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Experimental analysis on neat mustard oil methyl ester subjected to ultrasonication and microwave irradiation in four stroke single cylinder Diesel engine †

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Abstract

Transesterification of fatty acid using the application of ultrasound stirring and microwave irradiation has been used of late for biodiesel production from various vegetable oil and animal fats. However analysis on influence of these techniques on performance, combustion and emission aspects has received little attention. In this work, transesterification of mustard oil with methanol was performed using ultra sound stirring (42 kHz /170 W, 80 W) and microwave irradiation (230v AC, 50 Hz, 900 W). Reaction time, conversion rate, fuel properties, performance, emission and combustion characteristics were compared with conventional transesetrification. Results indicated that Mustard oil methyl ester subjected to ultrasonication and microwave irradiation (MOMESUM) has 5.71% more yield than conventional transesterification process. It was also observed that BTE for MOMESUM is improved by 5.84% with 5.14% reduction in BSFC when compared to MOME. CO, HC, NOx and Smoke emission was found to decrease by 11.39%, 3.81%, 7.99% and 5.3% respectively for MOMESUM.

Keywords: Microwave irradiation; Mustard oil; Transesterification; Ultrasonication

1. Introduction

Declining Reserves, alarming pollution, restricted availability and ever escalating cost is yet to deter the wage of diesel, thanks to its reliable characteristics. An alternative fuel technology must be developed to full fill the requirement. Vegetable oil and animal fats is found to be a promising and adaptable alternative fuel with properties similar to Diesel. Many countries have started using vegetable oil as an alternative fuel due to its manifold advantages [1-3]. Vegetable oil can be used in modern diesel engines with minor or no modifications. The main drawback of vegetable oil and animal fats are high viscosity, density, volatility, lower energy content, and higher NOx emission, among which higher viscosity and density is found to be a major concern [4]. There are numerous techniques employed to reduce the viscosity and density of vegetable oil and animal fats like blending of raw oils with diesel, thermal cracking, micro emulsions and transesterfication.

Among these techniques, transesterification is the advanced and commonly used technique to convert vegetable oils and animal fats into fatty acid methyl ester and glycerol in the presence of alcohol and catalyst. Methanol and ethanol are commonly used alcohols. Catalysts are used to increase the rate of reaction. Sodium hydroxide and potassium hydroxide are generally used as catalyst. Transesterification process involves three consecutive reversible reactions. In first step, triglyceride molecules react with alcohol to form diglyceride; in the second step, diglycerides are converted into monoglycerides. Finally monoglycerides are converted to glycerol [5]. Transesterification process is carried out by conventional heating requiring a long reaction time ranging from 30 minutes to 8 hours for a reasonable conversion [6]. The recent research indicates that the application of ultrasonic mixing and microwave irradiation in transesterification process is proficient and effective type of transesterification [7, 8]. Ultrasonic mixing is a valuable alternative means to achieve a better mixing in commercial biodiesel processing. Ultrasonic cavitations provide the necessary activation energy for the ester formation. In conventional mixing the reaction is of slow kinetics and hence poor mass transfer takes place. Ultrasound mixing causes cavitations of bubbles near the boundary of oil and alcohol which in turn increases the interaction between the phases. Ultrasound leads to impinge of one liquid to another producing disrupt phase boundary ensuing breaking of cells into smaller cluster resulting in efficient and quicker transesterification [9, 10]. Microwave irradiation is a proven method of accelerating and enhancing chemical reactions as it delivers

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the energy directly to reactant. Hence heat transfer is more effective than in conventional heating and the reaction can be completed in much shorter time [11]. Microwave irradiation is one of the best methods for reducing the reaction time and obtaining higher yields in biodiesel production with improved properties. By adapting ultrasound stirring and microwave irradiation techniques, purity of FAME is enhanced due to improved activation of chemical reaction by cavitations. Ultrasound stirring and microwave irradiation induces effective emulsification and high mass transfer resulting higher rate of ester formation [8-11]. Literature had been observed detailing the advantages of ultrasound stirring and microwave irradiation of neat vegetable oils. However, the impact of ultrasonic stirred and microwave irradiated fatty acid methyl ester with respect to fatty acid methyl ester resulting from conventional transesterification on performance, combustion and emission aspects has never been experimented, Hence this present work is aimed to investigate the impact of ultrasonication and microwave irradiation on performance, combustion and emission analysis of mustard methyl ester and compared with conventionally prepared MOME. Transesterification of mustard oil with methanol was performed using ultra sound stirring (42 kHz /170 W, 80 W) and microwave irradiation (230v AC, 50 Hz, 900 W). Reaction time, conversion rate, fuel properties, performance, emission and combustion characteristics were compared with conventional transesetrification. Results found that mustard oil Methyl ester subjected to ultrasonication and microwave irradiation (MOMESUM) has 5.71% more yield than conventional transesterification process. It was also observed that BTE for MOMESUM is improved by 5.84% with 5.14% reduction in BSFC when compared to MOME. CO, HC, NOx and Smoke emission was found to decrease by 11.39%, 3.81%, 7.99% and 5.3% respectively for MOMESUM.

2. Experimental material & methods

2.1 Materials and reagents

Mustard oil is obtained from seeds of the mustard plant. The oil is extracted from clean and sound mustard seeds, which belong to species of compestris and varieties of brassica. Large quantity of mustard oil is used for edible purpose in many states of India namely Jammu& Kashmir, Himachal Pradesh, Punjab, Haryana, Uttar Pradesh, Rajasthan, Madhya Pradesh, Bihar, Jharkhand, West Bengal and north eastern states. India ranks first in the world in respect of acreage of mustard, accounting for 31.8% of the world total and second in terms of production. The process of manufacturing mustard oil is well established and conventional. Mustard seeds are dried to remove the moisture content and are fed to oil extractor which extracts oil by crushing wherein about 90% of the oil is extracted. Further processing in expeller results in additional extraction of oil. Liquid and solid portion is then separated in filters. The solid portion known as oil cake is used as cattle feed. The oil contents depend upon quality of seeds with an average recovery of oil in the range of 30%~34% [2]. The mustard oil has been chose for the study owing to its least patronage as an alternative fuel and limited references citied in literature. The present investigation utilized refined mustard oil comprising water and Free fatty acid (FFA) of 0.12% and 0.04%, respectively. The alcohol and catalyst used in this work is methanol (99.75% pure) and KOH (98.3% pure).

Table 1. Specification of ultrasonicator.

Working frequency	42 kHz
Electrical input	170 W
Heating capacity	80 W
Tank dimensions	250×140×100 mm
Timing control	Digital (5 step)

Table 2. Specifications of microwave irradiation setup.

Electrical input	230V, AC
Microwave frequency	2450 mHz
Capacity	510×305×520 mm

2.2 Apparatus& procedure

2.2.1 Apparatus

Details of ultrasonicator and microwave apparatus used in the experimental work is mentioned in Tables 1 and 2.

2.2.2 Transesterification - conventional procedure

Ester preparation is done following batch transesterification process in a 600 ml glass vessel reactor equipped with a magnetic stirrer, resistance heater & 'K' type thermocouple. Suitable arrangements were provided to control reaction temperature and stirring speed. Molar ratio of 5:1 (methanol to mustard oil) and catalysts of 0.3% (wt/wt) to mustard oil was used in transesterification process adapting standard procedure as cited in Refs. [1-8]. 500 g sample of mustard oil in the reactor was heated till 60°C. Measured quantity of solution containing catalysts dissolved in methanol was then added and mixed at a constant stirring speed of 340 rpm for 45 minutes. This ensured uniform reactivity of solution and accelerated the reaction rate. The mixture was then allowed to cool in the vessel yielding two distinct layers of ester and glycerol. Ester was then separated and washed thrice with water and dried for further analysis. The ester thus obtained following conventional procedure is henceforth referred as MOME (Mustard oil methyl ester).

2.2.3 Transesterification - ultrasonication and microwave irradiation

A solution containing mustard oil, alcohol and catalyst in the same proportion as in conventional procedure, was subjected to ultrasound stirring at 2°C higher than room temperature for 80 sec at a frequency of 42 kHz. Subsequently the solution was subjected to closed microwave irradiation at

Table 3. Engine specifications.

Make	Kirloskar
Stroke	4
Cylinder	Single
Rated Power	4.4 KW
Rated speed	1500 rpm
Bore diameter (D)	87.5 mm
Stroke (L)	110 mm
Compression ratio	17.5;1
Injection timing	17°bTDC
Injection pressure	200 bar
Fuel pump plunger diameter	8 mm
Number of injector nozzle	4
Diameter of injector nozzle	0.32 mm
Cooling	Air cooled
Position	Vertical
Type	Eddy current dynamometer
Make	Benz systems
Dynamometer constant	2000
Supply voltage	240 ± 10 % AC, 50 Hz, 1ϕ
Maximum excitation current	6 to 8 Amp

333 K, with a microwave frequency of 2450 MHz for 90 seconds. The temperature was controlled by adjusting microwave power. A Fiber optic sensor unaffected by microwave irradiation having an accuracy of ±0.5°C is used to measure the temperature of solution. The mixture is then allowed to cool in the reactor result in formation of two separate layers of ester and glycerol. Similar washing procedure as followed in conventional transesterification process was followed and the ester henceforth referred as MOMESUM (Mustard oil methyl ester subjected to ultrasound stirring and microwave irradiation).

2.3 Engine test set-up & procedure

A four stroke, single cylinder, vertical, air cooled Diesel engine was used for the experimental analysis. The specification of engine is listed in Table 3. An eddy current dynamometer was coupled with engine so as to vary the load on engine and the load applied on the engine is measured using load cell attached with the arm. Layout of engine setup is shown in Fig. 1. Fuel tank is connected to graduated burette to gauge the quantity of fuel consumed per unit time and is measured using burette stop watch arrangements.

An Orifice meter with U-tube manometer (Diameter = 13.4 mm, C_d = 0.6) has provided at suction line of an air tank for measuring air consumption. An AVL444 di gas analyzer was linked to engine exhaust for monitoring the emissions. Pressure inside the cylinder was measured with the help of AVL pressure transducer with sensitivity of 16.04pc/bar, linearity of <± 0.3% and the crank angle is inferred using TDC encoder. Both the pressure transducer and TDC encoder were linked to a computer for monitoring and recording the combustion parameters through AVL 617 indimeter of software version V2.00. K type thermocouple is used to measure the different temperature on the test bed for analysis with a range of 0-1500°C and has a resolution of ±2°C. Engine performance was measured by DC motoring dynamometer and is equipped with a load cell for engine torque measurements. The torque is obtained by the net load at a known radius and is given in Eq. (1).

Table 4. Estimated uncertainty for the measured and calculated quantities.

Quantity	Estimated/calculated uncertainty
Load	± 1 N
Speed	±0.5%
Brake mean effective pressure (Mpa)	±1.0%
Cylinder pressure (bar)	±1.0%
Fuel injection start angle (°CA)	±0.5°CA
Temperature of exhaust gas (°C)	±2°C
TFC (kg/h)	± 2%
BTE (%)	±2.1%
BSFC (kg/Kwh)	±2.1%
Torque (Nm)	±0.5%
Brake power (Kw)	±2%

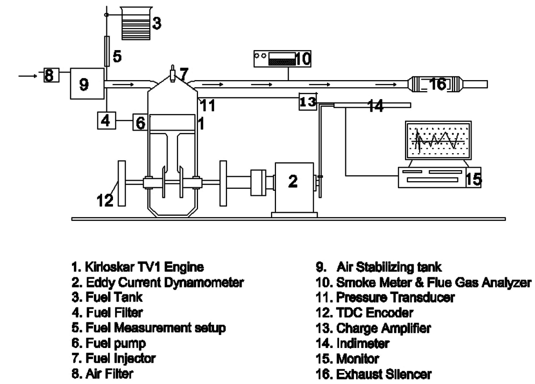

Fig. 1. Layout of engine set up.

$$T(Torque) = WR \quad (1)$$

where W = Net load, R = Radius.

Tables 4 and 5 show the estimated uncertainty for the measured and calculated quantities and accuracy details of gas analyzer and smoke meter. Experiments were initially conducted with Diesel at different loads viz 0% to 100% insteps of 25%. All the parameters required for analyzing the performance, combustion and emissions were recorded so as to fix the base line. Trails were conducted using MOME followed by MOMESUM by following the procedure similar to that of Diesel. The engine speed was maintained at 1500 rpm at all loads and for all test fuels.

Table 5. Accuracy details of gas analyzer and smoke meter.

Model of gas analyzer pollutant	AVL 444 di gas analyzer range	Accuracy
CO	0-10 % VOLUME	0.01%
HC	0-20000	± 10 ppm
NOx	0-5000 ppm	± 10 ppm
Smoke meter	AVL 437 smoke meter 0-100 % opacity	± 1% full scale reading

Table 6. Properties of MOME, MOMESUM and diesel.

Properties	MOME	MOMESUM	Diesel	ASTM
% yield during transesterification	90.8	96.2	-	-
Reaction time in minutes	45.1	2.6	-	-
Layer settling time in hours (Ester and glycerol)	8	7	-	-
Water content in %	0.12	0.09	Nil	D2709
Density @15°C in gm/cc	0.8829	0.8482	0.8200	D4052
Kinematic viscosity @30°C in mm^2/s	4.30	3.96	2.5	D445
Calorific value in kJ/kg	38108	38812	42957	D240
Cetane index (CI)	52	53	47	D976
Flash point in °C	140	136	50	D93
Iodine value (g Iodine/100 g oil sample)	65	64	-	D1510
C (%)	77.2	76		D5291
H (%)	11.4	11		D5291
O (%)	11.4	13		-
% of unsaturated fatty acids	50.88	47.88	-	

3. Results and discussion

The results on the experiments carried out with different fuels which include MOME, MOMESUM and diesel had been recorded. The measurements were analyzed with respect to Performance, combustion and emissions and the results of which are detailed below.

3.1 Comparisons on fuel properties of MOME and MOMESUM

MOME and MOMESUM were tested for their characteristics so as to gauge the influence of ultrasound stirring and microwave irradiation on transesterification. The observation on the characteristics of the fuel samples are listed vide Table 6.

Table 7. Fatty acid compositions.

Fatty acids	MOME (% mass)	MOMESUM (% mass)
Lauric C12:0	Trace	Trace
Myristic C14:0	0.00	0.24
Palmitic C16:0	24.20	26.88
Stearic C18:0	25.80	29.32
Oleic C18:1	37.20	32.30
Linoleic C18:2	12.80	11.22
Linoleic C18:3	0.00	0.04

Yield upon transesterification by subjecting the mustard oil to ultrasound stirring and microwave irradiation is observed to be about 5.71% more than conventional procedure. This may be attributed to the enhanced mixing, effective emulsification and increased interaction of phases owing to the collapse of cavitations and efficient heat transfer caused by both ultrasound stirring and microwave irradiation [7-11]. The transesterification time has been reduced from 45 minutes to 2.5 minutes, a whopping 94.4% reduction in process timing. The reason cited for higher yield is applicable for reduction in process timing as well.

Density and Kinematic viscosity of MOMESUM is observed to be 3.59% and 7.90% lower than MOME respectively. Hence it is understood that ultrasound stirring has played the key role in reduction of density and kinematic viscosity as compared to conventional stirring. Improvement in other desirable properties like calorific value, cetane index, flash point are possible due to enhancement of chemical reaction by microwave irradiation [6-8, 11] and better interaction of phases caused by ultrasound stirring [9, 10]. Table 7 show Fatty acid compositions of MOME and MOMESUM.

3.2 Performance analysis on the effect of ultrasonication and microwave irradiation

3.2.1 Brake thermal efficiency (BTE)

The ratio between the heat equivalents of brake output to the heat supplied to the engine is termed as Brake thermal efficiency. Brake thermal efficiency of MOME, MOMESUM and diesel at varying loads is shown in Fig. 2. It is inferred that BTE for Diesel is higher than MOME and MOMESUM. This could be due to higher calorific value of diesel and negligible moisture content as compared to both MOME and MOMESUM. Higher calorific value leads to lesser requirement of fuel for delivering any given rated power. Hence requirement of MOME and MOMESUM for delivering the same power of diesel would be higher. More the fuel admis-

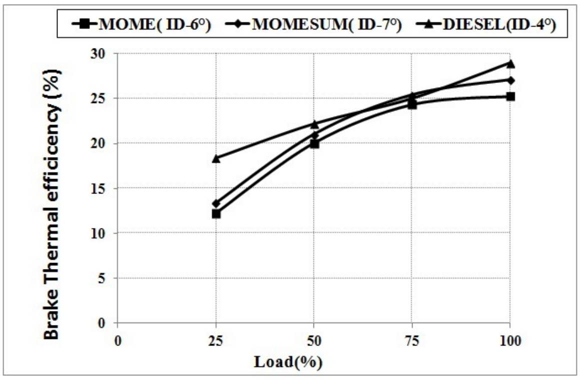

Fig. 2. Variation of brake thermal efficiency with loads.

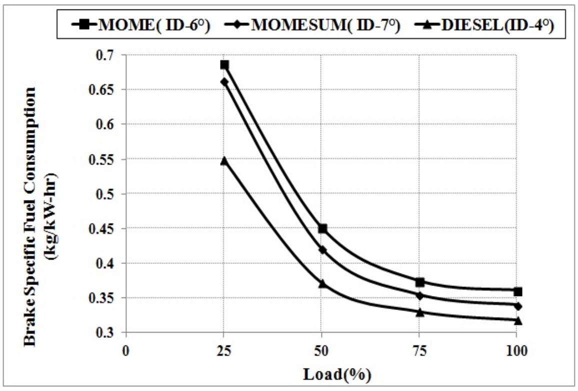

Fig. 3. Variation of brake specific fuel consumption with loads.

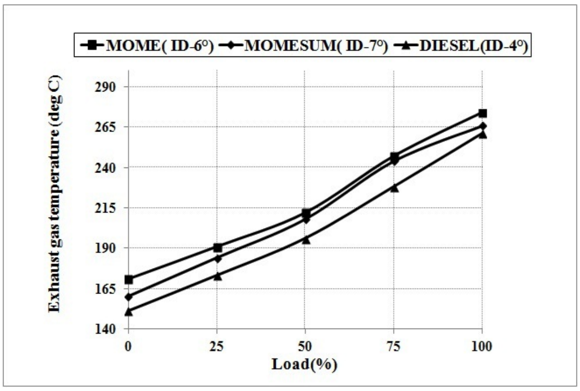

Fig. 4. Variation of Exhaust gas temperature with loads.

sion of MOME and MOMESUM, higher would be heat loss as moisture in these are significantly higher than diesel which is a possible reason for lower BTE.

Moreover, density and viscosity of MOME and MOMESUM is on higher side when compared to diesel. Due to higher viscosity of methyl esters the penetration, breakup distance increases causing increase in droplet size and result in poor mixing of fuel thereby influence combustion. Similar trend was observed in other study [12].

BTE for MOMESUM is higher than MOME at full load and similar at no and low loads. MOMESUM has comparatively lower density and viscosity than MOME due to improved transesterification process which aids better atomization of fuel droplets generating higher dispersion rate. In addition; it may also be due to higher moisture content in MOME which result in poor combustion causing comparatively lower efficiency. The other possible reason could be due to higher oxygen availability of MOMESUM which aids improved combustion and thereby enhancing BTE. It is also observed that at no and low load conditions BTE of all fuels are identical. This may probably be due to better mixing of fuels with air and higher temperature in the combustion chamber leading to better combustion irrespective of fuel viscosity and density. It is also observed that at full load condition the BTE for MOMESUM is 1.81% higher than MOME. This is due to higher fuel consumption as a result of poor physical properties of MOME through conventional transesterification at full load conditions.

3.2.2 Brake specific fuel consumption (BSFC)

Brake specific fuel consumption is parameter which defines the fuel consumption per unit power and time. BSFC of MOME, MOMESUM and diesel at varying loads is shown in Fig. 3. It is observed that BSFC for Diesel is least when compared with MOME and MOMESUM. This could be attributed to lower calorific value of both fuels comparing Diesel which result in additional consumption of fuel to maintain constant power output. Similar observations were also obtained in other studies [13]. It is also observed that average BSFC for MOMESUM is lesser than MOME by 5.14%. This could be due to reduced density and viscosity, higher calorific value and lesser moisture content of MOMESUM as compared to MOME as a result of improved esterification. The other possible reason for lower BSFC for MOMESUM is due to higher BTE.

3.2.3 Exhaust gas temperature (EGT)

Fig. 4 shows EGT variation with load for MOME, MOMESUM and diesel fuel. Higher EGT indicates the poor energy utilization by the engine, which in turn designates lower thermal efficiency. It is inferred that the EGT increases with load for all the fuels. As the load increases more quantity of fuel is injected to meet the extra power resulting in higher EGT. It is observed that the EGT for diesel is lesser comparing MOME and MOMESUM. This is due to better utilization of fuel and lesser heat loss for diesel which is evident from higher BTE and lower BSFC. The other possible reason for lower EGT for diesel is due to higher calorific valve, lesser ignition delay and ignition timing comparing MOME and MOMESUM.

Average EGT for MOMESUM is 3.01% lesser than MOMESUM. Since the viscosity of MOME is higher than MOMESUM adapting conventional transesterification process, the droplet size of the fuel gets affected which in turn affects atomization of fuel and thereby reducing combustion rate and result in higher EGT. The other possible cause for higher EGT

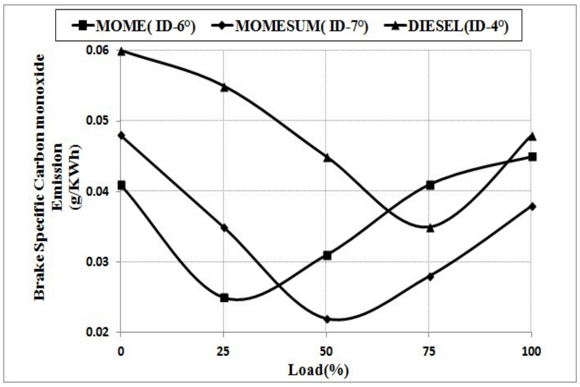

Fig. 5. Variation of CO emission with loads.

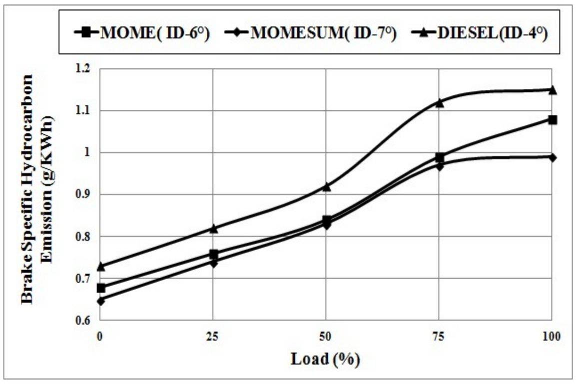

Fig. 6. Variations of HC emissions with loads.

for MOME is due to higher unsaturation causing more after-burning which increases EGT. Moreover BTE for MOMESUM is higher than MOME causing lesser EGT. The average EGT at all loads for MOMESUM is 212.4°C where as it is 219°C and 201.8°C for MOME and diesel.

The above analysis confirms that the production of methyl esters by means of ultrasonication and microwave irradiation is a promising technique to enhance performance aspects in CI engines.

3.3 Emission analysis on the effect of ultrasonication and microwave irradiation

The emissions of Carbon monoxide (CO), Hydrocarbon (HC), Oxides of Nitrogen (NOx) and Smoke density are measured and analyzed to view the effect of ultrasonication and microwave irradiation and found encouraging.

3.3.1 Carbon monoxide (CO)

Fig. 5 shows the CO emissions variation with load for MOME, MOMESUM and diesel fuel. The average CO emission from Diesel at all loads is found to be 0.0486 g/kWh while that from MOME and MOMESUM were 0.0386 g/kWh and 0.0342 g/kWh, respectively. CO emissions from MOME and MOMESUM are 20.57% and 29.62% lower than that of Diesel. This is due to higher oxygen content in both the methyl ester which promotes oxidation reaction resulting in lesser CO. Similar results were found by Raheman et al. [14].

CO emission is found to decrease at no and partial load conditions for all the tested fuels. As load increases the combustion temperature is found to increase and result in improved oxidation and complete combustion. It is also observed that at full load condition CO emissions tends to increase for all fuels. This is due to the fact that at higher loads the quantity of fuel injected is more for the same quantity of air in the cylinder causing inferior oxidation and higher CO emissions. Similar observations were also obtained in other studies [15-17]. The average CO emissions from MOMESUM at all loads was found to be 11.39 % lesser than MOME. Since the density and viscosity of MOMESUM is lower due to improved transesterification, less significant volume of fuel is admitted in same quantity of air in the cylinder leading enhanced mixing of fuel with air and thereby results in improved combustion and lesser CO emission than MOME.

3.3.2 Hydrocarbon (HC)

Fig. 6 shows the variation in HC emissions for all the test fuels with load. The average HC emission from diesel at all load is 0.968 g/kWh while that from MOME and MOMESUM are 0.87 g/kWh and 0.836 g/kWh, respectively. HC emissions from MOME and MOMESUM are 10% and 13.3% lower than diesel. This is due to higher oxygen content in both methyl ester promoting better combustion and resulting in lesser HC emission. With increase in load the average HC emission was found to increase for all the test fuels. This is because at high load the amount of oxygen available for combustion is inadequate causing inferior combustion and higher HC emissions. Similar observations were also obtained in other studies [18-21]. The average HC emissions from MOMESUM at all loads is 3.81% lesser than MOME. Since the viscosity and density of MOME is comparatively higher than MOMESUM adapting conventional transesterification, the time taken for the fuel to form droplets, vaporize and to mix with air in the cylinder is more and result in inferior combustion and higher HC emissions.

3.3.3 Oxides of nitrogen (NOx)

Nitrogen oxide is generalized term for NO and NO_2 representing as NOx. Nitrogen is formed by oxidation of nitrogen in air during combustion at very high temperature. It is evident that NOx emission increases with load as depicted in Fig. 7. At higher loads the peak gas temperature is raised promoting NOx formation for all the test fuels. The average NOx emission from Diesel at all loads was observed to be 14.128 g/kWh while that from MOME and MOMESUM were 15.54 g/kWh and 14.3 g/kWh, respectively. NOx emissions from MOME and MOMESUM were 7.99% and 1.96% higher than that of Diesel. The possible reason could be due to higher availability of oxygen in MOME and MOMESUM which in turns makes enhanced combustion compared to diesel.

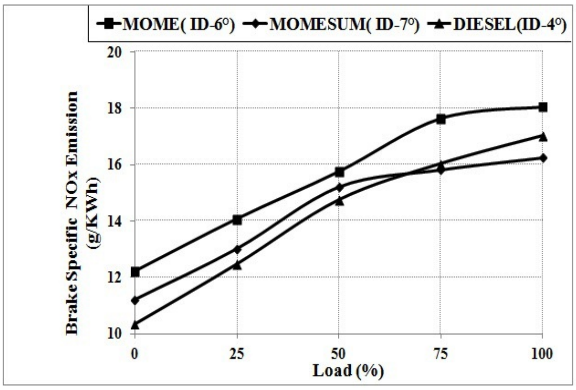

Fig. 7. Variation of NOx emission with loads.

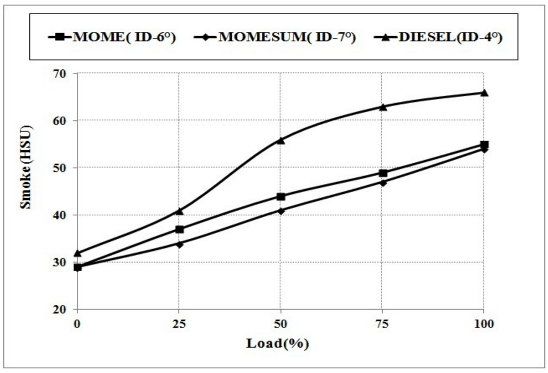

Fig. 8. Variation of smoke emission with loads.

The other possible reason is due to higher peak cylinder pressure of MOME and MOMESUM over diesel originating high NOx emissions. The possible reasons for higher NOx emission for MOME is due to higher percent of unsaturated ester and lower oxygen content as compared to MOMESUM. Since the unsaturation of MOME is higher, the fuel is advanced earlier causing advance in occurrence of peak heat release rate and pressure allowing more time to burn the mixture in high temperature region which may tend to increase NOx emissions. As the oxygen content in MOMESUM is higher the combustion is improved due to better mixing and result in lower NOx emissions. Similar observations were also obtained in other studies [22, 23].

3.3.4 Smoke intensity

Smoke opacity is strong dependent on amount of air in the cylinder and oxygen in fuel. Fig. 8 shows exhaust smoke emission of MOME, MOMESUM and diesel for various loads. Smoke intensity increases with load for all the fuels. The average Smoke emission from diesel at all loads is 51.6 (HSU) while that from MOME and MOMESUM are 42.8 and 41, respectively. Smoke emissions from MOME and MOMESUM are 15.8% and 19.3% lower than that of Diesel. This is due to comparatively lower availability of oxygen for Diesel owing in higher smoke emission.

It is clear from figure that the smoke emission for MOME and MOMESUM is less than diesel for all loads. This is possibly due to higher cetane number due to improved transesterification process promoting enhanced combustion and result in reduced smoke emission. The average smoke emission for MOMESUM is 5.3% less than MOME. This may be attributed to better atomization, vaporization and mixing of fuel with air. Since viscosity of MOMESUM is lesser than MOME due to improved transesterification, combustion is uniform causing lesser smoke emissions.

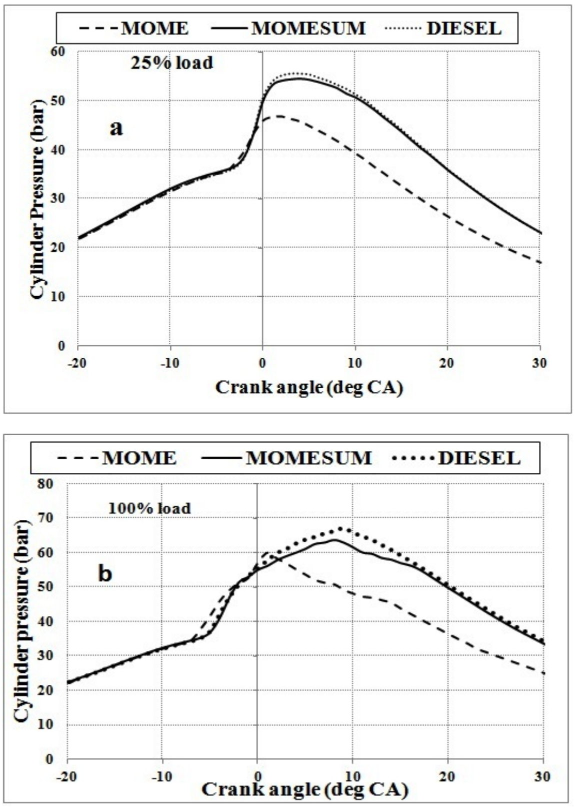

Fig. 9. Variation of pressure with crank angle.

The above analysis confirms that the production of methyl esters by means of ultrasonication and microwave irradiation is a promising technique to reduce emissions in CI engines.

3.4 Combustion analysis on the effect of ultrasonication and microwave irradiation

3.4.1 Pressure vs crank angle

Fig. 9 show the variation in instantaneous pressure with crank angle for MOME, MOMESUM and diesel at 25% and 100% load conditions. It is inferred that the pressure increases with load for all the test fuels. Peak pressure and its occurrence for Diesel, MOME and MOMESUM at full load conditions is 66.38 bar at 8° aTDC, 60.05 bar at 1° aTDC and 63.70 bar at 8° aTDC respectively.

The start of injection is calculated based on the dip in heat release diagram. From HRR it is inferred that the start of fuel injection for diesel, MOME and MOMESUM is 7°bTDC, 12°

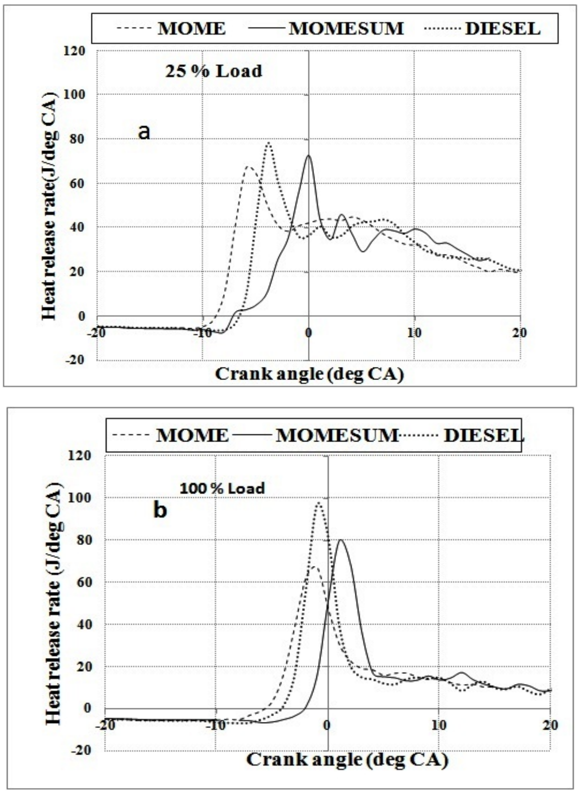

Fig. 10. Variation of heat release rate with crank angle.

bTDC and 10°bTDC respectively. Start of fuel injection is advanced by 2°CA as in the case of MOME compared to MOMESUM. Since MOME has lesser compressibility than MOMESUM due to higher density and viscosity, the time taken for the fuel to reach combustion chamber is lesser causing earlier fuel injection. In addition, higher viscosity of MOME reduces leakages in the fuel pump leading to an increase in the injection line pressure. Therefore, a quicker and earlier needle opening is realized with respect to MOME causing advanced fuel injection. Since the density and viscosity of MOME is higher, the time taken for the fuel to mix with the air in the cylinder is more and result in longer delay period. The advancement of fuel injection timing will increase NOx emissions for MOME. This is in agreement as pictured in Fig. 7.

It is also observed that the start of combustion for MOME is delayed by 2°CA when compared with MOMESUM. Since the density and viscosity of MOME is higher due to conventional transesterification process, more quantity of fuel is injected (with evidence from BSFC) leading poor atomization of fuel spray, reduced vaporization and incomplete mixing with air in cylinder and result in longer delay period [24].

3.4.2 Heat release rate

Heat release rate is the product of pressure work and change in internal energy of working fluid. Fig. 10 shows the heat release rate for MOME, MOMESUM and diesel at 25% and 100% load conditions. It can be observed that as the load increases there is a rise in heat release rate for all the test fuels. This implies that with rise in load air and fuel mixing rate is enhanced and thereby results in higher measure of heat release rate during premixed and mixing controlled combustion phase [25]. The other possible reason is due to additional supply of fuel at high loads ending in higher combustion temperature and higher heat release rate. It is clear that the heat release rate for diesel is higher than MOME and MOMESUM. Since the calorific value for diesel is higher, maximum heat release rate is obvious. It is also evident from the figure that the peak heat release rate is lower for MOME at both loads when compared with MOMESUM. Since the density and viscosity of MOME is higher, the fuel droplet size has increased which in turn reduces the mass fraction burnt in premixed combustion phase and resulted in reduction of maximum heat release rate.

The other possible reason for high peak heat release rate for MOMESUM could be explained as follows, for the same quantity of air supplied the burning volume for MOMESUM is more due to reduced density and viscosity following microwave and ultrasonication esterification. Since MOMESUM has less air fuel ratio, it could find more oxygen availability at given crank angle than that of MOME. This is in agreement with similar finding of Puhan et al. [15]. The maximum peak HRR and its occurrence at full load conditions for diesel, MOME and MOMESUM is 97.336 J/°CA at 1° bTDC, 67.05 J/°CA at 6° bTDC and 79.99 J/°CA at 1° aTDC, respectively.

4. Conclusions

The impact of ultrasonic stirred and microwave irradiated fatty acid methyl ester with respect to fatty acid methyl ester resulting from conventional transesterification on physical properties, performance, emissions and combustion aspects have been explored in this work. The result obtained suggests the following conclusions.

The percentage of yield for MOMESUM is increased by 5.71% when compared to MOME with 94.4 % reduction in esterification time due to enhanced esterifcation process.

Density and kinematic viscosity for MOMESUM is 3.93% and 7.9% lower than MOME respectively as a result of improved esterification process and result in superior physical properties of MOMESUM.

The average brake thermal efficiency of the engine is significantly improved by 5.84% for MOMESUM compared to MOME with 5.14% reduction in Brake specific fuel consumption as a result of superior esterification which in turn enhances the physical properties of MOMESUM. The brake thermal efficiency at full load is 27.06% for MOMESUM, whereas it is 25.25% and 28.92% for MOME and diesel, respectively.

Average CO, HC, NOx and smoke reduces by 11.39%, 3.81%, 7.99% and 5.3% respectively for MOMESUM compared to MOME attributable to better esterification process which in turn improves the physical properties of MOMESUM.

The cylinder pressure and heat release rate are low for MOMESUM compared to MOME due to shorter ignition delay period because of better esterification process which improves the physical properties of MOMESUM. At the full load, the cylinder peak pressure for MOMESUM was 63.708 bar compared to 60.05 and 66.38 bar for MOME and diesel, respectively.

From this experimental work, it is concluded that microwave irradiation and ultrasonication technique has many benefits over conventional technique favoring a suitable and promising alternative esterification process. The above conclusions were conducted in constant speed conditions and some deviations are anticipated to take place at different engine speed.

Nomenclature

MOME	: Mustard oil methyl ester
MOMESUM	: Mustard oil methyl ester subjected to ultrasound stirring and microwave irradiation
BTE	: Brake thermal efficiency
BSFC	: Brake specific fuel consumption
EGT	: Exhaust gas temperature
CO	: Carbon monoxide
HC	: Hydrocarbon
NO_x	: Nitrogen oxide
CA	: Crank angle
bTDC	: Before Top dead Centre
aTDC	: After Top dead Centre

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