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Effect of MWCNTs nano-additive on a dual-fuel engine characteristics utilizing dairy scum oil methyl ester and producer gas

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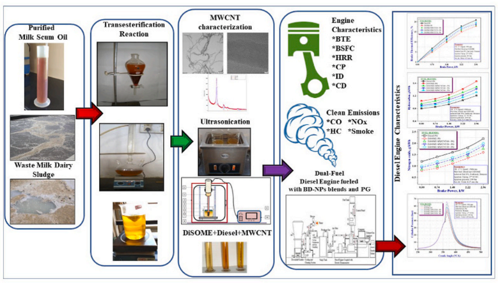
GRAPHICAL ABSTRACT



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A B S T R A C T

Alternative fuels are renewable sustainable and address socio-economic and environmental concerns. In this circumstance, this work is conducted in two stages. The first stage of the work involves, the preparation of nanoparticle (NP) blended fuels by adding 20, 40 and 60 ppm of multi-walled carbon nanotube (MWCNT) particles in dairy scum oil methyl ester (DiSOME) biodiesel using a mechanical homogenizer and ultrasonicator. Then, the steadiness characteristics of nanoparticle–mixed biodiesel fuels were studied under static state. In the next stage of the work, the effect of nanofluids on the attributes of combustion and emissions of aengine with 1-cylinder 4-stroke DI-direct injection),CI-compression ignition)which is run on DF-dual-fuel mode using DiSOME and PG-producer gas, has been examined. Investigation results indicated that at 80% load, DiSOME-PG combustion with 40 ppm of MWCNT nanoparticles provided 5.7% increased BTE, 23.5% decreased smoke opacity, 21.8% decreased HC, 22.4% decreased CO and 20.1% amplified NOx emissions related to the same fuel mixer but not with NPs. Adding NPs increased HRR - heat release rate and CP - cylinder pressure.

1. Introduction

The rapid unending growth in vehicle population due to increased human activities, tremendous load carrying and power generation capacity of diesel engines lead to increased emission levels [1,2]. Hence, investigation and/or monitoring of performance and emissions and air quality control significantly require emission reduction technologies in terms of fuel modification and changes in engine design. Drastic fuel utilization for combustion increased the cost of crude oil import due to the depleting nature of fossil fuel. Its dependency may directly cause a negative impact on the country's economy and increased greenhouse gas (GHG) emissions [3–5]. Diesel engines are more prevalent in India due to greater efficiency, lower carbon monoxide, lower fuel consumption, and hydrocarbon (HC and CO) exhaust gases. This results into drastic increase in acceptance by the world and has been used for transport, power generation and commercial vehicles. However, these engines are facing high smoke and nitric oxide emissions. In this regard, investigators attempted to lower emission levels using external emission control devices [6–8].

In this context, several have investigated mainly the burning attributes of CI engines using biodiesels of diversified sources and stated that biodiesel use generates the same, lower or amplified power output with satisfactory exhaust gases compared to diesel [9–12]. Neat biodiesel operation showed lowered performance with augmented smoke, HC and CO and lowered NOx levels. Also, biodiesel operation showed augmented ignition delay and combustion duration with diminished CP and HRR. Appavu et al. [13] examined the influence of quaternary blends with different pentanol concentrations (10%–40%) and fixed oil concentration of (5%) and diesel (50%). They have compared with diesel and biodiesel blends operation. They found reduced BSFC and BSEC with amplified pentanol proportion. In addition, smoke, HC and CO was found to be reduced. Pentanol of 40% blended fuel improves the peak pressure and HRR. Most unexplored biodiesel derived from diary scum has greater cetane number with higher energy content, but cold flow properties are poor. The availability of diary scum in India is more than 160 million tons per year, according to the biodiesel production from diary scum reserve appraisal. In Dharwad, India, there is a milk factory called Karnataka Milk Federation (KMF) Ltd. The KMF can handle about 3.0–3.25 lakh liters of milk per day. Processing of milk followed by equipment cleaning requires 3–4 lac water in liters per day. This water contains effluent scum about 100–150 kg as a waste, which is not easy to dispose of [14]. Diesel engine operation using DiSOME provided satisfactory thermal efficiency with lowered NOx emissions and better fuel burning caused by the greatercetane number [15]. Greater consumption of DiSOME to attain asimilar power output as compared withfossil fuel operation was observed. In addition, increased thermal efficiency, CP, HRR, increased smoke and NOx pollutants and decreased HC and CO pollutants have been noticed [16,17]. The influence of diary waste scum-derived biodiesel on the contaminants and combustion attributes of a 1- cylinder; 4- stroke CI engine has been studied by Srikant et al. [18]. They have conducted engine tests with a use of different fuel blends at different loading conditions in percentage i.e.10, 20, 30, and 100% biodiesel. They found better performance for B30 blend and observed a greater difference than diesel operation. However, they observed enhanced fuel consumption with reduced HC and CO pollutants as compared to diesel combustion [19]. But, NOx emissions were amplified with biodiesel and blends operation. Researchers have also attempted to achieve complete combustion; thereby, emissions were lowered significantly. Investigators employed injection timing (IT) and injection pressure (IP) adjustments, as well as nozzle and combustion chamber shape, to extract all of the energy from the biodiesel. Ardebili et al. [5] investigated the effect of mono ethylene glycol supported emulsion ratio on the combustion. At optimum condition, they found torque, BTE, BSFC, BSEC, CO, NOx, and soot were 17.24 Nm, 28.52%, 505.7 g/kWh, 9.48 MJ/kWh, 2123 ppm, 368 ppm, and 2.24 $m-1$, respectively. Solmaz et al. [20,21] examined the effect of MWCNT on the combustion and emission characteristics of diesel engine operated on diesel-biodiesel blends. They observed 28.57 (%), 269.84 (g/kWh), 0.03 (%Vol.), 44.16 (ppm), and 458.81 (ppm) for BTE, BSFC, CO, UHC, and NOx emissions respectively, at addition of 98 ppm MWCNT nano-particles.

Furthermore, Agarwal et al. [22] studied the effect of IP, IT, and blending ratio on the attributes of combustion and emission of a common rail direct injection (CRDI) engine. Injection pressure significantly affects the droplet size and profile of the injection rate. Increased injection pressure, on the other hand, boosts the thermal efficiency while lowering smoke, HC, and CO levels. The consequences of the geometry of combustion chamber on the combustion and pollutant attributed in biodiesel-powered CI engine has been studied by Karthickeyan [23]. Except for NOx, superior performance with condensed emissions has been observed with TCC than the operation with other combustion chambers. Higher swirl and squish obtained by the use of TCC leading to increased air-fuel mixing is responsible for the observed trends. Engine operation using diesel-biodiesel-ethanol blends with alumina nano additives and toroidal re-entrant combustion chamber increased thermal efficiency by 33.8% at 22°bTDC compared to other combinations tested. TCC and nano-additives boosted thermal efficiency, and at a 22°bTDC injection time, reduced HC and CO emissions were recorded with higher NOx emissions [24].

The NPs in blended diesel resulted in improved engine efficiency with reduced exhaust gases. NPs cause this as they have larger area (surface) and thermal conductivity, which may enhance heat transfer mechanism. In general, fuels scattered with nanoparticles typically have higher thermo-physical properties. Compared to B20 blended fuel, using 40 ppm of Al_2O_3 nanoparticles improves efficiency and reduces smoke, HC, and CO emissions at 80% load [25]. However, using B20 fuel with CuO NPs resulted in a 4.01% increase in BTE, a 1.0% reduction in BSFC, a 12.8% reduction in smoke, and a 9.8% reduction in NOx [26]. Compared to pure diesel operation, nanoparticle blended B20 operation raised CO_2 by 17.03%, decreased CO by 25.17%, and reduced HC by 28.56 percent but NOx emissions were increased by 14.21%. In addition, the affirmative influence of CeO_2 nanoparticles on emissions of biodiesel operation has been reported [27,28]. Literature pertaining up to 2015 has been reviewed by Vivek and Kriplani [29]. The use of exhaust gas treatment (EGT) devices to lower the engine out gases significantly affects the engine's performance. Still, additives like nanoparticles can reduce emission levels and improve the engine's performance. The power of an engine was proportional to the concentration of nanoparticles [30]. Improved ignition characteristics due to amplified oxygen and lowered aromatics in biodiesel and occurrence of nanoparticles provide complete combustion and amplified cylinder pressure and heat release rate. Fuel properties have a linear relationship with nanoparticle s quantity. In-cylinder distribution of soot and combustion character was investigated using 50 and 100 mg/L CeO_2 in diesel fuel [31]. They have stated that nanoparticles addition in a fuel proceed the combustion starting and increases CP and HRR. Nanoparticle addition to diesel (Catalytic diesel fuel) lowers the soot density, soot area occupied ratio and smoke emission levels. The further oxidation process will be improved with catalytic diesel. Hasannuddin et al. [32]evaluated the effect of number of nanoparticles on the fuel burning and pollutants of a diesel engine. They have prepared blend using 10% water in diesel and prepared emulsion called as E10. Nanoparticles of 50 ppm were mixed in E10 known as nano-additive emulsion fuel and blended fuel prepared are $E10Al_2O_3$, E10CuO, E10ZnO etc. $E10Al_2O_3$ provided improved performance from the fuels tested with drastic reductions in BSFC and lowered emission levels. They found Al_2O_3 is a good nano-additive due to little water droplet size, and its tendency to increase torque and lower NOx levels compared to other nano-additives. Nanofluids heat transfer performance using diesel and multiwalled carbon nanotubes (MWCNT) and graphene nano-platelets (GNP) with various concentrations and flow rates have been reported by Atiyeh et al. [33]. They have related the blended fuel combustion with neat diesel and biodiesel operation. They suggested that optimum blended fuel provides the amplified performance with diminished smoke levels, HC, CO, and NO by 25 39, 50 and 37%, respectively [34,35]. Venu and Appavu [36] and Venu and Appavu [37] examined the effect of zirconium nanoparticles' effect on biodiesel, which lowers fuel consumption and increases thermal efficiency with decreased emissions. Greater nitrogen oxides and CO_2 emissions have been stated.

However, several investigators used gaseous fuels for power production applications. Dual fuel operation decreased thermal efficiency and increased pilot fuel-saving and emissions. The dual fuel process mainly lowers the smoke and NOx emission levels [38,39]. Producer gas is a low calorific value gaseous fuel used for engine application without many main engine modifications. The main advantage of using producer gas is that it is renewable sources and can be produced using low grade biomass such municipal solid waste, carpentry waste etc. use of producer gas provide energy security and foreign exchange saving addressing environmental concerns, and socio-economic issues as well. Also use of gaseous fuel in diesel engine operating on dual fuel mode saves about 70–90% pilot fuel and lowers smoke and NOx emission levels. But engine power derating with increased carbon based emissions has been reported [3]. Compared to single fuel operation, dual fuel process at smaller loads results in less gaseous fuel usage, leading to worse thermal efficiency and increased emissions [40–42]. Advanced injection timing increased pressure of cylinder and heat release rate, but it increased NOx.

Further, retarded injection timing and exhaust gas recirculation decrease the NOx levels with significant loss of engine performance [43–45]. Increased nozzle hole, and decreased nozzle hole size and use of re-entrant piston bowl geometry increase thermal efficiency with decreased carbon-based emissions with marginally amplified NOx levels. However, the ignition delay and combustion duration were lowered, but the CP and HRR were raised [46]. Increased compression ratio raises combustion pressure and temperature, leading to increased BTE and lower pollutants excluding NOx and improved CP and HRR [3]. Improved power outputs with reduced emissions are noticed for hydrogen-enriched producer gas induction [47,48]. It could be due to the more incredible velocity of the flame of the hydrogen-PG mixture enhancing combustion rate leading to burning the entire fuel combination. The piston bowl with Re-entrant toroidal geometry improves the revolving moment of air and splash within the cylinder. It helps achieve the uniform mixture within a short time [49].

The literature review suggested that various nanoparticles were used in biodiesel and investigated the combustion behavior of a diesel engine. However, the use of nanoparticles in PG fueled engines is not explored. In view of this, the present work is conducted in 2 stages and are given below.

➢ At the 1st stage of the work, nano fluids are prepared by blending multi-walled carbon nanotube (MWCNT) particles of 20–60 (step of 20) ppm mass fractions in scum oil biofuel from dairy milk using a mechanical homogenizer and ultrasonicator.
➢ Steadiness characteristics of nanoparticle fuels were studied under static circumstances. In the next stage, the effect of nanofluids on the combustion and pollution attributes of a single cylinder 4 stroke CI engine working on DF mode by using DiSOME and PG was investigated.
➢ Finally, results obtained with DiSOME–MWCNT–PG operation is compared to diesel-PG operation.

2. Materials, methods, and properties of fuels

Diary scum oil, sodium hydroxide and methanol are employed for diary scum oil biodiesel production. Fig. 1 (a and b) shows the experimental set up for biodiesel production. As per the literature, the method and procedure for biodiesel production using well-established *trans*-esterification [14]. Another material used in the present work are Multi-walled carbon nanotube (MWCNTs) nanoparticles additive. The blending is carried out with the assistance of an ultrasonicator (Fig. 1 (c)). CNTs are categorized by single-walled CNTs and multi–walled CNTs. These nanomaterials have unique physical, mechanical and electrical properties. MWCNT in fuel increases the surface-to-volume ratio [50,51].

2.1. Preparation of nano biodiesel blends

For mixing MWCNT NPs with diary scum oil biodiesel, 1 L of biodiesel with 20 ppm of MWCNT nanoparticle was mixed and this mixture is denoted as DiSOME + MWCNT20 blend. Similarly, other blends were prepared. The nanoparticles are dispersed in biodiesel using an ultrasonicator. Ultrasonic equipment is commonly used for distributing the particles, which lowers the agglomeration of particles. Biodiesel contains oleic acid, which will act as surfactant. This can help in producing uniform suspension and helps in reducing the agglomeration. The nanofluid quality depends on the nanoparticles' homogeneous dispersion in the biodiesel. Nanofluid refers to fluids which contain dispersed nanoscale particles. Optimization of ultrasonication parameters succontaine ported and is responsible for stable suspension [52]. In the present work, the obtained mixture was agitated with the help of an ultrasonicator at a test 40 kHz frequency and for 1 h to get a uniform or homogeneous mixture. Then, prepared fuel blends are stored in glass bottles under the normal condition shown in Fig. 1 (d).

2.2. Properties of fuels used

In this present work, DiSOME, DiSOME blended fuel with MWCNT and PG have been employed as pilot injected and manifold introduced fuel, respectively. Diary scum oil biodiesel (DiSOME) with and without nanoparticle additive were characterized and tested for achieving the requirements. Fuel properties of DiSOME with and without MWCNT and biomass used are listed in Tables 1 and 2.

2.3. Experimental setup

Experimental tests were conducted using DI CI engine having 1 cylinder 4 stroke cooled by water and functioning on various fuel combinations. It had the usual mechanical fuel injection arrangement with inlet and outlet valves functioning with the help of push rods. It hadadis placement volume of 662 CC and developed 3.72 kW at 1520 rpm.Fig. 2 shows a photographic view of the experimental test rig. Engine and downdraft gasifier specification is provided in Table 3. Cooling of the engine was accomplished by circulating water through the jackets of the engine block and cylinder head and temperature of 70 °C was maintained. During the experimentation, compression ratio, injection timing and injection pressure are 17.5, 27°bTDC, 230 bar (DiSOME) respectively. For diesel-based operation, the injection pressure was 205 bar. The nozzle is with 3 hole and each orifice having diameter of 0.3 mm. Eddy current dynamometer is used for engine loading and water is circulated within the engine body and dynamometer. The governor is used for regulating the speed of an engine. Air and fuel flow indicators measure the air and fuel expenditure, and a piezo-electric sensor is installed in the head of the cylinder to monitor the CP at every crank angle. Fig. 3demonstrates PG quality measurement and venturi meter with digital gauge. Pilot fuel flow rate is measured using burette and stop watch method. To measure the flow rate of producer gas, a suitable venturimeter along with digital flow meter is provided in the producer gas flow line. After that, an exhaust gas analyzer (A DELTA 1600 S) identifies the HC, CO, CO_2, O_2level and Hartridge smoke meter to identify the smoke density of exhaust gas. Instruments calibration is done before the start of experimentation. Then, readings are documented five times after when engine attains steady-state and averaged out data are employed for analysis, which in turn lowers the error.

Preparation of Biodiesel on Magnetic hot plate and round bottom flask

Finished dairy scum biodiesel

Bath ultrasonicator

Probe ultrasonicator

Fig. 1. Experimental set up for transesterification and Ultrasonicator.

Table 1
Properties of DiSOME and blends [35].

Properties	Diesel	DiSOME	DiSOME + MWCNT20	DiSOME + MWCNT40	DiSOME + MWCNT60	Standard
Calorific value (MJ/kg)	43.5	35.82	37.14	37.64	38.20	ASTM D240
Kinematic viscosity (cSt) at 40 °C	3.4	5.3	5.32	5.65	5.81	ASTM D445
Fire point, °C	67	138	129	127	125	ASTM D93
Flash point, °C	55	134	118	115	104	ASTM D93
Density (kg/m^3) at 15 °C	840	890	894	896	898	ASTM D1298

Table 2
Properties of MWCNT and biomass [53].

No.	Parameters	MWCNTs Nanoparticles	Properties	Babul wood
1	Bulk/true density, g/cc	0.05–0.17	Moisture Content, % wlw	11.4
2	Average particle size, nm	20–30	Ash Content, % wlw	0.78
3	Surface area, m^2/g	350	Volatile Matter, % wlw	84.1
4	Purity, %	95	Fixed Carbon % wlw	14.5
5	Thermal conductivity, W/mK	3180	Sulphur, % wlw	0.09
6	–	–	Nitrogen, as N % wlw	0.37
7	–	–	Gross Calorific value, kJ/kg	17678.8
8	–	–	Density, kg/m^3	262

A downdraft gasifier was used to produce low calorific gas, providing reduced tar. Gas supply may change with the design of engine and operating circumstances. The suction pipe for mixing air and PG included a suitable mixing chamber. Fig. 4 illustrates the carburetor and piezo-electric transducer located on the head of engine cylinder. A venturimeter is employed at downstream and gas speed up with air flow as it is combined in the mixing chamber to gauge gas flow rate. During the experimentation, PG supply was unregulated, and the air was controlled manually to achieve maximum substitution of producer gas and better pilot fuel displacement. In this current study, pilot fuel is regulated optimally for each load to start the combustion properly and maximum gas supply was ensured in the inlet manifold. The engine was started with pilot fuel and when engine was achieved a steady state, PG was inducted through inlet manifold and performance and engine out gas compositions are recorded. A similar procedure was adopted for nano-fluids and PG combinations. During the complete trial tests, adequate preparations are made to achieve reliable and repeatable data.

2.4. Test procedure

The engine was made to run on diesel/DiSOME-PG at 27°bTDC injection timing and 230 bar injection pressure. During experimentation, Supply of producer gas is guaranteed when the producer gas is taking part in the combustion. at which pilot fuel consumption is lowered and is ensured by watching flow rate of pilot fuel. During the test run, initially the engine was made to run on pilot fuel (nanofluid) alone and producer gas is allowed through inlet manifold during suction stroke when engine attains steady state. Loading can be done after recording various data acquisition system. For loading conditions, data are recorded when engine attains steady state. The cylinder pressure-crank angle history is achieved for 100 cycles for diesel -producer gas and DiSOME (nanofluid)-producer gas combination at 80% load. For each set of test three times data were recorded and mean readings were used for analysis. Finally, the results obtained for the DiSOME producer gas operation with and without nano-particles addition were compared with that of the diesel based dual fuel operation.

2.5. Uncertainty analysis

Uncertainty of the investigational numbers is analyzed using methodical equations. The ambiguity analysis covers repeated measurement mean and evaluates the true value. The three readings average of an exacting parameter was viewed for the study of error. The error bars are symbolized for all attributes to designate the recorded measurements uncertainty.

The measured variable uncertainty (ΔX_i) is computed with Gaussian distribution (refer Equation (3)) having a limit of confidence of $\pm 2\sigma$. 95% of the calculated values depend on this 2σ which is the mean limit.

$$\Delta X_i = \frac{2\sigma_i}{\overline{X_i}} * 100 \tag{1}$$

In the above equation, X_i is the No. of evaluations, $\overline{X_i}$ implies to the investigational readings and σ_i signifies the std. deviation. The uncertainties of assessed factors were computed employing the given Eq. (2) expression as:

$$R = f(X_1, X_2, X_3 \quad X_n) \tag{2}$$

$$\Delta R = \sqrt{\left[\left(\frac{\partial R}{\partial X_1}\Delta X_1\right)^2 + \left(\frac{\partial R}{\partial X_2}\Delta X_2\right)^2 + \left(\frac{\partial R}{\partial X_3}\Delta X_3\right)^2 + \dots\dots\dots\dots\dots\dots \left(\frac{\partial R}{\partial X_n}\Delta X_n\right)^2\right]} \tag{3}$$

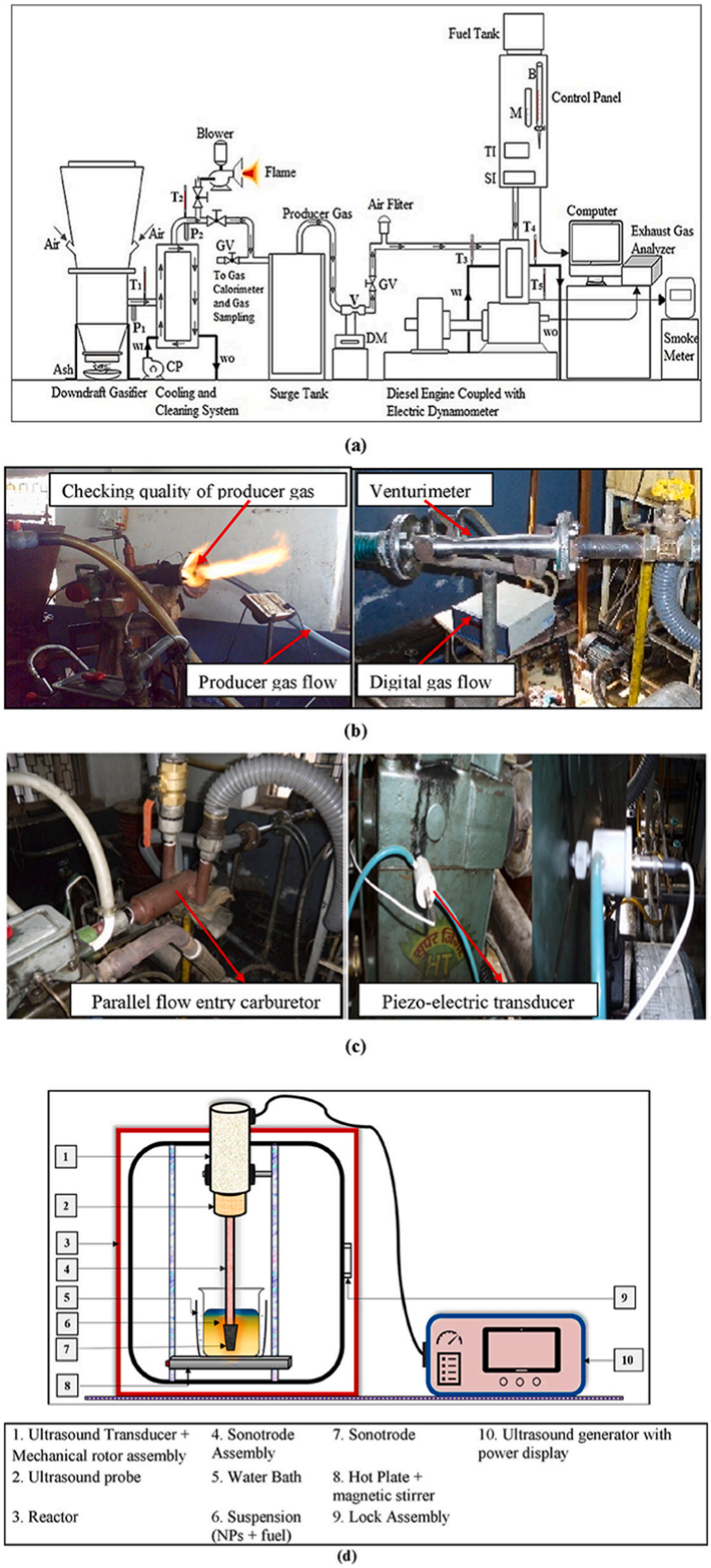

Fig. 2. **(a)** Schematic diagram of gasifier-engine system [54], **(b)** Digital flow indicator of venturimeter and quality checking of producer gas flaring [16], **(c)** Parellel flow gas entry carburetor and Piezo-electric transducer on a cylinder head [46],**(d)** Schematic diagram of probe sonicator used for ultrasonication process of nanofluids [55].

Table 3
Specifications of the diesel engine and Gasifier [54].

Sl No	Parameters	Specification	Type	Downdraft gasifier
1	Machine Supplier	Apex Innovations Pvt Ltd, India.	Rated capacity	15000 kcal/h
2	Engine Type	1 cylinder 4 stroke, water cooled, TV1 CI engine with a 662 cc of displacement volume, 17:1 compression ratio, developing 5.2 kW at 1500 rev/min	Rated gas flow	15Nm^3/hr
3	Software used	Engine Soft	Calorific value of gas	1000 kcal/m^3
4	Pressure of nozzle opening	200 bar–225 bar	Rated woody biomass consumption	5–6 kg/h
5	Governor	Mechanical centrifugal type	Hopper storage capacity	40 kg
6	Diameter of cylinder and Stroke length	0.0875 mtr and 0.11 m	Biomass size	10 mm (Minimum) 50 mm (Maximum)
7	Combustion camber	Direct Injection (open Chamber) with hemispherical cavity	Moisture content (Db)	5–20%
8	Eddy current dynamometer:	Model:AG – 10, 7.5 KW at 1500 to 3000 RPM	Typical conversion efficiency	70–75%

Where R in **Eq. (3)** indicates the function of $X_1, X_2 \ldots \ldots \ldots X_n$ and $X_1, X_2, \ldots \ldots X_n$ signifies the number of attained readings. Hence, ΔR is calculated by RMS (root mean square) of errors related to measured parameters. The current experiment's overall uncertainty was calculated to be 1.87%, which is less than 5%. The satisfactory range for the uncertainty has been determined to be lower than the above-mentioned number. As a result, the overall uncertainty found in the current investigation was well below acceptable bounds. The uncertainty in various individual and measured values are analyzed. The same is presented using Equations (4) and (5) in Table 4.

$$Uncertainty = \sqrt{Uncertainty(\%)\ of\ (sq.BTE + sq.BSFC + sq.CO + sq.HC + sq.smoke + sq.NO_X + sq.HRR)} \tag{4}$$

The output with standard uncertainty is calculated due to input parameters applying Taylor's series expansion of first order as follows:

Fuel type (f), load (l), and NPs concentration are the independent variables from which BTE (b) is obtained. In light of the input parameters' independence, the output parameter (b) having U_Σ (b) as standard uncertainty is computed as a square root (positive) of $U_\Sigma{}^2$(b) which is total variance as follows:

$$U_\Sigma(b) = \sqrt{U_\Sigma^2(b)} = \sqrt{\left(\frac{\partial b(l,f,n)}{\partial l}\right)^2 U^2(l) + \left(\frac{\partial b(l,f,n)}{\partial l}\right)^2 U^2(l) + \left(\frac{\partial b(l,f,n)}{\partial n}\right)^2 U^2(n)} \tag{5}$$

In this situation, the sensitivity coefficients of input parameter (l, f, n) are the partial derivative of outcome (b). In the most basic scenario, sensitivity coefficients show how variations in input constraint calculations X_i affect the output factor evaluation Y. If the value of the input parameter xi is changed significantly, Δxi if the value is altered, the evaluation will be changed as well. (Δy)i= (∂f/∂xi)(Δxi) value. Suppose X_i refers to the uncertainty (standard) associated with variations in the independent factor assessment, then Y links to Ui(y)= (∂f/∂xi)u(xi). The overall uncertainty was observed to be ±2.4% within the ±5% range.

2.6. Characterization of MWCNT

In this section, various characterization tests were carried out to understand the elemental composition, morphology, and synthesized MWCNTs nanoparticle energy content. Table 5 illustrates the properties and specifications of MWCNTs nanoparticles.

The structural characterization (SEM, morphology) of MWCNT nano powder was carried out using Jeol JSM/JSMIT500LA XL 30 ESEM (having inbuilt EDAX) and2nm LaB6 filament, 10x to 4x10^{5}x of Magnification, 0.2–30 kV of accelerating Voltage. The crystalline nature of MWCNT nano powders were calculated using XRD diffractometer (powder) Philips Xpert MPD 3°–136° of Range (2θ),2θ vs intensity plots/X-ray diffractograms, JCPDF database Cu made X-ray tube. TEM representations illustrated in Fig. 3 (a)and **(b)**show a rod-like structure of multiwalled carbon nanotubes. The EDX analysis shown in Fig. 3(c) illustrates the elemental content of nanoparticles, the dispersive spectrum of energy (EDX) illustrates the uppermost atomic concentration of carbon 91.92%, oxygen 7.9%, and Al, CI, and NI as few impurities within 1%. The XRD analysis is shown in Fig. 3 (d), the values of 2θ and respective hkl values obtained for the peaks are 25.85321 (002), 27.65527, 42.85531 (101), 44.6402, 52.8952 (004), 78.66218 (110), 81.6737, 84.57552 which are in accordance with the [JCPDS 41–1487]. Due to interlayer stacking of carbon sheets the XRD peak in MWCNTs (hkl: 002) occurs. It reveals the concentric cylindrical form of carbon sheets blended collectively confirms the multiwalled nature of carbon nanotubes [57–59].

3. Results and discussions

This section presents the effects of MWCNT nanoparticles on the combustion parameters of a dual-fuel CI engine. DiSOME and PG combinations with and without nanoparticles are used in this investigation. In this case, a quick synopsis of groundwork trial testing is provided in the next section.

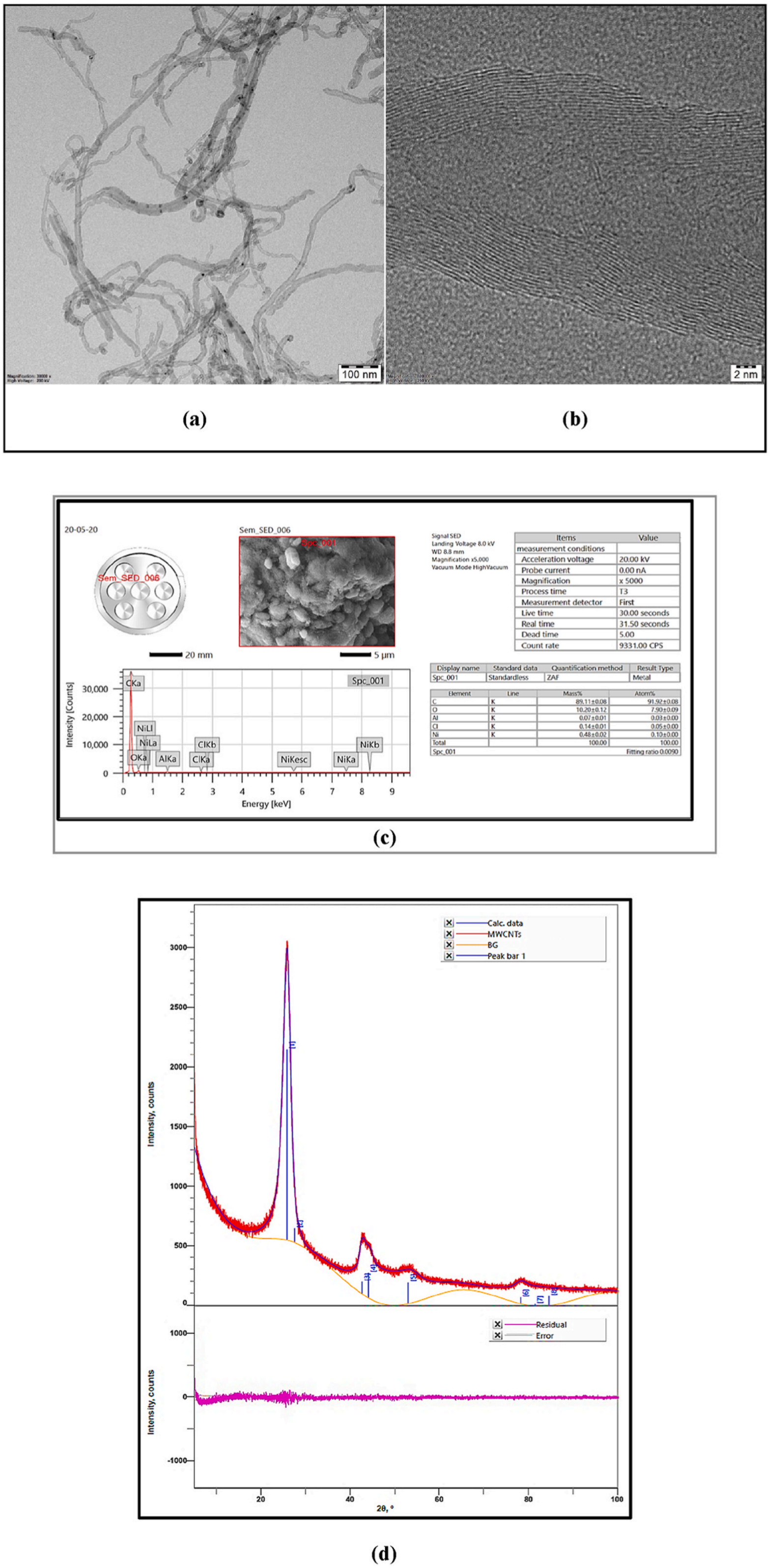

Fig. 3. (a) TEM image **(b)** SAED pattern **(c)** EDX analysis of MWCNTs [56] (L/N:5459410980164)**, (d)** MWCNTs synthesized XRD analysis (L/N:5459410980164) [56].

Table 4
The accuracies of the measurements and uncertainties.

Measured variable	Accuracy
Load (N)	0.1
Engine speed (rpm)	1.98
Pressure transducer (bar)	0.1
Encoder reading, Crank angle (deg., CA)	0.1
Exhaust gas temperature ^{0}C	1.5
Measured variable	**Uncertainty**
Smoke density	± 1.1
Carbon monoxide	± 2.4
Hydrocarbon	± 1.2
Nitric oxide	± 1.0
Calculated parameters	**Uncertainty**
Brake thermal efficiency (%)	± 1.28
Heat release rate (J/deg., CA)	± 0.9

Table 5
Properties and specification of MWCNTs nanoparticles.

Description	Additive
Chemical Name	Multi-walled carbon nanotubes
Linear Formula	MWCNT
Nanoparticle avg. size	20–30 nm
Molecular weight	146.23
Appearance	Black

3.1. Performance and emission characteristics

Fig. 4 (a) demonstrates a variation of BTE for diesel-PG, DiSOME-PG and DiSOME-MWCNTs-PG mixtures. Owing to its higher viscosity and lower volatility, as well as the united effect of low calorific value of both biodiesel and PG, the DiSOME-PG operation performed poorly. Different proportions of MWCNT nanoparticles (20–40 ppm) in a DiSOME biodiesel, on the other hand, offer an amplified thermal efficiency with an average amplification of 2–9% compared to DiSOME-PG operation for the same producer gas induction. It could be due to MWCNTs' superior burning properties and the employment of nanoparticles as catalysts during the burning of DiSOME-PG mixtures, increasing the oxidation rate and improving volumetric efficiency [60]. Generally, nano-size particles have elevated surface area and reactive surfaces that provide amplified chemical reactivity to act as a possible catalyst [61]. However, concentration of limited nanoparticles in a biodiesel does not affect the viscosity. Hence, nanoparticle blended fuel resulted in better performance along with gaseous fuel [62,63].

Mixing the correct quantity of nanoparticles in biodiesel offers lowered ignition delay (ID) and accelerates the fuel conversion process, leading to enhanced combustion of blended fuel and PG. For the same PG induction, the DiSOME + MWCNT60 combination gives out poorer thermal efficiency because of the increased viscosity of blended fuel and the reduced atomization of fuel droplets with nanoparticles, catalytic activity may be slowed. At 80% load, the thermal brake efficiency of DISOME + MWCNT20-PG and DISOME + MWCNT40-PG is increased by 3.1% and 4.2%, respectively, compared to DISOME + MWCNT60-PG.

3.2. Emission characteristics

The smoke opacity for diversified fuel combinations with and without nanoparticles is illustrated in Fig. 4 (b). The DiSOME-based dual fuel operation produced more smoke opacity than diesel operation when using the same PG supply. This could be due to the pilot's high viscosity biodiesel fuel's low mixing rate, which was induced by the air and PG combination. In addition, the combustion was dominated by the oxidation rate and fuel properties. However, using NPs from the pilot fuel accelerates the rate of oxidation, resulting in more efficient fuel mixture burning. When nanoparticles are added to biodiesel, the air-fuel mixing rates, and oxidation rate improve, resulting in better combustion. Also, the evaporation rate of fuel becomes faster due to improved spray characteristics caused by the increased volatility of biodiesel. MWCNT nanoparticles have a lower burning temperature, which assists speedy oxidation, resulting in better fuel burn [29]. In addition, addition of nanoparticle in a biodiesel improves the thermo-physical and chemical properties of fuel, such as, high surface to volume ratio, higher responsive mode for ignition. Hence, lower smoke levels were observed with biodiesel blended fuel and gaseous fuel combination [62,63]. PG being same, investigation demonstrated that DiSOME + MWCNT20 and DiSOME + MWCNT40 blended fuel-based dual-fuel combustion showed lower smoke opacity by 10.2% and 18.1% than DiSOME + MWCNT60 based operation. This may be due to partial combustion due to inhomogeneous mixture formation. Increased dosage of nanoparticles in the fuel is limited; hence it results in reduced smoke levels. Therefore, the smoke levels obtained were proportional to the nanoparticle concentration.

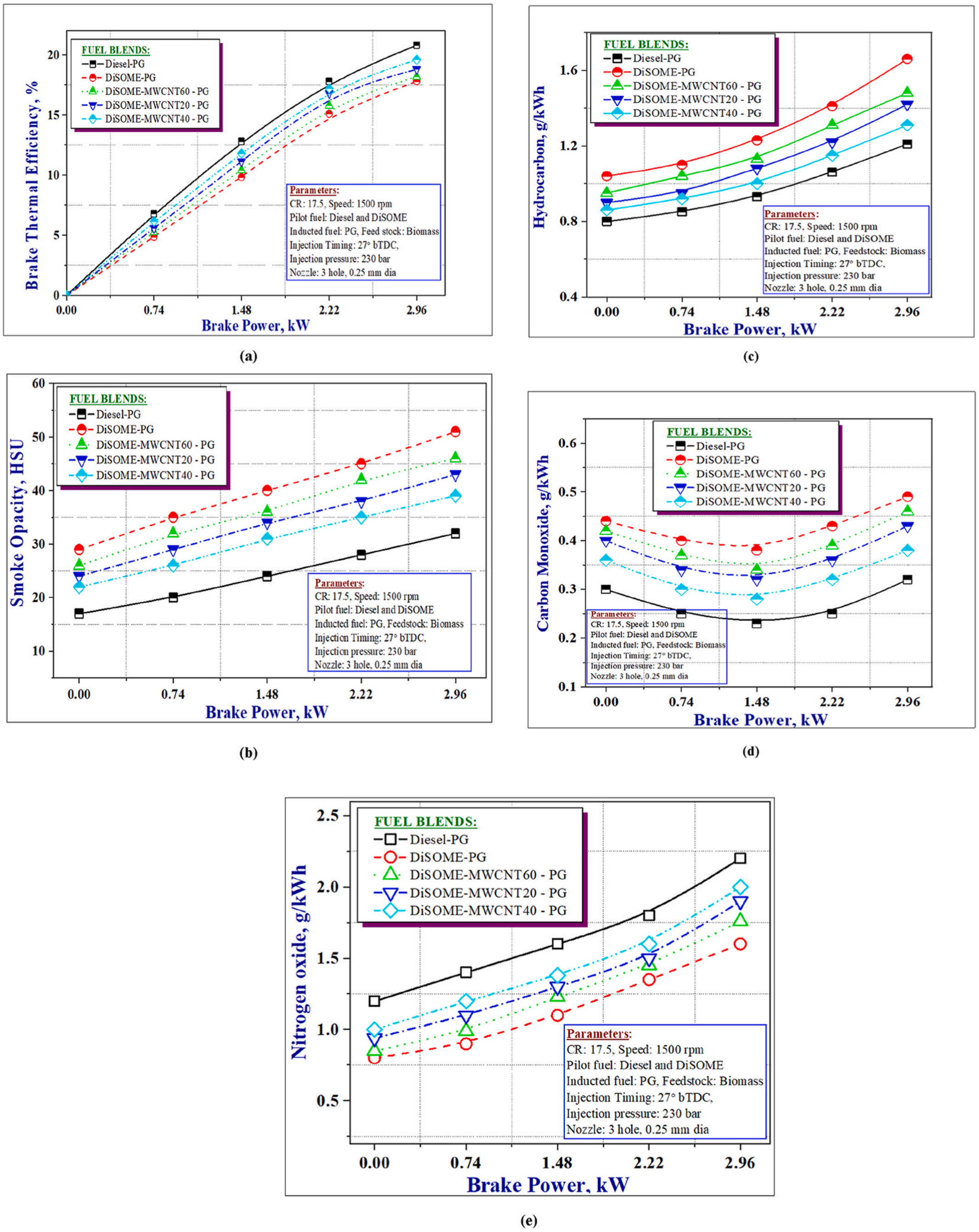

Fig. 4. **(a)**MWCNT nanoparticle influence on BTE, **(b)** MWCNT nanoparticle influence on the smoke opacity, **(c)** Influence of MWCNT nanoparticles on HC emission, **(d)** MWCNT nanoparticle influence on the CO emission, **(e)**MWCNT nanoparticle influence on the NOx emission.

Fig. 4 (c) and (d) show the levels of HC and CO in the exhaust gas for different fuel mixtures with and without nanoparticles. Producer gas induction is the same, but DiSOME-based dual fuel operation exhibited 32.6% and 29.8% higher HC and CO levels at an 80% load than diesel operation without MWCNT. This could be due to partial burning of the fuel mixture due to deprived oxygen availability and reduced mixing of the air-PG combination with the high viscosity biodiesel. DiSOME-PG combustion was deteriorated because of air replacement by PG, leading to a lower oxidation rate than diesel operation. However, pilot fuel having NPs boosts the oxygen supply rate, allowing the biofuel combination to burn more efficiently. Also nano-particles presence can make the fuel better combustioble due to improved thermo-chemical properties of biodiesel. In relative to DiSOME-PG process without MWCNT at 80% load, investigations with MWCNT60, MWCNT40, and MWCNT20 indicated 21.6%, 11.4%, and 5.8% lower HC levels with MWCNT60, MWCNT40, and MWCNT20. At an 80% load, CO levels were lowered by 20.6%, 14.8%, and 8.2%, respectively, compared to DiSOME-based dual fuel operation without MWCNT. Nanoparticle addition in biofuel advances the oxygen availability rate triggered by a better rate of evaporation [64,65]. It amplifies ignition characteristics, i.e., carbon nanoparticles in DiSOME resulted in secondary atomization, which lowers the HC and CO emissions and catalyzes the fuel oxidation resulting in carbon dioxide and water [29].

Nitric oxide emission levels from DiSOME-PG fueled engines with and without MWCNT have been presented in Fig. 4 (e). NOx emission levels are dependent on combustion behavior. Complete combustion of the fuel mixture results in a higher combustion temperature due to better oxygen consumption, which results in higher NOx levels. In addition, this is greater when combustion of fuel combination is with a lean mixture [45]. High NOx level magnitude in the exhaust represents lower HC and CO emissions.

When comparing DiSOME-based dual fuel operation to fossil fuel-based dual fuel operation at an 80% load, experimental results showed that DiSOME-based dual fuel operating reduced NOx levels by 12.8%. This may be due to diminished premixed combustion rather than diffusion combustion phase and is caused by the poorer properties of DiSOME and PG. DF operation with diesel provided amplified NOx levels and it may be because of enhanced burning of diesel. However, lesser NOx levels are further noticed with DiSOME-PG combination when MWCNT nanoparticles were added in the base DiSOME fuel. DiSOME and Producer gas combination being same, results of the investigation showed that MWCNT60, MWCNT40 and MWCNT20 based operation showed 21.8%, 12.5% and 6.3% decreased NOx levels in comparison with DiSOME operated dual-fuel combustion without MWCNT at 80% load. This may be because nanoparticles addition lowers the ignition delay and enhances the fuel-burning caused by the improved combustion reaction and homogenization of air-producer gas mixture with pilot biodiesel. The presence of nanoparticles in the pilot fuel can act as an NO decomposer, enhancing oxygen stability and absorbing oxygen. Also, nanoparticles may hinder the time required for the NOx production [26,29].

3.3. Combustion characteristics

The use of nanoparticle blended fuel showed significant variations pertinent to characters of combustion. Various factors for PG-nano-blended biofuel operation are concisely presented as below.

The effect of MWCNT on the ignition delay (ID) for dual fuel operation is depicted in Fig. 5 (a). The ID is calculated using a cylinder pressure vs. crank angle graph. ID was determined to be lower for diesel-PG operation than DiSOME-PG operation with and without nano-article under the same working conditions. Producer gas being same, inferior quality of biodiesel used significantly increases the ignition delay. However, the addition of MWCNT nanoparticles in the pilot DiSOME showed significant dissimilarities in the ignition delay. It may be due to the rapid burning of nanoparticles and enhanced premixed combustion, leading to an increase in-cylinder gas temperature. Variations in the fuel properties due to nanoparticles provide extra oxygen for combustion, catalytic effect in the fuel during the combustion and improved mixing rates caused by enhanced fuel evaporation [5]. Results of the investigation demonstrated that, for the identical induction, the addition of 60 ppm nanoparticles in the pilot DiSOME fuel resulted in higher reduction in the delay period due to amplified evaporation caused by the improved ignition characteristics compared to the same dual fuel operation with 20

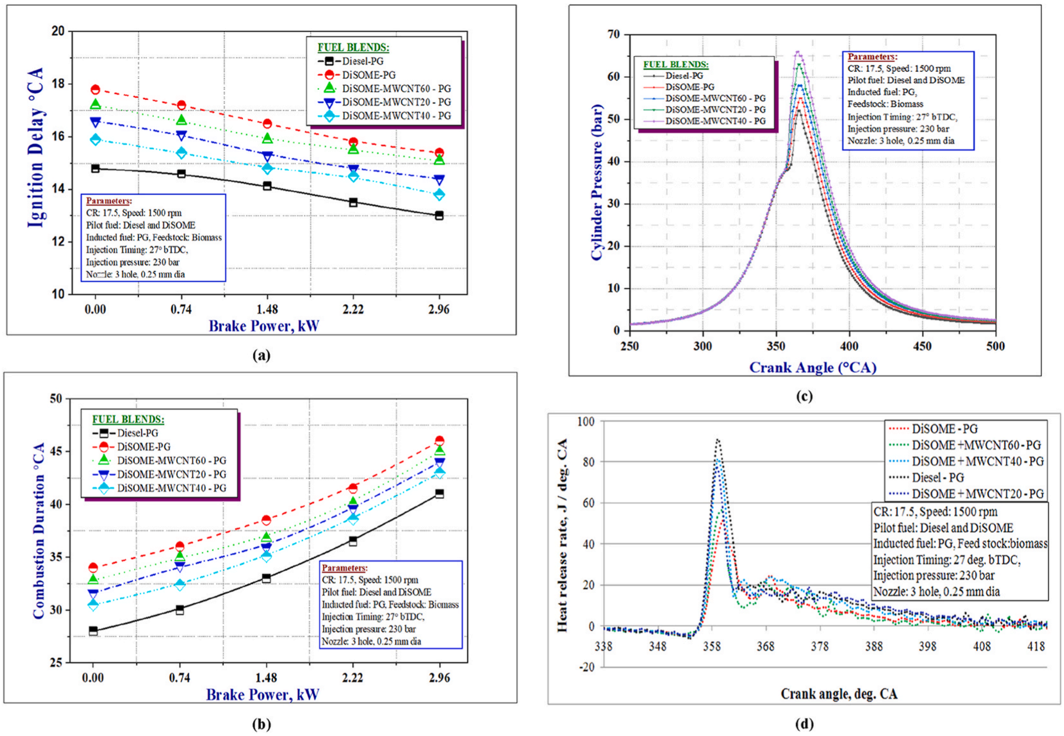

Fig. 5. **(a)** MWCNT nanoparticle s Influence on the ignition delay, **(b)**Effect of MWCNT nanoparticles on duration of combustion, **(c)** Cylinder pressure vs. crank angle (CA) for various fuel combinations at 80% load, **(d)**Diagram of heat release rates for various fuel mixtures at 80% load.

and 40 ppm nanoparticles. Results illustrated that, for the same PG induction, the addition of 60 ppm nanoparticles in the pilot DiSOME fuel presented reduced ID due to amplified evaporation compared to the same dual fuel operation with 20 and 40 ppm nanoparticles. It is seen that nanoparticles in the blended fuel have greater surface area-volume ratio characteristics; therefore, physical mixing and chemical reactivity are increased, leading to shorterignition delay [35].

Fig. 5 (b) shows the relationship between combustion duration (CD) and brake power for various fuel companions. DiSOME-PG operation with and without MWCNT nanoparticlespresented amplified CD by 4.12–10.8% compared to diesel-producer gas combinations owing to its elevated viscosity and poorer volatility and increased ID caused by biodiesel and producer gas. However, for the same producer gas induction, MWCNT nanoparticles (20–60 ppm) in diverse proportions in a biodiesel presented lower CD by an average of 2.4–6.5% compared to DiSOME-PG operation. The prime reason possibly due to the faster combustion of DiSOME instigated by the improved evaporation of nanoparticles of MWCNTs and nanoparticle s act as catalyst during combustion of DiSOME-PG combinations, this in turn enhances the oxidation rate and this may lead to improved combustion. MWCNTs can oxidize successfully. Higher chemical reactivity and higher surface area contribute to act as a potential catalyst [60]. Blending of accurate quantity of MWCNT in DiSOME resulted in the lowered CD and speed up fuel conversion process leading to fastest combustion of blended fuel in conjunction with PG. For the identical supply induction, DiSOME + MWCNT60 amalgamation resulted in marginally amplified CD because, the retarded volatility of nanoparticles caused by the augmented viscosity of blended fuel and reduced atomization with nanoparticles. Due to this effect, the CD for DISOME + MWCNT20-PG and DISOME + MWCNT40-PG is reduced by 4.1% and 4.9% compared to that of DISOME + MWCNT60-PG, respectively at 80% load.

Fig. 5 (c) represents the influence of MWCNT nanoparticles on the cylinder pressure of DiSOME-PG operation at a load of 80%. For the identical PG supply, results presented that the addition of nanoparticles in DiSOME provided diminished ID due to increased catalytic activity leading to earlier combustion start. Due to the ubiquitous use of DiSOME and producing gas, the nanoparticle characteristics added to biodiesel caused changes in combustion behavior. Therefore, MWCNT nanoparticles have more significant catalytic activity and thermal conductivity resulting in amplified peak pressure. In addition, amplified evaporation rates, lower ID, high flame temperature, and sustenance are also responsible [29,66]. In addition, higher surface area-to-volume ratio of nano-particle addition enhances the fuel-air mixing in the combustion chamber and this in turn leads to better and complete combustion. According to the findings, the nanoparticles had a larger surface area to the volume ratio than biodiesel for the same PG Supply. As a result, DiSOME-MWCNT with 20 and 40 ppm nanoparticles resulted in an advanced heat transfer rate. Using nanoparticles in biodiesel enhances combustion characteristics, increasing the cylinder pressure and lowering the combustion duration.

Fig. 5 (d) illustrates HRR variation with crank angle at a load of 80% for various DiSOME-PG combinations having no NPs and having NPs. When related with diesel-based DF operation, the HRR for DiSOME-nanoparticle blended fuels with PG was launched to be lower. During the diffusion combustion stage, all DiSOME-PG combinations had a lower HRR during the phase of premixed combustion and a higher HRR.

Further this in turn enhances the temperature of exhaust gas, with DiSOME-PG operation and MWCNTs, enhanced premixed combustion was noticed compared to DiSOME-producer gas operation without MWCNT. The presence of MWCNT nanoparticles in the pilot injected biodiesel enhances the fuel evaporation and density of the air-fuel charge. This could minimize the ID and CD, resulting in amplified cylinder pressure and high HRR. The observed trend is due to increased cetane number, higher surface to volume ratio, and enhanced supply of oxygen to the fuel mixture, catalytic activity, and thermal conductivity with nanoparticle addition [6]. The combustion chemistry and heat transmission within the cylinder would be different if nanoparticles were included, as evidenced by the enlarged peak pressure [67–69].

4. Conclusions

Dual-fuel combustion with DiSOME and nanoparticle s provided better performance than neat DiSOME-PG operation. The investigation revealed that MWCNT40 provided excellent performance with diminished emission levels and smooth engine operation. This research focuses on an innovative line for extracting energy from high viscosity fuels in a DF engine. The following are some of the investigation's most noteworthy findings.

➢ DiSOME-MWCNT40 with producer gas induction enhanced thermal efficiency by 9.1% with decreased emissions compared to the identical fuel combination without nanoparticles. However, further increase in nanoparticles in a DiSOME does not provide positive results.
➢ Dual fuel engine operated at 80% load on DiSOME-MWCNT40 with PG induction provided 5.7% decreased BTE, 17.9% increased smoke opacity, 14.1% increased HC, 12.4% increased CO and 8.6% reduced NOx emission levels when related with a diesel-PG combination.
➢ DiSOME-PG and DISOME-PG combustion with 20 and 60 ppm of MWCNT nanoparticles provided decreased BTE by 4.08% and 7.1%, increased smoke opacity by 15.2% and 9.5%, increased HC emissions by 7.8% and 12.5%, increased CO pollutants by 11.6% and 17.8%, amplified NOx pollutants by 12.1% and 5.6% in comparison with DISOME + MWCNT40-PG correspondingly at 80% applied load.
➢ Diesel-PG combustion showed increased cylinder pressure and HRR as compared to DiSOME-PG with and without nanoparticles addition.
➢ Dual fuel operation provided 56%–66% pilot fuel savings. The maximum diesel replacement obtained was a maximum of 66% at 80% load.

According to the findings, DiSOME and PG containing nanoparticles could be employed as substitute fuel in diesel engines. The existing diesel engine does not need to be modified in any way to run in dual fuel mode. DiSOME combustion with the best parameters leads to in improved engine performance and lower emissions.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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