

Experimental Study on Combustion Characteristics of Biodiesel–Ethanol Dual Fuel: An Overview

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ABSTRACT

Biodiesel and bioethanol are two renewable fuels available on the market, both of which have been used on internal combustion engines as an additive as they have physicochemical properties similar to commercial petroleum fuels. However, different properties of biodiesel and ethanol in terms of viscosity and energy density directly affect the combustion process of internal combustion engines. This article aims to analyze and evaluate the influence of 100% blended biofuels including biodiesel-ethanol on combustion characteristics and emissions under diesel engine conditions, as well as the status of biodiesel-ethanol fuel use, a recommended orientation for the development of adaptive diesel engine in the future at Vietnam. These studies on the influence of biodiesel-ethanol fuels blend were carried out on the optical research engine system (constant volume combustion chamber) and the actual engine testing. The results revealed that change in the concentration of ethanol affects the physicochemical properties of BE fuels blend, and using more ethanol in the mixture causes more effect on the trend of combustion characteristics and emissions. Consequently, it is possible to use a 100% biodiesel-ethanol blend on conventional diesel engines with little modifications.

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1. Introduction

The energy crisis and obligations to comply with increasingly stringent emissions norms have prompted the fuel industry to shift away from fossil fuels into eco-friendly sustainable fuel sources. Agreements on reducing emissions and protecting the global environment have motivated scientists around the world to explore several new alternative energy resources and additives to reach low emissions and optimize the available engines. During the development of the world, diesel engines have become the first choice in the fields of transportation, industry, and agriculture, because of more advantages in power and thermal efficiency [1], [2]. However, studies around the world have repeatedly accused diesel engines of using diesel fuels to generate many harmful emissions to the environment and people [3]. Nowadays, biodiesel is widely used in many countries as an alternative fuel for traditional diesel fuel due to its sustainable supply of energy [4], [5]. To low carbon emission targets, the increase of applying biodiesel percentage is possible and demonstrated in laboratories [6]. However, the difference in compositions of biodiesel as compared with diesel fuel causes significantly vary their fuel properties in terms of density, viscosity, volatility, etc. [7]. These factors limited the concentration of biodiesel use less than 20% in a diesel-biodiesel mixture to ensure that the diesel engine can operate stably without any engine modifications [8]. As a consequence, the widespread use of biodiesel fuel in diesel engines is obstructed and only considered as an additive mix with conventional diesel fuel. For overcoming the obstacles, a research direction in multiple blending biofuels such as diesel-biodiesel-ethanol has been carried out so that biodiesel use rises above 20%. Jha et al. [9] studied the effects of the diesel-biodiesel-ethanol blends on the emissions of the used and new engines including Ford 4000, John Deere 5103, and John Deere 4039DF008, respectively in which fueled DBE blends with fraction

70:25:5 (D70BD25E5), 70:20:10 (D70BD20E10), and 70:15:15 (D70BD15E15). The paper reported that the used engine running the D70BD25E5, D70BD20E10, and D70BD15E15 blends orderly showed an average increase in NO_x emissions of 16%, 21%, and 24% as compared to D70BD30. On contrary, the new engine showed an average reduction of 12%, 16%, and 22% in NO_x. Shi et al. [10] researched the ethanol-methyl soyate-diesel fuel blend in a ratio of 5:20:75 and revealed a decrease in the particulate matter (PM) by 30% on average, a slight increase of NO_x in a range of 5.6–11.4% at tested condition on Cummins-4B diesel engine. The mentioned results show that traditional diesel fuel has still played a leading role in the fuel mixture diesel-biodiesel. With the goal of reducing CO₂ relating to sustainable energy development, the research on this aspect continues delving into strategic-technological solutions to increase the biofuel blending ratio, thus reducing dependence on traditional diesel fuel.

Ethanol as a promising biofuel for diesel engines has been shown feasibility in replacing diesel fuel by studies of BE fuel mixtures on performance and emissions since the early years of the 20th century. Kass et al. [11] studied the effect of ethanol mixing of 10% and 15% with diesel fuel on the 5.9-liter Cummins B series engine. It is noted that a significant effect of ethanol on reducing PM while increasing the CO, HC and a negligible impact on the NO_x. On this aspect, several studies on the effect of ratios up to 20% ethanol blend in the single cylinder DI engine were conducted by Cole et al. [12], and Xingcai et al. [13]. These researches concluded at 1760 rpm, low load to full load conditions, that the brake thermal efficiency improved about 1-1.5% (absolute). In general, studies on the effect of ethanol fuel on the DE blends show ethanol has positive effects regarding PM and NO_x emissions [14].

In the effort to further understand the influences of ethanol use as appropriate biodiesel for diesel engines, the evaluation of fuel types such as ethanol, methanol, and n-butanol combined with biodiesel on performance characteristics have been investigated [15], [16]. Experimental results show that blended fuels biodiesel-ethanol and biodiesel-methanol reduce NO_x while increasing carbon monoxide and unburned hydrocarbon compared with pure diesel at below 70% load conditions. In addition, BE gives better results in terms of emissions and overall engine performance compared to BDM. Wei et al. [15] compared two types of blends of biodiesel-ethanol (BE) fuels and biodiesel-n-butanol (BBu) fuels, the BE blends presented a higher maximum heat release rate and peak in-cylinder pressure, while longer ignition delay and shorter combustion duration than BBu blend. The brake thermal efficiency of the BE blends is lower than biodiesel at low loads, but almost the same compared with the BBu blends while the difference is insignificant with increasing load conditions. Thus, ethanol is a suitable choice of use when combined with biodiesel for the purpose of reducing emissions while ensuring the performance. Moreover, the advanced atomization property and high oxygen content of ethanol provide more mixing time at the premixed combustion phase, and the PM emissions of BE fuel blend is lower than diesel.

Through some highlight research in the literature, most of the studies focus on analyzing the effect of the blended BE fuel on the combustion characteristics and emissions formation, as well as an overview of performance of diesel engines with ethanol ratios in less than 20%. However, the use of various biodiesel and ethanol feedstocks directly affects the fuel properties then to the final result. This study focuses on collecting, analyzing, and evaluating fuel characteristics, combustion characteristics, NO_x, and PM emissions of blended biodiesel-ethanol fuel at different ethanol concentration conditions. Besides that, the experiment system named Constant Volume Combustion Chamber (CVCC) will be introduced as a solution to perform the experiments on measuring the effect of BE blends fuel to diesel combustion characteristics. Therefore, it serves as a premise for empirical studies to evaluate the effects of resources biofuels (biodiesel and bioethanol) available locally within the countries.

2. Methods

2.1. Experimental setup

The optical research experiment system (constant volume combustion chamber - CVCC) is commonly used for observing the combustion process [17]-[20]. The CVCC allows for simulation of dynamically changing conditions inside the cylinder such as pressure, temperature and density gases, EGR ratio, etc. Figure 1 (a) showed a schematic of the CVCC system with mainly systems consisting of a CVCC chamber, high-pressure injector, air supply, intake/exhaust line, sensor, and data acquisition system. The operation condition of the diesel engine before activating injection has been simulated by the pre-combustion technique [18]. Besides that, to evaluate the effect of blended BE fuels at various

load and engine speeds conditions as well as determine performance and emission characteristics, the engine test dynamometer has been used. The engine experiment apparatus as Figure 1 (b) included a CI engine, a dynamometer system used to control the engine speed and torque; pressure transducer and temperature sensor are used to monitor combustion characteristics; the emissions test system is used to determine the emissions concentrations of the fuel blend.

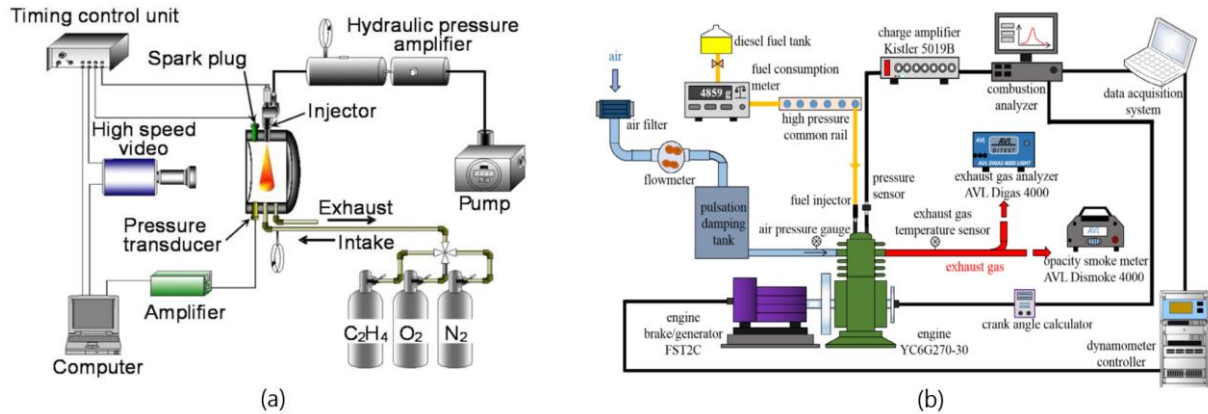


Figure 1. (a) Experimental setup of CVCC [18]; (b) engine system test for BE duel fuel testing [21]

2.2 Fuel properties

Biodiesel has been used in diesel engines as a fuel additive to reduce emissions by mixing less than 20% without changing the engine structure [22]. Many studies has been carried out the influences on combustion and emissions characteristics of higher mixing ratios of biodiesel up to 100% [6]. However, replace the diesel fuel has dealt with many obstacles because of its high viscosity, and high freezing point, etc. [22], and especially its difficult application to high-compression combustion engines. Ethanol is a commonly used substance in daily life and has been applied in spark ignition engines combined with gasoline fuel [23] and in CI engines in terms of 100% blending between BE fuel [16], [21], [24]. The fuel properties of BE blend fuel are shown in Table 1. Ethanol will decrease the density of BE, in other to compensate for engine performance when using BE blend, advanced injection timing is needed [25]. The pure biodiesel viscosity of 5.47mm²/s approximately is too high compared with pure diesel of 3.58mm²/s. Ethanol dilution in the biodiesel blend is proven to reduce the viscosity [25]-[27]. Additional ethanol will help decrease kinematic viscosity to close to that of the viscosity of diesel.

Table 1. Fuel properties of blend BE fuel [21]

Fuel properties	BDO	BD100	BD90E10	BD80E20	BD70E30
Density (g/cm ³)	0.837	0.878	0.866	0.861	0.856
Kinematic viscosity at 40°C (mm ² /s)	3.58	5.47	4.15	3.57	3.28
Boiling point (°C)	198-350	310-360	78-360	78-360	78-360
Surface tension at 20°C (10 ⁻³ N/m)	26.55	28.63	<28.63	<28.63	<28.63
Cetane number	45.4	50.8	<50.8	<50.8	<50.8
Low heating value (MJ/kg)	42.52	38.43	37.52	36.28	35.20
Carbon content (wt%)	87.05	76.59	74.38	72.14	69.80
Hydrogen content (wt%)	12.95	12.06	12.15	12.24	12.33
Oxygen content (wt%)	0	11.35	13.47	15.62	17.87

3. Results

3.1. Ignition Delay

The ignition delay period (IDP) is the most important property as it diesel engines, it influences the emissions, peak cylinder pressure, and combustion noise [28]. IDP itself has also been affected by many factors of fuel properties such as latent heat of vaporization, self-ignition temperature, and the reaction

of hydroxyl radical ($-OH$) produced [29]-[31]. The ignition delay of biodiesel is generally shorter because of the lower compressibility and high cetane number [32]. Geng et al. [21] conducted an experiment on measuring the IDP of diesel and BE blends. The result showed that IDP of biodiesel fuel is lower than diesel as shown in Figure 2, despite the fact that biodiesel has a higher cetane number. But higher viscosity for biodiesel leads to less effective atomization and prolonged IDP [32]. Ethanol has high octane number but the cetane number is too low compared with biodiesel [2], when increasing the ethanol ratio in blended BE fuel, the cetane number will decrease, leading to the IDP of BE increase.

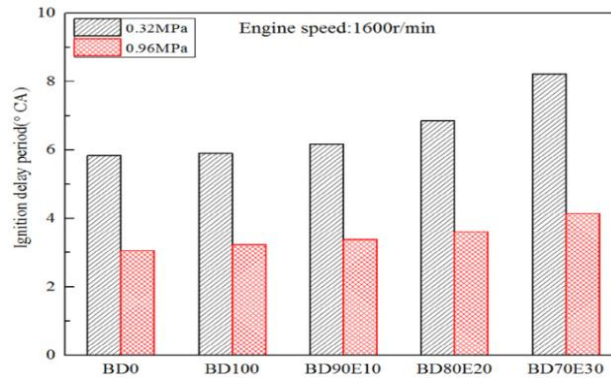


Figure 2. The ignition delay period of fuels at low and high load conditions [21]

3.2. Combustion Analysis

3.2.1. Heat Release Rate

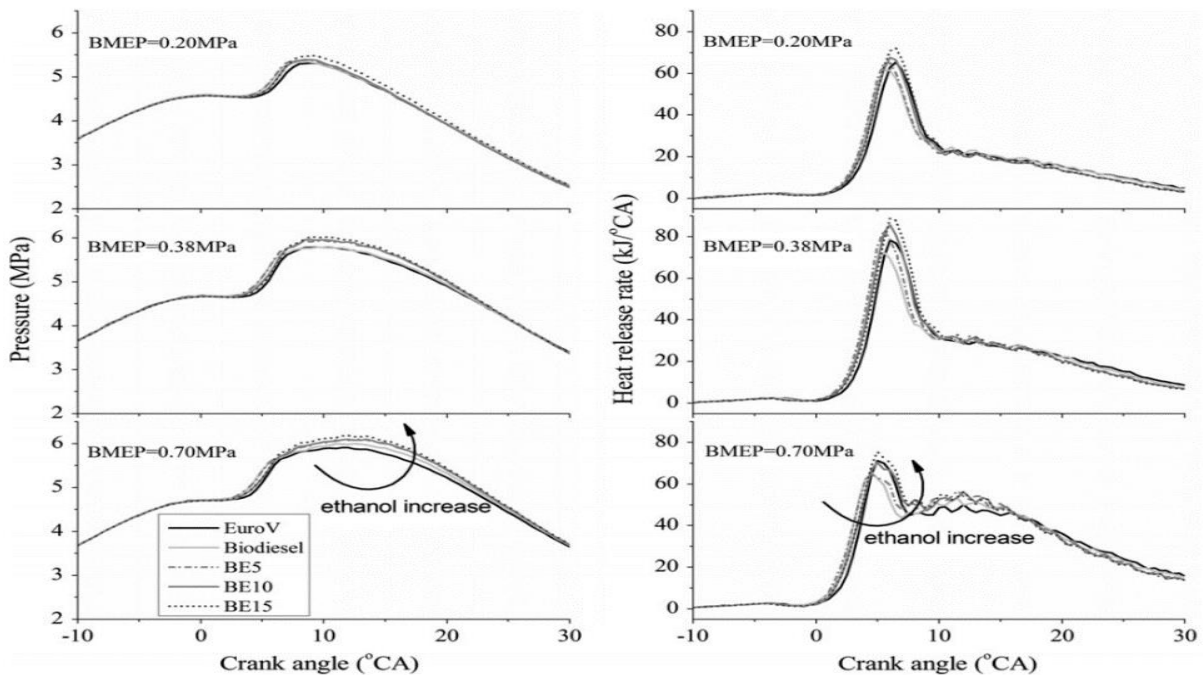


Figure 3. Cylinder pressure and heat release rate of blend BE fuel at different load conditions [33]

The heat release rate (HHR) of fuel biodiesel-ethanol blended is higher than pure biodiesel and diesel. Zhu et al. [33] observed the effect of blending BE fuels, in which biodiesel derived from waste cooking oil blended containing 5%, 10%, and 15% ethanol by volume, running on the diesel Isuzu 4HF1 engine. They reported that as the ethanol concentration increases, the HHR of BE increases at low load conditions but decreases at high load conditions compared with Euro V diesel fuel (Figure 3). Interestingly, these findings are consistent with the experiments on a high-speed diesel engine when varying the ethanol, and n-butanol percentage with diesel under different engine loads by Lu et al. [34] and Wei et al [15]. This may be caused by the low cetane content of BE, and the high latent heat of ethanol. Load condition set the stage for prolonged ignition delay timing and thus more time to prepare

for premixed combustion phase, leading to more fuel combusted in the premixed combustion phase and increase peak heat release rate [15], [33], [35]. A larger amount of fuel burned in premixed phase results in less burn in diffusion phase and improving fuel pyrolysis. Moreover, combined with the higher oxygen content of ethanol and biodiesel, improved diffusion combustion and hence shorter diffusion combustion phase, the result are shorter combustion duration and less heat loss [29], [33]. High volatility, and lower viscosity, density, surface tension of ethanol help improve spray characteristics and atomization of fuel become easier, thereby advancing premixed fuel/air [8]. Besides that, more factors have been found to demonstrate that adding ethanol to BE blend contributes to the decrease in HHR. Anbarasu et al. [36] used blended BEB15 (85% cottonseed oil and 15% ethanol) fuel to evaluate HHR. The study reported that HHR of BEB15 ($61\text{kJ/m}^3 \text{ deg}$) is lower than diesel fuel ($99\text{kJ/m}^3 \text{ deg}$). Factors contributing to the decrease of HHR of blends BE fuel is higher latent heat of vaporization of ethanol. The significant cooling effect of the increased percentage of ethanol to combustion temperature, ethanol with the higher latent heat of evaporation and lower value LHV will decrease HHR [37], [38].

Furthermore, when increasing ethanol percentages up to 30% in biofuel at high load conditions, the mixture BE fuel have the peak heat release rate lower than diesel fuel. Tutak et al. [39] reported that after exceeding 30% of EF fraction in the blend, the lower value of LHV of blend and relatively high value of heat of evaporation dominantly effect on the results decrease HRR. At high load conditions, fuel has been injected more into the cylinder, at this time low heating value property of ethanol and biodiesel dominated and made the heat release rate of BE blend fuel lower than diesel, combined with the latent heat of ethanol that contributes to a lower total heat release of BE [21], [40].

3.2.2. In-cylinder Pressure

The change of pressure inside the cylinder (ICP) of BE fuel with the change of ethanol concentration at different engine speed conditions as shown in Figure 4. BE blend fuel gives a higher maximum ICP than diesel because the higher oxygen content properties in ethanol fuel promote the combustion reaction [15], and the lower cetane number of ethanol, leading to more fuel combusted in the uncontrolled combustion phase [29], [33], [41]. However, maximum ICP slightly changes as well as has a trend to go down when increasing the concentration of ethanol in the BE blend, because more concentration of ethanol leads to better uncontrolled combustion [15], [29]. On the other hand, prolonging the ignition delay timing could shift the combustion phases away from the top dead center and combine the trend of the piston to go down and hence reduce the maximum pressure inside the cylinder [42], [43].

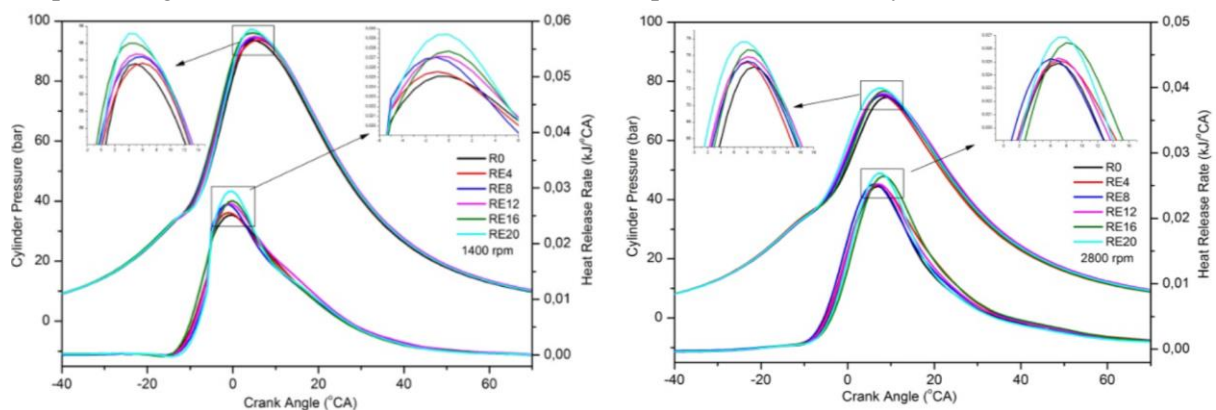


Figure 4. Cylinder pressure and heat release rate graphics of rapeseed biodiesel-ethanol mixture at 1400 rpm (left) and 2800 rpm (right) [41]

Furthermore, the lower heating value of ethanol also affects decreased combustion pressure. Datt et al. [44] reported when increasing ethanol concentration from 5% to 15%, the maximum combustion pressure decreased from 80.6bar to 79.14bar, and the crank angle of the peak in-pressure cylinder decreased from 4° after TDC to 7° after TDC. One reason used by the authors to explain the decrease in the peak pressure inside the cylinder with increasing ethanol content is the cooling effect of ethanol.

3.3. Emissions characteristics

3.3.1. Oxides of Nitrogen

NO_x emissions in the diesel engine have been mainly formed by combustion temperature, local oxygen concentration, exposure time in the high-temperature region [3]. The higher oxygen content of BE causes more complete combustion which makes the temperature of combustion too high, leading to higher NO_x [6], [41], [46]. Longer ignition delay of BE blend and good air-fuel mixing leads to an increase of burned fuel in the uncontrolled combustion phase, thus increase the combustion temperature [47].

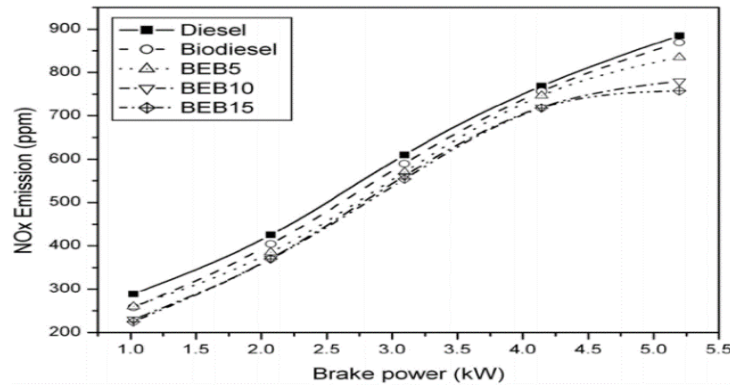


Figure 5. NO_x emissions of BE blends fuel at load conditions [36]

However, aside from the factors that increase the NO_x of the BE fuel blend, the fuel properties of ethanol also have the tendency to restrict NO_x formation (Figure 5). In the research of Anbarasu et al. [36] and Teoh et al. [48], the dominant factor to reduce NO_x is the cooling effect of ethanol base latent heat of evaporation and lower heating value, thus decreasing the combustion temperature. Wei et al. [15] revealed similar results in terms of NO_x emissions and the additional reason is the short burning time at high temperatures of BE blended fuel. Moreover, adiabatic temperature of ethanol contributes to reducing the combustion temperature of the fuel mixture, leading to a decrease in the NO_x [49].

Table 2. Trend NO_x emissions with different ethanol content in BE blend fuel

References	NO _x emissions follow concentration ethanol					
	5%	10%	15%	20%	25%	30%
István Barabás et al. [50]	↑	↓	ND	ND	ND	ND
Anbarasu et al. [36]	↓	↓	↓	ND	ND	ND
Wei et al. [15]	↑	↓	↓	ND	ND	ND
Datta et al. [44]	↓	↓	↓	ND	ND	ND
Shi et al. [51]	ND	ND	↑	↑	ND	ND
Geng et al. [21]	ND	↑	ND	↑	ND	↑
Tutak et al. [39]	↑	↑	↑	↑	↑	↑

(↓) Decrease, (↑) Increase, (ND) No Data

Moreover, the addition of percentage ethanol in the BE leads to differences in the result of NO_x. Barabás et al. [50] increased ethanol from 5% to 10%, the result reported at high load conditions of blended with 5% ethanol showed NO_x higher than diesel fuel, but with 10% ethanol, the NO_x is lower than diesel. This result was also proven in the study of Wei et al. [15]. The NO_x decreased when used 15% ethanol in the study by Anbarasu et al. [36]. However, Shi et al. [51] observed that NO_x gradually increased with 20% ethanol. This result is similar to that of Geng et al. [21] when increasing the ethanol ratio in the fuel blend to 30%. From the differences in the results of NO_x emissions in the studies, a table summary as in Table 2 has been established to give an overview of the NO_x emissions in the studies.

3.3.2. Particulate Matter (PM)

The change in the PM emission of diesel, biodiesel and BE blend fuel is shown in Figure 6 (a). The formation of PM at the crank angle of BE is lower compared with diesel and biodiesel. Most of the

investigations about the formation of PM of blended BE fuel have indicated that used ethanol helps reduce the PM [8], [15], [16]. Chen et al. [8] investigated the PM emissions with different fuel blends of ethanol 10%, 20%, and 30% (by volume) on diesel and 10% vegetable ester based on the Cummins 4B diesel engines. PM emission at BMEP of 4.6KPa, E10B decreases the PM by 25% compared to diesel, while E20B and E30B reduce the PM by 50% (Figure 6 (b)). The study concluded when used BE blends fuels and increases the proportion of ethanol in the blended fuel, the PM emissions decrease.

The factors affect decreasing PM emissions of the BE blended fuels:

- Firstly, the higher oxygen content property of biodiesel and ethanol fuels which improved the combustion, in turn, resulted in completing the combustion, decreasing the PM formation process, and increasing the PM emissions oxidation process [41], [52]. Moreover, the PM formation process can be inhibited by the ethanol low carbon/ hydrogen ratio property [15]. Besides that, group R-OH and HO₂ derived from ethanol combustion are more effective in inhibiting the PM formation than the R(C=O) OR in the biodiesel [15], [21].
- Secondly, the properties of low viscosity, low surface tension, and higher fuel volatility of ethanol, the vaporization and atomization process quicker than biodiesel and diesel, and the IDP longer [43], lead to better fuel/air mixture at the uncontrolled combustion phase, resulting in a decrease local equivalence ratio and consequently, lowering the smoke level [53]. The enrichment of oxygen content in the biodiesel and ethanol fuels results in more complete combustion and reduces the probability of soot nuclei formation in locally rich regions [54].
- Thirdly, a lower stoichiometric air-fuel ratio of BE reduces the probability of local fuel-rich zones in the non-uniform fuel-air mixture contributing to the reduction of smoke [55], [56].
- Finally, the lack of aromatics and sulfur of biodiesel and ethanol contributes to the reduction in PM emissions of blend BE [55], [56].

However, with the addition of ethanol percentage of up to 15% in BE fuel blends, the reducing efficiency of PM emissions is insignificant. Figure 6 (b) showed E30B has the same reduction level of PM as E20B at full range load and 1600 rpm. The main reason is due to the dominant cooling effect of ethanol leading to decreased combustion temperature, causing arising PM emissions.

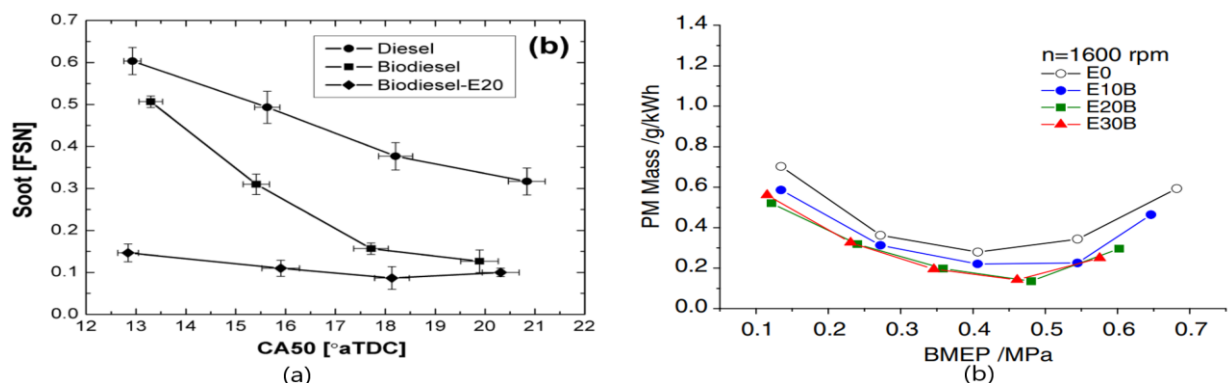


Figure 6. (a) PM emissions for diesel, biodiesel and BE at combustion phasing [55]; (b) Effects of ethanol content on PM mass at various loads [8]

3.4. Development trend of biodiesel-ethanol in Vietnam and a design testing equipment for combustion diagnostics

Biodiesel and bioethanol have been widely used in agriculture, transportation, construction, etc. in Vietnam due to abundant reserves. They have been produced from different resources such as basa catfish, coconut, waste cooking oil, etc. [57], [58]. The biofuels are classified into 4 groups of generation products based on feedstocks and method [59], several kinds of resources have been selected with criteria: avoid competition with food resources, sustainable sourcing potentials, and little effect on the environment. Outstanding one is microalgae, which corresponds to third generations production biodiesel. Microalgae have several important advantages such as requiring less space to grow, high oil content, the ability to grow in both artificial and natural environments, consume CO₂, being eco-friendly and especially from which biodiesel and bioethanol can be produced [60], [61]. Vietnam is a country with a long coastline, more lagoons, and ponds, very suitable for microalgae growth [62]. Currently,

bioethanol has been applied with 5 percent by volume combined with gasoline fuel use on conventional fuel for spark ignition engines, biodiesel has not been applied for commercial diesel engines yet. From the overview effect of blend biodiesel-ethanol, fuel to combustion, emission formation in diesel engine, the BE blend fuels are a promising alternative for diesel fuel use on the diesel engine.

The conventional diesel engine usually is used to conduct experiments on combustion, performance, and emissions. However, the limitation of available structure and technology on the test engine systems affects the development of the study in many respects. The optical combustion experimental system with the advantage of allowing the simulated diesel combustion conditions to be flexible in ambient temperature inside the chamber, oxygen concentration (EGR), has been selected for studies related to biodiesel-ethanol [63], [64]. Besides, the powerful feature of the experiment system allows for accessible visualization of the entire combustion process inside the cylinder, so, the studies to diagnose fuel combustion, spray characteristics and emissions formation inside combustion have been performed on the experimental system of optical research combustion chamber [17], [65].

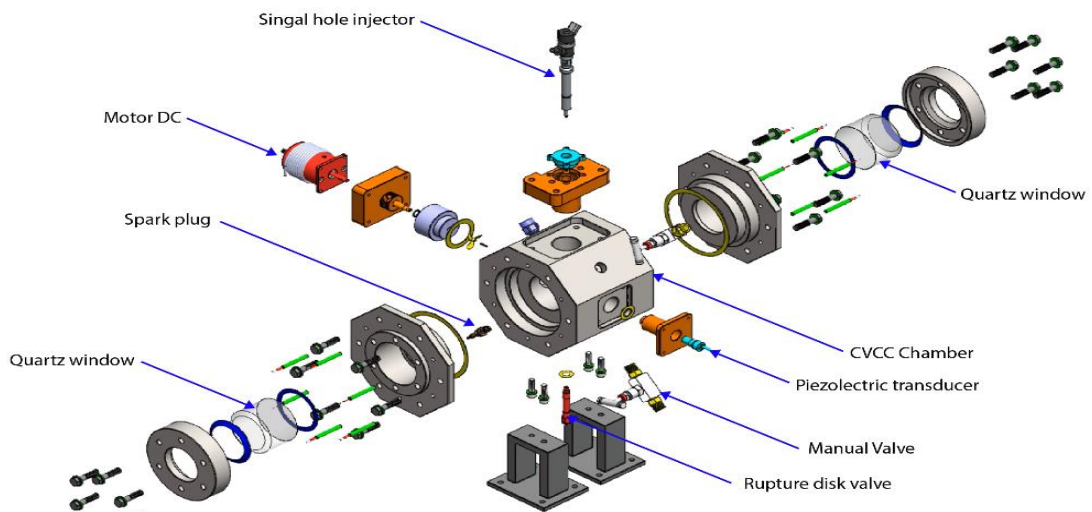


Figure 7. 3D exploded overview of the constant volume combustion chamber

An experiment system named constant volume combustion chamber (CVCC) has been built for the purpose of researching and analyzing combustion characteristics of biodiesel-ethanol blend fuel from the available feedstocks in Vietnam at a wide range of conditions operation of diesel engine. Figure 7 generally describes the main components of a proposed CVCC designed and analyzed by CAE software. In the test rig, the CVCC system allows the combustion of fuels under diesel engine conditions to happen inside the chamber, high fuel pressure up to 1600bar is created by a common rail system and injected into the chamber via a single hole injector. The pre-combustion technique has been applied to create diesel engine operating conditions prior to fuel injection. The two quartz windows were installed for visualizing the evolution of flame inside the chamber by using the schlieren experiment. The combustion pressure inside the chamber was detected by a piezoelectric transducer sensor type. The results of the combustion characteristics such as ignition delay, heat release rate, combustion pressure and efficiency, emissions, spray visualization, etc. can be obtained when combined with high-speed video registration.

4. Conclusions

The fuel properties of biodiesel-ethanol blend fuel will be effect by ethanol concentration in blend fuel and different sources of biodiesel will result in different fuel properties.

The heat release rates and combustion pressure of BE blends fuel increase with low ethanol percentage, due to improving the mixing processes, better-premixed combustion, and shorter diffusion combustion duration phase. The resulting trend will be opposite when increasing amount of the ethanol, the cooling effect and longer ignition delay move the combustion phases away from the top dead center.

The results of NO_x emissions were not consistent between studies and ethanol percentage in blend dual fuels. The cetane number lower and higher oxygen content of fuel promotes NO_x formation.

However, the high burning rate of BE leads to short combustion duration (decreased residence time) and high latent heat of evaporation, which are positive factors to reduce NO_x emissions.

The PM emissions of BE blend fuel with the ethanol concentration from 5% to 20% reduces the PM emissions compare with pure diesel fuel. However, when continue to increase the ethanol concentration up to 30% in the fuel blends, the PM emissions reduction is insignificant.

The detailed design of the optical test rig (CVCC) as well as the strength of material analysis, and practical operating evaluation will be presented in the next works. Generally, a constant volume combustion chamber will be a good test rig under approaching the Schlieren image processing method for renewable fuel combustion research.

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