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EXPERIMENTAL INVESTIGATION OF BIOGAS-BIODIESEL DUAL FUEL COMBUSTION IN A DIESEL ENGINE

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SHRNUTÍ

Předložená studie je pokusem jak získat ekvivalentní parametry vznětového motoru při spalování paliv z obnovitelných zdrojů, jako při spalování nafty. Práce byla navržena jako analýza vlivu bionafty B20 Algae jako pilotního paliva v duálním motoru bionafta bioplyn; výsledky jsou porovnány s funkcí motoru při kombinaci bionafta a nafta při stejných nastaveních motoru. Experimenty byly provedeny při různých zátěžích od 0 % po maximální (100 %) zátěž při konstantních otáčkách 1500 1/min. B20 Algae bionafta je porovnatelná s naftou z hlediska výkonu a charakteristik spalování. Dvojpalivový mód vykazuje nižší tepelnou účinnost a vyšší spotřebu paliva než při ostatních módech skrz celé spectrum zátěží. Dvojpalivový mód vede k nižším emisím NO_x a kouřivosti, zatímco koncentrace HC a CO byly výrazně vyšší v porovnání s ostatními palivy. Ve dvojpalivovém módu došlo k lehkému nárůstu špičkového tlaku, stejně jako k mírně vyššímu odvodu tepla v porovnání s funkcí na naftu a bionaftu v celém spektru zátěží.

KLÍČOVÁ SLOVA: **BIONAFTA ALGAE, BIOPLYN, DVOJPALIVOVÝ MOTOR, VÝKON A EMISE, CHARAKTERISTIKY SPALOVÁNÍ**

ABSTRACT

This study is an attempt at achieving diesel fuel equivalent performance from diesel engines with maximum substitution of diesel with renewable fuels. In this context the study has been designed to analyze the influence of B20 algae biodiesel as a pilot fuel in a biodiesel biogas dual fuel engine, and results are compared to those of biodiesel and diesel operation at identical engine settings. Experiments were performed at various loads from 0 to 100 % of maximum load at a constant speed of 1500 rpm. In general, B20 algae biodiesel is compatible with diesel in terms of performance and combustion characteristics. Dual fuel mode operation displays lower thermal efficiency and higher fuel consumption than for other fuel modes of the test run across the range of engine loads. Dual fuel mode displayed lower emissions of NO_x and Smoke opacity while HC and CO concentrations were considerably higher as compared to other fuels. In dual fuel mode peak pressure and heat release rate were slightly higher compared to diesel and biodiesel mode of operation for all engine loads.

KEYWORDS: **ALGAE BIODIESEL; BIOGAS; DUAL FUEL ENGINE; PERFORMANCE AND EMISSIONS; COMBUSTION CHARACTERISTICS**

1. INTRODUCTION

Diesel engines have a wide range of applications including transportation, locomotives in offshore drilling, military, marine, and telecommunication generator sets. Modern areas also include countryside construction projects, rice mills, pump sets, and small rural transportation vehicles [1]. The added advantages of high thermal efficiency, excellent fuel economy, and regulated emissions of hydrocarbons, carbon monoxide and carbon dioxide compared to spark ignition engines have led to the high usage of compression ignition engines. However, emissions of nitrogen oxides, along with smoke opacity in comparison with ignition engines remain issues that need to be tackled [2, 3].

Strict exhaust emission regulations in recent times have forced manufacturers to modify vehicles accordingly and come up with new developments. However, a combination of internal and external measures is needed to attain an absolute environmentally friendly solution. One such solution is the use of biodiesel. Biofuel is any form of fuel derived from biomass, namely sugars, vegetable oils and animal fats. Production

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of biofuels helps to improve local agriculture, reduce the dependence on oil imports, and also reduce emissions. Unlike fossil fuels, production of biofuel is more evenly distributed and can be produced with minimal investment costs [4, 5]. Biodiesel is obtained by reacting alcohol with vegetable oils, in the presence of an alkali catalyst such as KOH or NaOH, using a process called trans-esterification. The purpose of the trans-esterification process is to lower the viscosity and oxygen content of the vegetable oil. The use of biodiesel in compression ignition engines leads to the reduction or suppression of the formation of sulfur dioxide (SO_2), carbon monoxide (CO), hydrocarbon (HC) and smoke opacity emissions during the combustion process. This result is due to the low sulfur and aromatic content, and the presence of oxygen-containing compounds in biodiesel [6]. In addition, biodiesel has good ignition ability in an engine due to its relatively high cetane number compared to that of conventional diesel fuel [7, 8].

In this context, the focus has been concentrated on algae biomass for the production of biodiesel, for reasons such as photosynthetic efficiency, fast growth rate and high biomass productivity. Algae also possess the ability to produce high oil per unit area of land compared with other traditional crops [6]. Algae have rapid growth and they can be grown and harvested on a cyclic basis throughout the year under controlled and suitable culture conditions. They are also well known for their CO_2 fixation and can be grown in intensive culture on limited areas of land [9-12]. Like most vegetable oil sources currently used for biodiesel production, algae will not compete with food sources as it is not a food providing crop. Most importantly, algae oil typically has a free fatty acid content of 20 % to 50 %, which is problematic for conventional biodiesel production processes due to unwanted by-product formation [13, 14, 15].

The high cost of biodiesel is a major obstacle to its commercialization, with the price of raw materials responsible for 65–88 % of the total production cost. It proves to be a major drawback in the production of energy [16, 17]. With this high energy sustainability and debates going on, there is a pressing need to find other alternative and cheaper forms of fuel to run engines; this has provided a platform enabling the dual fuel mode of combustion to enter the picture. Dual fuel mode of operation utilizes a high cetane, easy to ignite pilot fuel to combust a low cetane primary fuel such as natural gas, biogas, propane, etc. [18]. Biogas is a potentially renewable fuel, producible by cheap and environment friendly methods. It is obtained by the anaerobic digestion of organic substances, the vital components of the gas being methane and carbon dioxide. The composition of biogas depends on the type of feed stocks, and production processes. Multiple variants of feed stock, such as cow dung, poultry waste, non-edible seed cakes, animal waste, food waste and agricultural waste have been explored for the production of biogas [19]. It is a low cetane fuel and has to be used with the presence of a pilot fuel possessing a high cetane number [20]. The pilot fuel helps in the ignition of the biogas [21]. Several researchers have documented the use of biogas in conventional diesel engines via a dual fuel mode. Thermal efficiency and BSFC were reported to have dropped in partial loads, but remained unaffected in full load operation [22, 23]. The CO and HC are reported to have been higher in a few cases and lower in the remaining few. Significant decreases in the smoke opacity and NO_x were observed [21, 22, 24, 25]. The volumetric efficiency of the biogas engine was found to be lower than that of the conventional diesel engine, and the ignition delay was found to be longer in the dual fuel mode of operation. The value of peak pressure was found to be highest in the biogas engine [20, 21].

The objective of this study is to experimentally investigate performance, combustion and emission characteristics in a dual fuel CI engine using a B20 blend of algae biodiesel (AOME), as pilot fuel and to further replace biodiesel with biogas, which is also a renewable fuel. The suffix B with the numerical signature indicates the percentage of algae biodiesel by volume in the biodiesel blend. From the literature it is evident that B20 algae biodiesel achieves better results compared to the other blends of biodiesel with diesel [9]. Experimentation was also conducted using diesel and AOME as fuel to serve as the baseline for comparison. Experiments were conducted at various loads at rated RPM for diesel and biodiesel in single fuel mode, and biodiesel and biogas in dual fuel mode of operation. The engine behavior with respect to combustion, performance, and emission characteristics are compared against a baseline of a standard diesel run.

2. EXPERIMENTAL SETUP

The experiments were conducted on a 7.5 kW (10HP), single cylinder water cooled CI engine with compression ratio of 16.5:1, fuel injection at 24 BTDC, injection pressure of 180 bar, and an eddy current dynamometer to apply the load. Other engine specifications are given in Table 1. B20 algae biodiesel was used as a pilot fuel and biogas was supplied through the air inlet manifold. Engine sensors and dynamometer were interfaced to a computer via a serial cable for recording data such as temperatures, air flow rate, fuel flow rate, load, combustion pressure, etc. To record the data online, software was logged every time and data was stored on the computer hard disk, which could be retrieved as and when required. Experimentation was carried out for various loads with 25 % increments at 1500 rpm to evaluate the CI engine with respect to

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its combustion, performance and emission characteristics. Water flow to engine cooling jacket was maintained at about 75 cc/min. Fuel rate of pilot fuel was restricted to 30 % in reference to the AOME operation, the rest of the fuel required to run the engine was supplied through biogas, which was introduced into the combustion chamber via the air inlet manifold, controlled by a regulator. The rate of flow of biogas was measured by a flow meter and the data was recorded. Figure 1 shows the engine setup used for conducting the experiment, and Figure 2 shows the arrangement to convert single fuel mode into a dual fuel mode of operation. A DELTA 1600-L make of MRU exhaust gas analyser is used to determine NOx (ppm), CO (%), and UBHC (ppm) emissions in the exhaust. The AVL437C smoke meter was used to measure the opacity of the exhaust gases. Opacity is the extinction of light between light sources and receiver. Smoke opacity is measured as a percentage. The exhaust gas analyser and smoke meter are shown in Figure 3 and Figure 4.

FIGURE 1: Kirloskar Engine
OBRÁZEK 1: Motor Kirloskar

FIGURE 2: Dual fuel arrangement
OBRÁZEK 2: Uspořádání pro přívod dvou paliv

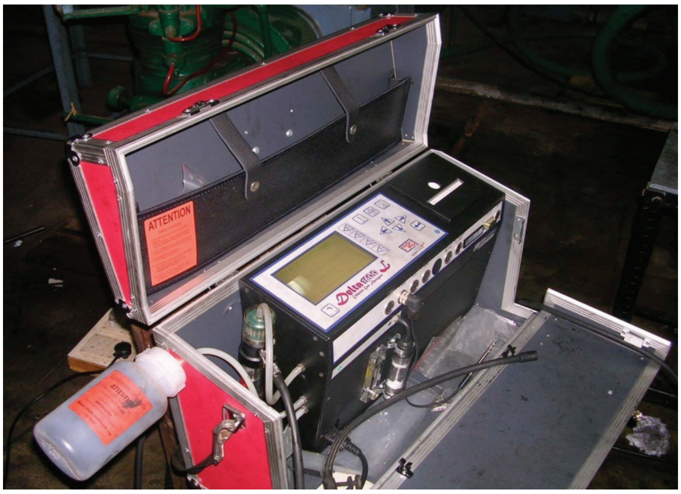

FIGURE 3: Exhaust Gas Analyzer
OBRÁZEK 3: Analyzátor výfukových plynů

FIGURE 4: Smoke Meter
OBRÁZEK 4: Kouřoměr

TABLE 1: Engine Specifications
TABULKA 1: Parametry motoru

Make	Kirloskar
Capacity	10HP
Compression Ratio	16.5:1
Cylinder Bore	80mm
Stroke	110mm
Cylinder Capacity	553cc
Cooling	Water Cooled
Loading	Eddy Current Dynamometer
Speed	1500RPM
Maximum Load	40 N-m
Injector opening Pressure	180 bar
No. of Cylinders	1

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3. TRANSESTERIFICATION

The transesterification process of oil with an alcohol (methyl or ethyl) provides a cleaner burning fuel (commonly known as biodiesel) having less viscosity. At an industrial level, biodiesel is normally produced by this transesterification process, a chemical process in which triglycerides react with an alcohol (methyl or ethyl) in the presence of an alkali catalyst (usually NaOH or KOH in proportions of about 1 % weight of oil) to form fatty acid alkyl mono esters (biodiesel) and glycerol (by-product). This occurs in a multiple reaction process including three reversible steps in series, where triglycerides are converted to diglycerides, then diglycerides are converted to monoglycerides, and monoglycerides are converted to esters and glycerol. The algae oil obtained after this transesterification process is usually referred to as algae oil methyl ester (AOME) [26, 27]. Figure 5 shows the chemical reaction of the transesterification of algae oil. The algae biodiesel and biogas properties are evaluated and tabulated in Table 2 and Table 3.

TABLE 3: Properties of biogas
TABULKA 3: Vlastnosti bioplynů

Property	Value
Methane (% by vol.)	70-75
Carbon dioxide (% by vol.)	25-30
Nitrogen (% by vol.)	5-20
Oxygen (% by vol.)	0-5
Boiling point (°C)	(-)126-162
Density (kg/m^3)	0.65-0.91
Octane number	130
Auto-ignition temp. (°C)	632-813
Lower heating value (MJ/kg)	26.17

FIGURE 5: Transesterification of oil and fat
OBRÁZEK 5: Transesterifikace oleje a tuku

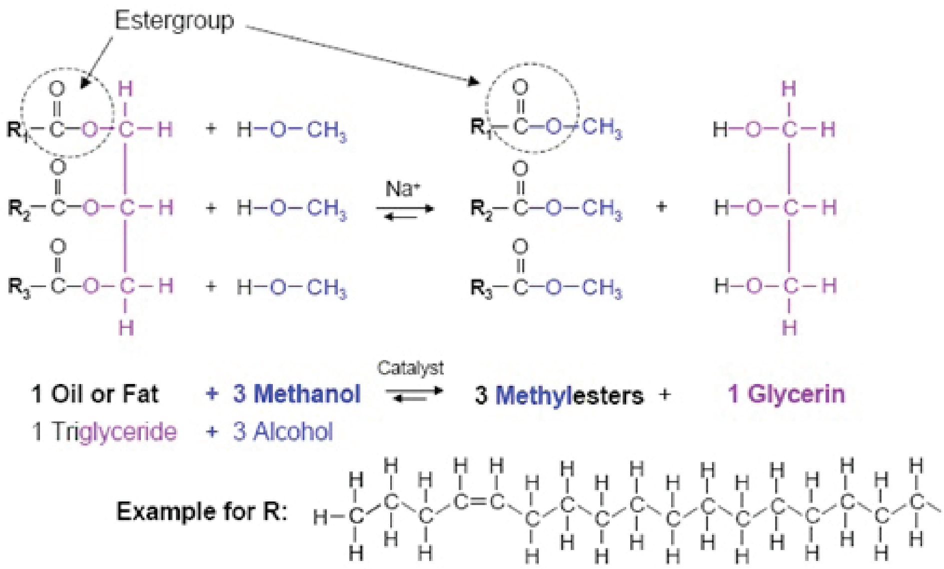

TABLE 2: Properties of various fuels
TABULKA 2: Vlastnosti různých paliv

Property	Algae Oil	AOME	ASTM D975 Petro Diesel	ASTM D6751 Biodiesel
Density at 40 °C (g/m^3)	0.871	0.864	0.834	0.85-0.90
Specific Gravity at 40 °C	0.916	0.894	0.851	0.88
Flash point (°C)	145	130	60-80	100-170
Kinematic Viscosity, 40 °C (mm^2/s)	5.76	5.2	2.5	1.9-6.0
Iodine Value (g/100g oil)	124	75	38.30	-
Acid Value (mg KOH/ g oil)	0.46	0.374	0.34	0.8(max)
Calorific value (kJ/kg)	37200	40920	42000	-

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4. RESULTS AND DISCUSSION

A) PERFORMANCE ANALYSIS

1. Brake Thermal Efficiency (BTE)

Figure 6 presents a graph of BTE versus load for varying load conditions in steps of 25 % of full load condition. It is found that the Brake Thermal Efficiency of the single fuel mode of operation is always higher than for the dual fuel mode of operation. This can be explained by the fact that addition of biogas into the air fuel mixture replaces fresh air and the increase in the quantity of biogas leads to a direct drop in efficiency of the engine [29]. Also, biogas residuals, combusted residual gas and also low combustion temperature are present in the combustion chamber, which together reduce the efficiency of the operation [21]. Amongst the liquid fuels it can be observed at high loads that AOME has higher values of efficiency than Diesel operation. The presence of oxygen particles in the biodiesel helps improve the combustion process [30].

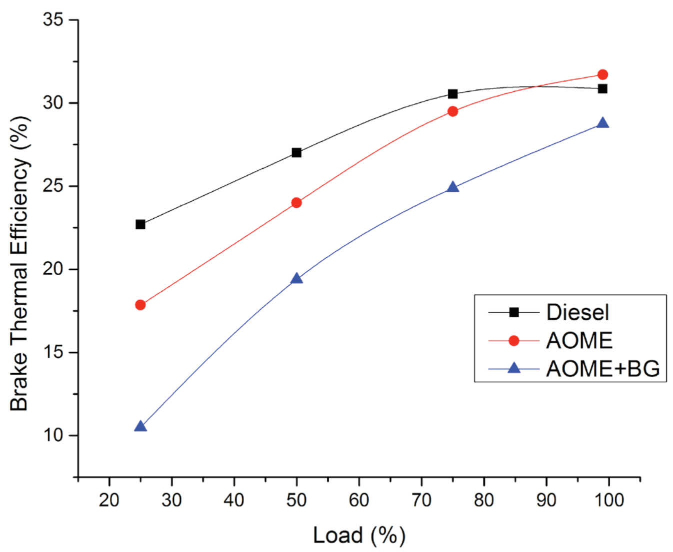

FIGURE 6: Variation of BTE with Load
OBRÁZEK 6: Změna tepelné účinnosti v závislosti na zátěži

B) COMBUSTION ANALYSIS

1. Heat Release Rate (HRR)

In Figure 7a we see the HRR variation of every fuel with respect to load. A significant increase in the values of HRR for increasing loads can be noted, owing to the fact that at high loads more fuel is burnt and thus a much higher heat release rate is achieved. The dual fuel mode of operation gives a much higher HRR reading than the single fuel mode of operation. This is due to the combustion of gaseous fuel in the immediate vicinity of the pilot fuel [30]. The maximum amount of energy is found to be released immediately following the commencement of auto-ignition of the pilot fuel, caused by an increase in concentration of biogas in the air, which modifies and extends significantly the flammability zone around the pilot fuel [31, 32]. This behavior can be observed in Figure 7b, where the dual fuel operation peaks much later than the single fuel modes, showing that the combustion of the gaseous fuel happens much later and into the expansion stroke. The single fuel mode of operation gives a slightly lower HRR as compared to the dual fuel mode of operation, and the AOME gives a slightly higher reading than diesel. This can be attributed to the fact that Methyl esters have a high content of oxygen molecules and a higher cetane number.

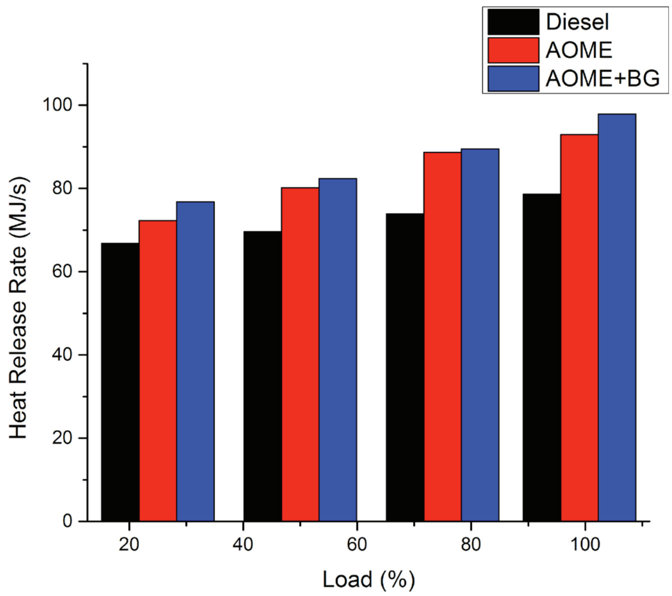

FIGURE 7A: Variation of peak HRR with load
OBRÁZEK 7A: Změna HRR v závislosti na zátěži

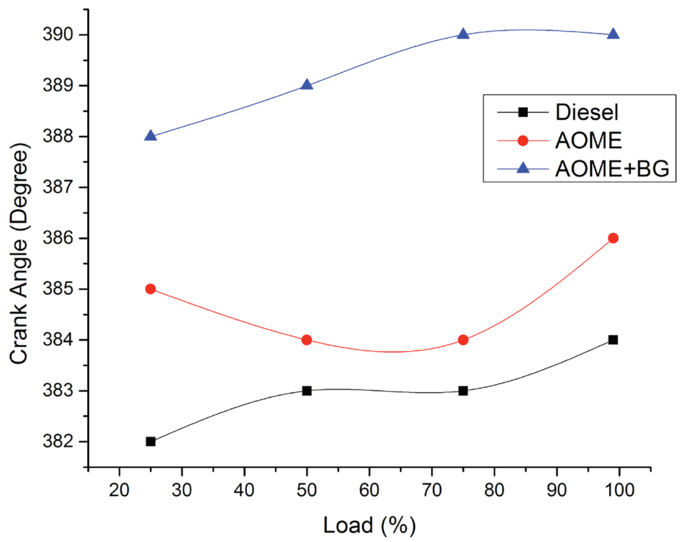

FIGURE 7B: Variation of crank angle at peak HRR with load
OBRÁZEK 7B: Změna úhlu klikového hřídele při nejvyšším HRR v závislosti na zátěži

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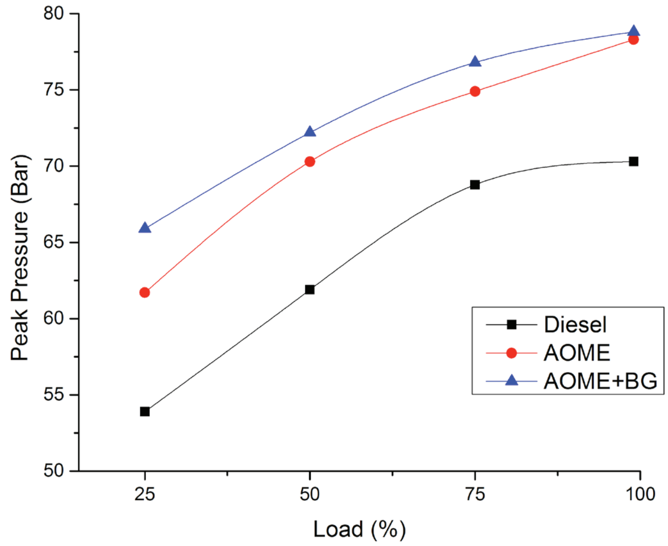

FIGURE 8: Variation of peak pressure with load
OBRÁZEK 8: Změna nejvyššího tlaku v závislosti na zátěži

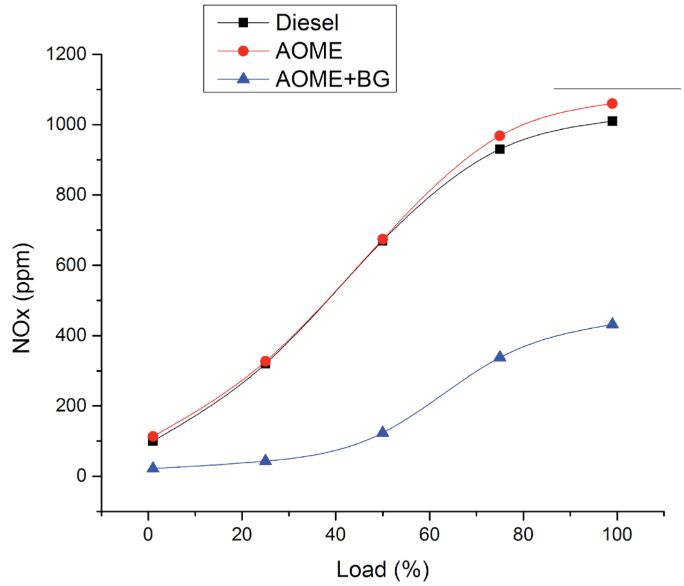

FIGURE 9: Variation of NO_x with load
OBRÁZEK 9: Změna emisí NOx v závislosti na zátěži

2. Peak Cylinder Pressure

The comparison of Peak Cylinder Pressure with load is shown in Figure 8. The injection pressure and injection timing was kept constant at 180 bar and 24 Degree BTDC respectively. From the figure it was observed that the dual fuel value peaks higher while single fuel operations peak at a lower pressure at all load conditions. The AOME blend peaks at a higher pressure than diesel, but lower than that of dual fuel mode of operation. A general trend is observed that as the load increases the peak pressure also increases. The reason for such an increase in ignition delay is due to the larger amount of biogas fuel in the intake and compression processes, and the lower charge temperature of the gas–air mixture over the duration of the injection compared to single-fuel mode because of the high overall specific heat capacity of biogas [21, 33].

C) EMISSION ANALYSIS

1. Oxides of Nitrogen

NO_x emissions for the various fuel operations are shown in Figure 9. It is notable that for all loads in the dual fuel mode the values of NO_x are much lower than for the single fuel operation. This is due to the fact that at around 30 % of the pilot fuel injected, the amount of pilot fuel decreases, and thus the jet becomes progressively smaller [18]. Also, the introduction of biogas increases the specific heat capacity of the fuel mixture, which thereby slows the flame propagation and consequently the production of NO_x emissions is reduced [34, 35, 36]. Methyl esters show marginal in NO_x emissions when compared to diesel, due to high temperatures present inside the cylinder [30]. At full load conditions the determined values of NO_x were 432 ppm for AOME+BG mode, 1060 ppm for AOME and 1010 ppm for diesel.

1. Carbon Monoxide and Unburnt Hydrocarbons

Figures 10 and 11 show the variation of CO and HC emissions with respect to load. It can be noticed for all loads that the values of CO and HC for the dual fuel mode of operation are considerably higher than for the single fuel modes. This can be explained by the presence of CO_2 in biogas, which brings about a dilution of oxygen content. Also, the flame cannot propagate through the entire cylinder volume in the timeframe of combustion. This is why at lower loads, CO and HC emissions are higher [37]. At higher load conditions, the higher amount of biogas flow reduces the air and thus the oxygen supply through the inlet manifold. This causes an increase in HC and CO emissions in dual fuel operation [1]. The HC emissions of single fuel methyl ester are lower than for dual fuel due to the presence of oxygen molecules, which leads to complete combustion of the fuel [6]. The values of CO emissions are 0.45 % for diesel, 0.3 % for AOME, and 0.52 % for AOME+BG. The UBHC emissions are 63 ppm for diesel, 46 ppm for AOME, and 93 ppm for AOME+BG.

2. Smoke Opacity

Smoke opacity was reduced in dual fuel operation when compared to single fuel mode of operation. The smoke opacity at various loads is shown in Figure 12. It can be attributed to the absence of aromatics, and low sulfur content, which are major contributors to smoke formation [6]. The presence of methane in biogas, which is lower than the paraffin family, means it has a very low tendency to produce soot [35]. In general the reduction of smoke opacity is due to the reduction of flame temperature and increased oxidation of soot particles [25]. The values of smoke opacity are 67 % for diesel, 63 % for AOME, and 14 % for AOME+BG.

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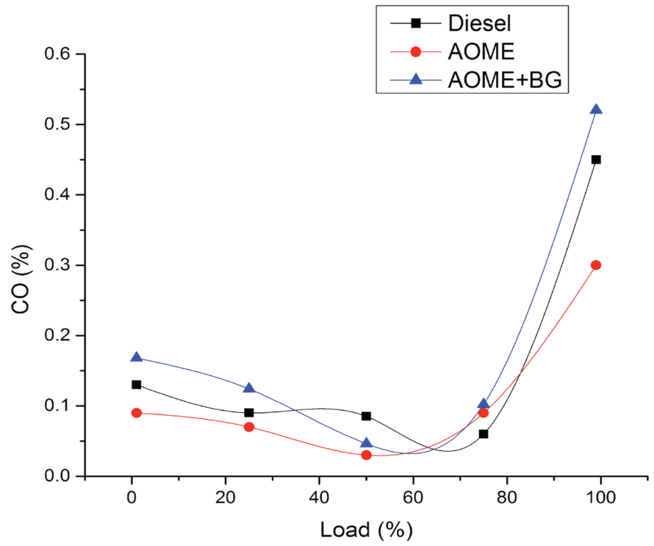

FIGURE 10: Variation of CO with load
OBRÁZEK 10: Změna emisí CO v závislosti na zátěži

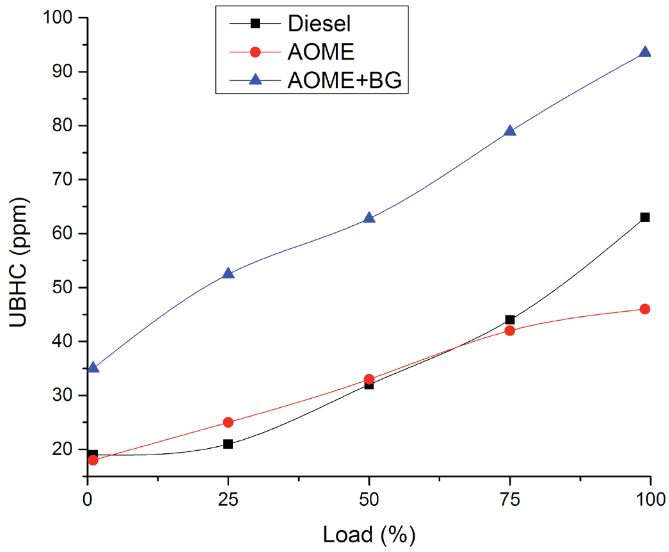

FIGURE 11: Variation of HC with load
OBRÁZEK 11: Změna emisí HC v závislosti na zátěži

5. CONCLUSION

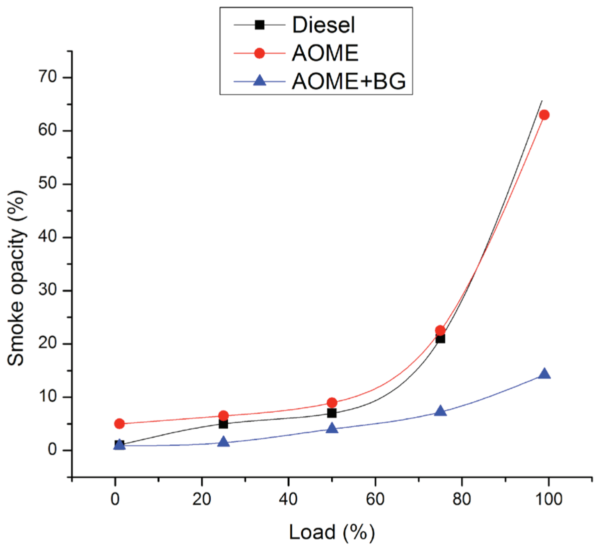

FIGURE 12: Variation of smoke opacity with load
OBRÁZEK 12: Změna kouřivosti v závislosti na zátěži

The brake thermal efficiency values of the dual fuel mode were lower for all loads when compared with the single fuel modes. In the combustion analysis it is evident that the HRR and peak pressure values of the AOME-Biogas dual fuel mode were always higher for all loads when compared to their corresponding single fuel values, owing to the fact that more fuel is burnt and thus a much higher heat release rate and a higher build up of pressure in the chamber occurs. In dual fuel operation, NO_x emissions are significantly lower when compared to single fuel mode under all test conditions. Dual fuel mode of operation shows a better ability in the reduction of smoke opacity emissions due to the absence of aromatics, a lower sulfur content, and lower air-fuel ratio. The CO and HC emissions are considerably higher for dual fuel mode than those for single fuel mode under all load conditions. This is due to the presence of CO_2 in biogas, which brings about a dilution of oxygen content. The adoption of this AOME–biogas dual fuel is viable as an equivalent fuel source for diesel engines. Usage of a biogas dual fuel engine has the potential to avoid most of the current and future problems associated with diesel engines, including offering very significant reductions in their exhaust emissions.

LIST OF NOTATIONS AND ABBREVIATIONS

CI	Compression Ignition
SI	Spark Ignition
BTDC	Before top dead centre
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
HRR	Heat Release Rate
UBHC	Unburned Hydrocarbons
CO_2	Carbon Dioxide
CO	Carbon Monoxide
NO_x	Oxides of Nitrogen
	AOME – Algae oil methyl ester
	AOME+BG– Algae oil methyl ester and Biogas

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