Experimental investigation on effect of zinc oxide nanofluid on performance, emission and combustion characteristics of CI engine fuelled with waste cooking oil biodiesel

V Ramanathan¹, M Jaikumar¹, Shaik Abdul Aleem¹, S Induja², E SangeethKumar⁴

¹ Department of Automobile Engineering, Hindustan Institute of Technology and Science, Chennai-603103, Tamil Nadu, India.
² Department of Chemistry, Hindustan Institute of Technology and Science, Chennai-603103, Tamil Nadu, India

Email: vramanathan@hindustanuniv.ac.in

Abstract. Environmental effluence and fossil fuels exhaustion are the main reasons to use alternate biofuels worldwide in engines. Many researchers focused their research on biodiesel which were extracted from eatable and non-eatable vegetable oils, used them in diesel engines. In this context, biodiesel derived from Waste Cooking Oil (WCO) was taken as a substitute fuel for diesel engine because of two reasons; one reason was some of the properties of this biodiesel were very nearer to diesel and another reason was giving second life to the waste cooking oil instead of disposing of in the land. In the first stage, Waste cooking oil Biodiesel (WCOB) was produced from WCO by transesterification process and experiment was carried out using diesel and WCOB and considered as base readings. In the second stage, Zinc oxide nanofluid in the mass proportions of 50ppm, 75ppm and 100 ppm were synthesised using a novel wet chemical method and blended with WCOB and considered as WCOBZN50, WCOBZN75 and WCOBZN100 and their properties were tested. Then the experiment was conducted in a fully equipped engine test set up. The engine was loaded at various loading conditions. The readings were measured and analysed. The results exhibited that the blending of zinc oxide nanofluids with WCOB improved engine performance characteristics. Also, it was observed that the addition of zinc oxide nanofluids reduced the engine tailpipe emissions compared to neat WCOB. It was also found that the combustion characteristics of ZnO nano blended biodiesel were increased marginally.

1. Introduction

Diesel engines are extensively used in gensets, agricultural machines and medium & heavy automotive vehicles. Emissions from the diesel engines by burning fossil fuels have a serious impact on human health and the ecosystem. Over past decades, many pieces of research were carried out to lessen the emissions and to progress the engine performance by finding new biodiesel as a supernumerary for fossil fuel. It is a renewable fuel and emits less detrimental gases. Researchers have already used biodiesel derived from WCO as a fuel. It was observed that WCOB found a prominent place for its use in engines due to its comparable physio-chemical properties closer to diesel. Non-toxicity, bio-degradability, renewability and lesser emissions were the few advantages of WCOB over neat waste cooking oil. To encourage the
collection and reducing the disposal of WCO, it could be converted into biodiesel and utilized in engines. The detailed study carried out by various scientists using waste cooking oil biodiesel is discussed below.

G.R. Kannan et al. conducted research by changing the fuel injection pressure and timing fuelled with WCOB. RSM optimization technique was handled to optimize the production process of WCOB. It was observed that by modifying the fuel injection pressure and timing, higher engine efficiency, in-cylinder pressure and net heat release rate were produced. In the emission side, NOx and smoke were found lower [1]. An, H., W. M. Yang et al. evaluated the engine performance using WCOB and its blends with diesel. The results showed that the BSFC was higher at part load; BTE was slightly higher at 50% and 100% load. Further, it was noted that a shorter delay period, lower heat release rate, slight reduction in NOx and hydrocarbon emissions [2]. Mohammed EL Kassaby et al. investigated the diesel engine output by fluctuating the compression ratio and WCOB- diesel blend ratio. The results revealed that BTE, BSFC were increased when increasing compression ratio and fuel blend ratio. The results showed that an increase in CO2 emission, drop-in CO, NOx emissions when compression ratio was increased [3]. Joonsik Hwang et al. led research on CRDI diesel engine ran with WCOB by varying the fuel injection timing and pressures. The output of the experiment revealed that higher SFC; lower in-cylinder pressure, and heat release rate; longer ignition delay than diesel. In the exhaust gas, there was a drop of CO, HC and smoke at higher injection pressures. NOx was found slightly higher than diesel [4]. K. Nantha Gopal et al. conducted experimentation using WCO methyl esters (WCOME) and its blends with diesel as fuels. It was noted from the experiment that BTE, CO, HC, smoke emissions were lower; SEC, NOx was higher for WCOME and its blends with diesel [5]. S. Kathirvel et al. did a detailed literature review on the behaviour of the CI engine using WCOME and its blends as fuels. Investigations showed that WCOME might be a viable alternative fuel for CI engine due to its properties closer to diesel. Most of the researchers found that BMEP, BTE was increased while using WCOME compared to neat WCO whereas tailpipe emissions such as CO, HC were lower than diesel. It was also observed by many researchers that BSFC was higher due to the heavier density of fuel and a slight increase in NOx emission because of better combustion of WCOME [6]. Peng Geng et al. did research using WCOB and its blends with diesel in a marine engine. It was found that cylinder pressure increased slightly, heat release rate and NOx decreased significantly [7]. K.A. Abed et al. led research utilizing WCOB and its blends with diesel. The results revealed that BTE was lower; BSFC was higher due to reduced combustion characteristics and volatility; CO, HC were lower; NOx and CO2 emissions were higher while increasing the quantity of biodiesel in the blends [8].

From the above investigations, it was observed that emissions from WCOB depend very much on variation in physical properties. It was discovered that HC, CO and smoke were considerably reduced, at the same time NOx and CO2 were slightly augmented due to boosted combustion and oxidation properties of WCOB. Also, it was noted that lower BTE, higher BSFC due to higher kinematic viscosity, density and lower heat energy of WCOB. So, this research was focused on reducing the above-said drawbacks.

In this context, many experiments were done to progress BTE and BSFC, at the same time, reducing the NOx by several methods. One of the approaches is the blending of nanoparticles or nanofluids in the biodiesel to improve the output of diesel engine characteristics. Nanoparticles such as alumina, CuO, ZnO, titanium dioxide and cerium oxide were used as additives in the biodiesel, diesel/ biodiesel blends without any engine modifications. The results revealed that the blending of nano particles/ nanofluids in the biodiesel, improved the properties of biodiesel. Also, engine characteristics were improved. The following articles are the detailed investigations carried out by various scientists related to the addition of nanoparticles/ nanofluids in the biodiesel and their output.
S. Karthikeyan et al. conducted a research using pomolion stearin wax biodiesel blended with zinc oxide nanoparticles. It was found that zinc oxide nanoparticles upgraded the BTE and BSFC due to the optimistic effect of nanoparticles by improving the properties of fuel. It was also observed that there was a drop in CO, HC and smoke, but no changes in NOx emissions for all blended fuels [9]. S. Karthikeyan et al. conducted research using Grapeseed oil methyl ester blended with ZnO nanoparticles in a marine engine. There was a rise in BTE and decline in BSFC due to faster burning rates and higher heat release rate of zinc oxide nanoparticles were observed. However, there was a surge in NOx and CO2 emissions and a decline in CO, HC and smoke emissions was found [10]. S. Karthikeyan et al. did research using methyl esters of Canola oil with ZnO nanoparticles. It was observed that there was an improvement in BSFC and BTE while increasing the quantity of nanoparticles in the biodiesel at higher engine load. There was a drop in HC, CO emissions with surge in NOx emission was noted [11]. B. Prabakaran et al. did research using diesel-biodiesel-ethanol blended with ZnO nanoparticles in CI engine. It was found that lesser BTE and higher BSFC formed due to the drop in heat energy content of ethanol blended fuels. In the emission side, HC, CO, NOx and smoke were lesser due to nanoparticles [12]. T. Shaafi et al. reviewed the literature about several nano additives dispersed in biodiesel/ diesel blends and its effect on engine characteristics. From the literature, it was detected that the nano additives improved the flow properties, thermal properties, mass diffusivity, high SA/V ratio depends upon the quantity of nano additives added to the base fuel. One thing was observed that blending of nano additives in diesel amplified the NOx emission, at the same time, nano additives blending in biodiesel lessening the NOx emission. This was due to micro explosion and heat transfer property of nano particles. Also, it was suggested that the emulsification technique was a good method for reducing NOx emission. Further, information collected from the literature that CO emissions were abridged while using nano additives because of complete combustion and oxidation [13]. Chandrasekaran et al. conducted research using methyl esters of mahua oil blended with 50ppm of copper oxide nano additives. It was noted that methyl esters of mahua oil and its blends released lesser BTE compared to diesel at all loads due to its higher viscosity, poor spray behaviour and lesser heat energy value. The nano blended fuel exhibited lower CO, HC and smoke due to improved spreading property and fuel- air mixing rate inside the chamber. NOx emissions were found increased slightly due to the increase in combustion temperature [14]. Vivek W. Khond et al. did a literature review on the influence of nano additives on emulsified biodiesel and diesel. The results presented that BTE increased, BSFC decreased with an increase in dosage of nano additives due to boosted oxidation, heat energy value and ample combustion of fuel. HC and NOx were found lower due to high cetane number, catalytic oxidation and higher evaporation rate of nano additives. Smoke emission was lower due to lengthier ignition delay. The decrease in CO emission was found due to upgraded ignition characteristics [15]. Gumus, Soner et al. led a study to evaluate the influence of aluminium oxide and copper oxide nano additives with diesel on engine characteristics. In this study, synthesis of nanoparticles, stability characteristics, effect of nano particles on physio-chemical properties and on engine characteristics were analysed. It was found that adding nanoparticles in diesel were not changing the physio-chemical properties except a slight rise in cetane index and flashpoint. It was noted that adding aluminium oxide and copper oxide in diesel had good stability. Increase in torque and brake power was noticed when diesel blended with nano particles. CO, HC, NOx was considerably abridged by adding nanoparticles [16]. B. Ashok et al. conducted research using Calophyllum Inophyllum Methyl Ester (CIME) blended with nano zinc oxide and ethanox additives in CI engine. In this study, ZnO nano additives at two mass proportions of 50 ppm and 100 ppm while ethanox at two mass proportions of 200 ppm and 500 ppm were blended with the fuel. An improvement in BTE and BSFC was observed due to the addition of nanoparticles. It was also observed that HC and CO emissions were reduced because oxygen buffer of nanoparticles promoted ample combustion of fuel. But there was an increase in NOx and smoke emission [17]. K. Nanthagopal et al. did research by blending ZnO and titanium dioxide nanoparticles in an emulsified CIME. It was found that the dosing of nanoparticles upgraded the BTE and
BSFC due to the spread of large surface area of nanoparticles which exhibited speedy evaporation and improved atomization. It was noted that there was a discount in HC and CO due to the oxidation effect of TiO₂ and ZnO nanoparticles. It was also observed that there was a drop in NOx and smoke due to the water particle present in the CIME nano emulsion which has a higher latent heat of vaporization [18]. G Najafi did an experimental study using biodiesel and diesel blended with nano silver particles. Experimental results showed that the engine brake torque and power were increased, BSFC was abridged. HC and CO emissions were reduced, NOx emission was increased [19]. Suresh Vellaiyan et al. conducted research by adding ZnO nanoparticles in water emulsified Soya bean biodiesel. It was found that a drop in BTE and rise in BSFC due to the lower heating energy content of ZnO blended biofuel. The exhaust emissions such as HC, CO and smoke opacity were found significantly abridged and NOx emission was augmented due to the increase in combustion temperature that was encouraged by higher oxygen content [20].

From the above pieces of literature, scientists found that the addition of nanoparticles/ nano fluids in biodiesel enhanced the engine characteristics. The nano additives have many advantages like high thermal conductivity, faster oxidation, higher surface area to volume ratio, catalytic reactivity and chemical reaction which improved the thermal efficiency, BSFC by enhanced combustion. Also, nano additives reduced the harmful tailpipe emissions such as HC, CO, NOx and smoke. By considering all the positive aspects of nano additives, this research was conducted using zinc oxide nanofluids prepared by the wet chemical method in three mass fractions of 50ppm, 75ppm and 100ppm and blended with WCOB. The test fuels were named as WCOBZN50, WCOBZN75 and WCOBZN100.

2. Materials and Methods

2.1 Source
Hotels and restaurants are consuming vegetable oils in large quantities for the preparation of food items, after making food items, the remaining vegetable oils might have disposed in land surface and polluting the surroundings. These consumed vegetable oils were brought from the restaurant. It was considered as a waste cooking oil. This waste cooking oil contains micro and macro impurities which were filtered before going for trans-esterification process.

2.2 Trans-esterification process of WCO
In this experimental study, the trans-esterification method was used for preparing methyl esters of WCO and considered as WCOB. During this process, the high viscosity of WCO has been considerably reduced. The materials involved in the production of WCOB were WCO, methanol, potassium hydroxide. One litre of WCO had been taken and poured into the transesterification equipment, then it was heated to 60°C and continuously stirred for half an hour. Next, potassium hydroxide and methanol were taken and mixed them to form a solution. This prepared solution was poured into the equipment where WCO was in the heated condition. Further, WCO with catalytic KOH Methanol solution was continuously stirred and heated for an hour and stopped the process. The final product contains methyl esters of waste cooking oil and glycerides. These heavy glycerides were allowed to settle in the lower part of the equipment and the methyl ester of waste cooking oil in the upper part were removed and collected in a container.

2.3 Preparation of ZnO Nanofluid
In this research, a novel wet chemical method was chosen to prepare zinc oxide nanofluid in mass fractions of 50ppm, 75ppm and 100ppm. For preparing different mass fractions of 50ppm, 75ppm and 100ppm ZnO nanofluid, 0.27g, 0.40g and 0.59g of zinc nitrate and hexahydrate were mixed with 10ml of sodium hydroxide separately and each nanofluid were ultrasonicated separately for 15minutes. Then, each
prepared Zinc oxide nanofluid were blended with 1 litre of WCOB and sonicated using ultrasonicator. By this method, three blended fuels such as WCOBZN50, WCOBZN75 and WCOBZN100 were prepared and their fuel properties were tested. The ZnO nano fluid prepared by wet chemical method and blended with WCOB was found stable for 4 weeks. These fuels were prepared for experimentation. The photographic view of ZnO nano fluid is shown in the figure 1 and photographic view of ZnO nanofluid blended with WCOB is shown in the figure 2. The ultrasonicator setup is shown in the figure 3.

Figure 1. Photographic view of ZnO Nanofluid

Figure 2. Photographic view of ZnO nanofluid blended with WCOB

Figure 3. Ultrasonication set up for preparing WCOB blended with ZnO nanofluid

2.4 Properties study and analysis
The fuels were tested and fuel properties were measured and given in the table 1. It was observed that there was an increase in the properties of fuels while increasing the dosage of nanofluids. Physical properties such as density and viscosity were found increasing due to the addition of nanofluids. It was observed that Calorific value of nano blended fuels were increased, this might be due to energy content in
the nano fluid. Due to the enhancement in calorific value, BTE and BSFC were improved. Cetane number of the nano blended fuels were found increasing due to the dosage of nanofluids.

Table 1. Fuel Properties

| Properties                  | Diesel | WCOB | WCOBN50 | WCOBN75 | WCOBN100 |
|-----------------------------|--------|------|---------|---------|----------|
| Density (kg/m³)             | 830    | 880  | 881     | 882     | 883      |
| Viscosity@40℃(Cst)         | 2.95   | 4.48 | 4.51    | 4.53    | 4.56     |
| Calorific Value(kJ/kg)     | 44,500 | 37,195| 37,512  | 37,923  | 38,213   |
| Flash Point                 | 52     | 178  | 177     | 176     | 175      |
| CetaneNumber (or)Cetane Index | 50     | 44   | 45.1    | 45.29   | 45.83    |

3. Experimental Setup

![Figure 4. Schematic diagram of engine test set up](image)

A single-cylinder, four strokes, water-cooled, diesel engine was used for testing the engine characteristics of ZnO nano fluids blended with WCOB. The schematic diagram of fully equipped engine test bed is
shown in the Figure 4. The photographic view of engine experimental setup is presented in Figure 5. The
detailed specification of the experimental engine is given in table 2. Experimental Engine flywheel was
joined with water-cooled eddy current dynamometer which was used for applying load on the engine. To
measure TDC and BDC position of the piston, Kubler made crank angle sensor was used. To measure the
pressure inside the engine cylinder, AVL made piezoelectric pressure sensor was installed in the engine
cylinder head. A control unit in the engine set-up was used to receive the signals from the pressure sensor
and the signals were processed to calculate the combustion data such as in-cylinder peak pressure, the heat
release rate and the rate of pressure rise. To measure the exhaust gas inlet and outlet temperatures, K-type
chrome thermocouples were fitted on the exhaust manifold. A controller in the eddy current dynamometer
was used to vary the engine load. AVL made DiGAS 444N model exhaust gas measuring unit was used to
measure the engine tailpipe gases. The exhaust emission gas analyser with smoke meter is shown in the
figure 6. AVL made 437C model smoke meter was used to calculate the smoke opacity. In this study,
standard fuel injection timing (230bTDC) and fuel injection pressure (200bar) with mechanical fuel
injector was used. The engine was loaded from no load to full load, maintained a constant speed of
1500rpm with the help of a governor and engine was allowed to run for 10 minutes in each load, then the
readings were taken. Engine performance, combustion and emission measurements at different loadings
were taken for three trails for the test fuels.

![Figure 5. A photographic view of engine test setup](image)

![Figure 6. AVL Gas Analyzer with smoke meter](image)

| Table 2. Specification of Engine |
|--------------------------------|
| **Description** | **Specification** |
| Make & Model | Kirloskar/240PE |
| Bore/Stroke | 87.5mm/110mm |
| Rated Power | 3.5KW @ 1500rpm |
| Compression Ratio | 17.5:1 |
| Swept Volume | 661CC |
| Injection timing | 230bTDC |
| General Details | Four stroke, Single cylinder, CI Engine |
| Loading | Eddy current Dynamometer |
4. Results and Discussion

4.1 Performance characteristics

4.1.1 Brake Thermal Efficiency

Brake thermal efficiency (BTE) is an important measurement to determine engine performance. The BTE of diesel, WCOB, WCOBZN50, WCOBZN75 and WCOBZN100 for different Brake power (BP) is shown in the figure 7. BTE was found augmented as the engine load increased for all the test fuels. It was clearly observed that WCOBZN100 released higher brake thermal efficiency compared to WCOB, WCOBZN50 and WCOBZN75. It was found that the BTE (in %) of diesel, WCOBZN100, WCOBZN75, WCOBZN50 and WCOB were 27.55, 24.39, 23.58, 22.83 and 22 respectively. It was noted that BTE of WCOBZN100 at full load was 24.39%, which is 10.86 % higher than WCOB. This was due to higher SA/V ratio phenomenon of nanoparticles, enhanced combustion due to micro-explosion characteristics and faster rate of oxidation.

4.1.2 Brake Specific Fuel Consumption

The discrepancy of BSFC with respect to BP for test fuels is shown in figure 8. The BSFC for the ZnO nanofluid blended WCOB fuel was found decreasing when the amount of ZnO nanofluid increasing in the fuel blends. In the figure 8, it was found that WCOBZN100 had lesser BSFC compared to neat WCOB, WCOBZN50 and WCOBZN75. At full load, the BSFC in kg/ KW-hr of diesel, WCOBZN100, WCOBZN75, WCOBZN50 and WCOB are 0.30, 0.38, 0.40, 0.42 and 0.439 respectively. The BSFC of WCOBZN100 was 13.43% lesser than neat WCOB. This was due to the nanoparticles in the fuel enhancing faster oxidation and catalytic combustion, thereby reducing the fuel consumption.

![Figure 7. Variation of BTE with BP](image7)

![Figure 8. Variation of BSFC with BP](image8)

4.2 Emission characteristics

4.2.1 Hydrocarbon Emission

The hydrocarbon emissions emitted by various blends of ZnO nanofluid with WCOB is shown in the figure 9. It was found that WCOB fuel released more hydrocarbon emissions due to higher density of WCOB. At maximum engine load, the HC emissions (in ppm) of diesel, WCOBZN100, WCOBZN75, WCOBZN50 and WCOB are 48, 39, 43, 45 and 55. The HC emission for WCOBZN100 is 18.75% lower
than diesel and 29.09% lesser than WCOB. By adding ZnO nanofluids with WCOB released lesser HC emissions because ZnO nanoparticles present in the fuel droplet enhances the hydrocarbon oxidation process.

4.2.2 Carbon monoxide emission
CO emission is influenced by many details such as fuel injection pressure, fuel injection timing, quality of air-fuel mixture, engine speed and load. The CO emission with respect to BP for various blends of ZnO nanofluid with WCOB is shown in figure 10. It was found that WCOB released higher CO emissions in comparison with other test fuels, due to poor combustion. WCOB blended with ZnO nanofluid in different proportions produced lesser CO emissions compared with neat WCOB. This was due to enhanced oxidation process by nanofluid during combustion.

At full load, CO emissions (in % by volume) of diesel, WCOBZN100, WCOBZN75, WCOBZN50 and WCOB are 0.17, 0.18, 0.19, 0.2 and 0.21. At full load, CO emission of WCOBZN100 is 0.18% which is 14.28% lesser than CO emission of WCOB (0.21%). This was due to healthier mixing of air and fuel; faster oxidation and catalytic reaction.
4.2.3 Nitrogen Oxide Emission
The NOx creation is due to high in-cylinder combustion temperature, oxygen availability and reaction time. At full load, the NOx emission (in ppm) of Diesel, WCOB, WCOBZN50 WCOBZN75 and WCOBZN100 are 814, 664, 590, 551 and 529. The NOx emission of WCOBZN100 was 35.01% lesser than diesel. It was absorbed that NOx emission was lower for WCOBZN100 related to other test fuels as shown in figure 11. This NOx reduction was due to faster heat transfer characteristics of ZnO nanofluid in the combustion stage by enhanced catalytic combustion. ZnO nanofluid enhanced faster oxidation, chemical reactivity, reduced delay period which resulted in a reduction in cylinder peak temperature.

4.2.4 Smoke opacity
The smoke emission depends on fuel density, viscosity and fuel droplet size. Smoke emission was found higher for WCOB because of higher density and viscosity. Adding ZnO nanofluid with WCOB boosted the combustion process. It was observed that WCOBZN100 produced lesser smoke opacity than neat WCOB as shown in figure 12. This reduction was due to better mixture formation, micro explosion, improved explosion characteristics of nanoparticles in the fuel droplet. At full load, the smoke opacity values of WCOBZN100, WCOBZN75, WCOBZN50 neat WCOB and diesel are 55, 61, 64, 80 and 47. It was noted that WCOBZN100 fuel emitted lesser smoke opacity which is 31.25% lower than neat WCOB.

4.3 Combustion characteristics
4.3.1 In-cylinder pressure
The engine was operated using different test fuels. The discrepancy of in-cylinder pressure with crank angles for the prepared fuels is shown in figure 13. The peak pressure values (in bars) for diesel, WCOB, WCOBZN50, WCOBZN75 and WCOBZN100 are 57.81, 53.94, 54.57, 55.59 and 56.14 respectively. Diesel fuel has shown maximum cylinder pressure due to its higher calorific value. WCOBZN100 exhibited higher in-cylinder pressure value due to its catalytic reactivity and oxygen buffer of nanoparticles which enhanced the combustion. WCOBZN100 produced 4% higher in-cylinder pressure than neat WCOB because ZnO nano fluid in the fuel supported for faster combustion.

Figure 13. Variation of in-cylinder pressure with crank angle
Figure 14. Variation of net HRR with crank angle
4.3.2 Heat Release Rate (HRR)

The data on cylinder design, type of fuel, fuel injection type and combustion process are important parameters related to HRR. The variation of HRR with crank angles for test fuels is exposed in figure 14. At full load condition, the heat release rate (in KJ) for diesel, WCOB, WCOBZN50, WCOBZN75 and WCOBZN100 are 66.75, 34.83, 47.04, 49.67 and 51.59 respectively. Diesel showed higher HRR and pure WCOB had the lowest value. It was observed that the fuels containing nano fluid, WCOBZN100 released higher value of HRR due to enhancement in the oxidation of fuel droplets and faster combustion.

4.3.3 Rate of pressure rise (RoP)

From the figure 15, the rate of pressure rise increases due to surge in quantity of nano additives with WCOB. The highest rate of pressure rise values (in bars) for diesel, WCOB, WCOBZN50, WCOBZN75 and WCOBZN100 are 6.83, 3.88, 4.61, 4.99 and 5.66 respectively.

![Figure 15. Variation of rate of pressure rise with crank angle](image)

Diesel showed higher RoP and pure WCOB had the lowest value. It was observed that the fuels containing nano additives, WCOBZN100 showed higher value for RoP due to faster and enhanced combustion.

5. Conclusion

This experimental research on engine performance, emission and combustion parameters fuelled with WCOB, WCOB blended with zinc oxide nanofluid in three mass proportions (50ppm, 75ppm and 100ppm) and detailed evaluation was carried out. With the source of experimental outputs, the following inferences were made.

- The engine was running satisfactorily with all the test fuels.
- The zinc oxide nanofluid prepared by a wet chemical method is the new technique and the stability of the ZnO nanofluid blended with WCOB was good.
- The BTE of WCOBZN100 was higher than WCOB and other blends because ZnO nanoparticles dispersed in the biodiesel boosted the catalytic reaction and combustion process. The maximum BTE for WCOBZN100 was 24.39% which is 10.86% higher than WCOB.
- The BSFC of WCOBZN100 fuel was found lesser than neat WCOB and other blends. This was due to faster oxidation of nanoparticles which spreads over the larger surface area in the
combustion chamber and produced more power with less fuel consumption. The BSFC value for WCOBZN100 is 0.38kg/kW-hr which is 13.43% lesser than neat WCOB.

- The HC emission of WCOBZN100 was significantly reduced because nanoparticles available in the fuel droplet augments the oxidation and combustion process. The HC emissions for WCOBZN100 is 39ppm which is 29.09% lesser than WCOB.

- ZnO nanofluid blended with WCOB in different proportions have produced lesser CO emissions compared with neat WCOB. This was due to the presence of oxygen in the nanoparticles and supplies sufficient oxygen during combustion. The CO emission of WCOBZN100 is 0.18% by volume which is 14.28% lesser than CO emission of WCOB.

- The NOx value for WCOBZN100 was drastically abridged compared to other test fuels. This reduction was due to faster heat transfer characteristics of ZnO nanoparticles in the WCOB in the combustion chamber by improved catalytic combustion. ZnO nanoparticles enhanced faster oxidation, chemical reactivity which resulted in reduced in-cylinder combustion temperature. The NOx emission of WCOBZN100 is 529ppm at full load which is 35.01% lesser than diesel fuel.

- It was detected that the smoke opacity was higher for WCOB than other fuels. It was due to higher density of biodiesel which primes to large-sized fuel droplets and smoke emission. The smoke opacity values of WCOBZN100, WCOBZN75, WCOBZN50, neat WCOB and diesel are 55, 61, 64, 80 and 47 respectively. It was noted that WCOBZN100 fuel emitted lesser smoke opacity which is 31.25% lower than neat UCOB.

- There was a surge in peak cylinder pressure for WCOBZN100 due to the augmentation in combustion. At high load, the peak pressure values (in bars) for diesel, WCOB, WCOBZN50, WCOBZN75 and WCOBZN100 are 57.81, 53.94, 54.57, 55.59 and 56.14 respectively.

- The peak HRR values (in KJ) for diesel, WCOB, WCOBZN50, WCOBZN75 and WCOBZN100 are 66.75, 34.83, 47.04, 49.67 and 51.59 respectively. It was noticed that the HRR value was found to be higher for WCOBZN100 due to the catalytic reactivity of nanofluids.

- The rate of pressure rises increased due to increase in quantity of nanofluid with WCOB. It was noticed that WCOBZN100 showed higher RoP due to the enhancement in combustion. The peak rate of pressure rises values for diesel, WCOB, WCOBZN50, WCOBZN75 and WCOBZN100 were 6.83, 3.88, 4.61, 4.99 and 5.66 respectively.

After analysing the experimental results, it was clearly observed that ZnO nanofluid prepared by wet chemical method and blended with waste cooking biodiesel would be the novel fuel for diesel engine without any engine dimension modifications which boosted the performance of the engine with reduced harmful exhaust emissions.

References

[1] Kannan, G. R., & Anand, R. (2012). Effect of injection pressure and injection timing on DI diesel engine fueled with biodiesel from waste cooking oil. *Biomass and bioenergy*, 46, 343-352.

[2] An, H., Yang, W. M., Maghbouli, A., Li, J., Chou, S. K., & Chua, K. J. (2013). Performance, combustion and emission characteristics of biodiesel derived from waste cooking oils. *Applied energy*, 112, 493-499.

[3] EL_Kassaby, M., &Nemit_allah, M. A. (2013). Studying the effect of compression ratio on an engine fueled with waste oil produced biodiesel/diesel fuel. *Alexandria Engineering Journal*, 52(1), 1-11.

[4] Hwang, J., Qi, D., Jung, Y., & Bae, C. (2014). Effect of injection parameters on the combustion and emission characteristics in a common-rail direct injection diesel engine fueled with waste
cooking oil biodiesel. *Renewable Energy, 63*, 9-17.

[5] Gopal, K. N., Pal, A., Sharma, S., Samanchi, C., Sathyarayanan, K., & Elango, T. (2014). Investigation of emissions and combustion characteristics of a CI engine fueled with waste cooking oil methyl ester and diesel blends. *Alexandria Engineering Journal, 53*(2), 281-287.

[6] Kathirvel, S., Layek, A., & Muthuraman, S. (2016). Exploration of waste cooking oil methyl esters (WCOME) as fuel in compression ignition engines: a critical review. *Engineering Science and Technology, an International Journal, 19*(2), 1018-1026.

[7] Geng, P., Mao, H., Zhang, Y., Wei, L., You, K., Ju, J., & Chen, T. (2017). Combustion characteristics and NOx emissions of a waste cooking oil biodiesel blend in a marine auxiliary diesel engine. *Applied Thermal Engineering, 115*, 947-954.

[8] Abed, K. A., El Morsi, A. K., Sayed, M. M., El Shaib, A. A., & Gad, M. S. (2018). Effect of waste cooking-oil biodiesel on performance and exhaust emissions of a diesel engine. *Egyptian Journal of Petroleum, 27*(4), 985-989.

[9] Karthikeyan, S., Elango, A., & Prathima, A. (2014). Performance and emission study on zinc oxide nano particles addition with pomolion stearin wax biodiesel of CI engine.

[10] Karthikeyan, S., Elango, A., & Prathima, A. (2014). An environmental effect of GSO methyl ester with ZnO additive fuelled marine engine.

[11] Karthikeyan, S., Elango, A., & Prathima, A. (2014). Diesel engine performance and emission analysis using canola oil methyl ester with the nano sized zinc oxide particles.

[12] Prabakaran, B. (2015). Investigation of Effects of addition of zinc oxide nano particles to diesel ethanol blends on DI diesel engine performance, combustion and emission characteristics. *Int. J. Chem. Sci, 13*(3), 1187-1196.

[13] Shaafi, T., Sairam, K., Gopinath, A., Kumaresan, G., & Velraj, R. (2015). Effect of dispersion of various nano additives on the performance and emission characteristics of a CI engine fuelled with diesel, biodiesel and blends—a review. *Renewable and Sustainable Energy Reviews, 49*, 563-573.

[14] Chandrasekaran, V., Arthanarisamy, M., Nachiappan, P., Dhanakotti, S., & Moorthy, B. (2016). The role of nano additives for biodiesel and diesel blended transportation fuels. *Transportation Research Part D: Transport and Environment, 46*, 145-156.

[15] Khond, V. W., & Kriplani, V. M. (2016). Effect of nanofluid additives on performances and emissions of emulsified diesel and biodiesel fueled stationary CI engine: A comprehensive review. *Renewable and Sustainable Energy Reviews, 59*, 1338-1348.

[16] Gumus, S., Ozcan, H., Ozbey, M., & Topaloglu, B. (2016). Aluminum oxide and copper oxide Nano diesel fuel properties and usage in a compression ignition engine. *Fuel, 163*, 80-87.

[17] Ashok, B., Nanthagopal, K., Mohan, A., Johny, A., & Tamilarasu, A. (2017). Comparative analysis on the effect of zinc oxide and ethanox as additives with biodiesel in CI engine. *Energy, 140*, 352-364.

[18] Nanthagopal, K., Ashok, B., Tamilarasu, A., Johny, A., & Mohan, A. (2017). Influence on the effect of zinc oxide and titanium dioxide nanoparticles as an additive with Calophyllum inophyllum methyl ester in a CI engine. *Energy Conversion and Management, 146*, 8-19.

[19] Najafi, G. (2018). Diesel engine combustion characteristics using nano-particles in biodiesel-diesel blends. *Fuel, 212*, 668-678.

[20] Vellaiyan, S., Subbiah, A., & Chockalingam, P. (2019). Multi-response optimization to improve the performance and emissions level of a diesel engine fueled with ZnO incorporated water emulsified soybean biodiesel/diesel fuel blends. *Fuel, 237*, 1013-1020.