions in the nano-additive blended fuels.

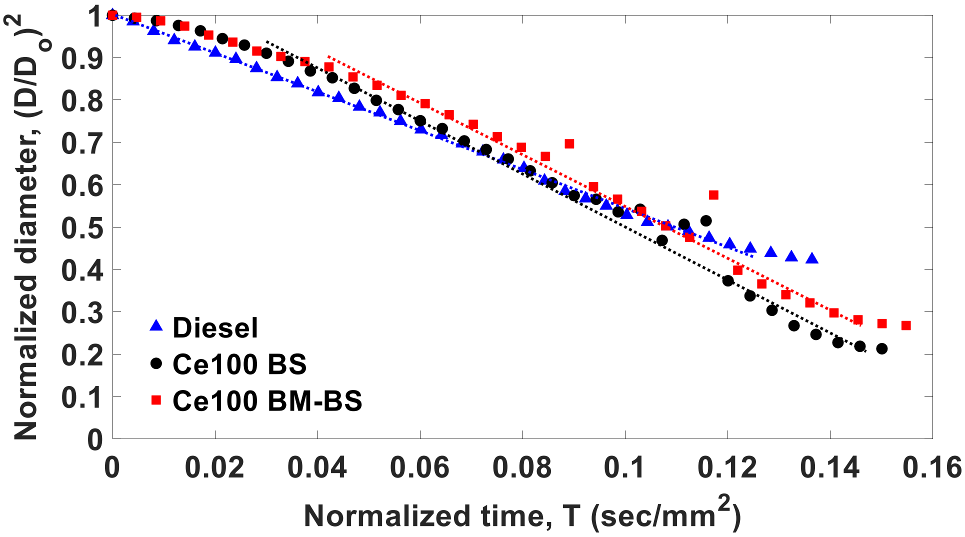

Figure 5: D^2 plot for droplet combustion of various fuels.

4 Conclusion

The performance characteristics of the VCR engine are investigated for diesel fuel blended with CeO_2 nano-additives. It has been found that the ball-milling and span80 surfactant are helpful in the preparation of stable nanofuel samples, and aids in improving the combustion performance of the engine when run with the prepared nanofuels. Size analysis of the samples using DLS shows the reduction in nanoparticle size due to ball milling. Consequently, the ball-milled sample 'Ce100 BM-BS' showed superior engine characteristics. At 100 ppm concentration, the ball-milled ceria nano additive yielded a maximum improvement in brake-specific fuel consumption was 14.6%. At the same time, the maximum improvement in brake thermal efficiency was 15.5%.

The droplet combustion experiments clearly indicated the occurrence of micro-explosions due to the presence of CeO_2 nanoparticles. Micro explosions are suggested as a possible reason for the enhanced performance of the nanofuel. Consequently, resulting in the improved performance characteristics of the engine. A marked difference in the slope of the D^2 plot was observed, indicating a significant change in the droplet burning rate constant due to the addition of ceria nanoparticles.

The study so far proved to be an excellent starting point for a detailed future study aimed at obtaining physical insight into droplet combustion of nano-additive blended fuels. Additional experiments will be conducted by varying the parameters such as initial droplet size, ambient temperature, ambient pressure, and concentration of nano-additives to elucidate the phenomena completely.

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