Prediction of Mixture Ratio of Ethanol Blended with Bio-diesel as Ignition Improver on CI Engine Startability

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Abstract

This work investigates the effect of bio-diesel as an ignition improver on engine startability. Semenov's theory of spontaneous ignition is applied to predict the ignition of ethanol with improver at elevated pressure and temperature. The results of these predictions are compared with engine startability tests. Results show that increased improver concentrations requires higher equivalence ratios to ignite. The higher compression ratio reduces the equivalence ratio for spontaneous ignition. There is a discrepancy between the results of Semenov's theory and the experiment by a factor 2 to 4.

***Keywords**: Startability, Ethanol, Ignition Improver, CI Engine.*

1. Introduction

The burning of fossil fuels is the major source of greenhouse gases (GHGs) and is considered to be the main cause of global climate change. Increasing carbon dioxide levels are leading to global warming. Renewable alternative fuels, as a substitute for petroleum fuels, have become increasingly important due to environmental problems. Ethanol, a renewable alternative fuel, is produced domestically in Thailand from raw materials such as sugar cane, molasses, cassava, etc. Usage of ethanol for the transport sector reduces net CO_2 emissions to the atmosphere. Carbon dioxide produced from the combustion of ethanol is absorbed from the atmosphere by feedstock plants during photosynthesis. Thus, the process of making and burning bio-ethanol does not increase atmospheric CO_2 levels.

Ethanol, mostly often blended with gasoline, is an unfavorable net fuel in diesel engines because of its low cetane rating. Methods of using ethanol fuels in CI engines include solutions, emulsions, fumigation, dual injection, spark ignition, glow plugs, and ignition improvers [1-2].

Simonsen et al [3] investigated ignition delay of ethanol with different ignition improvers. Ethanol with the ignition improvers Isopropyl nitrate, Polyethylene glycol (Beraid) and Nitrate ester (Avocet) were investigated in a single-cylinder DI Diesel engine. The results showed nitrate ester (Avocet) was the most efficient ignition improver, providing the shortest ignition delay.

Research carried out at Luleå University of Technology on an ethanol-fuelled diesel engine [4] studied the impact on engine performance and emissions. The six cylinders, 11 liters CI engine turbocharged with an intercooler was modified for use with ethanol fuel. The modification parts included fuel pump, fuel injector, turbocharger, injection timing, compression ratio and piston.

The compression ratio of the engine was increased from 18:1 to 24:1. The engine ignition improvers Avocet and Beraid were used in the testing. The hydrous ethanol with these ignition improvers, “Etamax D”, was provided by Sekab [5]. They concluded that the proper use of ethanol reduced the CO_2, PAH and other HC in the exhaust gas. However, they noted an increase of aldehydes and CO.

Nord et al [6] investigated rapeseed methyl ester (RME) as an ignition improver in an ethanol fueled CI engine. RME 16-25% by volume in ethanol was used for the tests in an 11 liters, six cylinder, in-line diesel engine turbocharged with intercooler. The ethanol contained denaturants 3%, and 250 ppm corrosion inhibitor. Results from the engine performance test of ethanol-RME and Etamax D showed the ignition delay of 16% RME was longer than Etamax D, In case of 18 and 20% RME, the ignition delay was shorter than Etamax D. The power output increases with increasing RME concentrations. These are probably related to the energy content in the fuel. The energy content of ethanol is about 27.1 MJ/kg and RME is 37.2 MJ/kg.

Ethanol is difficult to ignite under CI engine conditions. To solve this problem, addition of ignition improvers is required. Also, using ethanol in CI engines can result in poor startability. This study considered a simple model to determine the critical conditions for ignition of an ethanol CI engine. The spontaneous ignition explained by Semenov and Frank-Kamenetskii’s theory [7]. In these models heat generation is approximated by the Arrhenius law. Thermal ignition occurs when the rate of heat generation is greater than the rate of heat loss.

2. Semenov’s theory of spontaneous ignition

Semenov’s theory explained the phenomenon of spontaneous ignition in a combustible gas mixture in a vessel [8]. Pressure, temperature and composition of the mixture are assumed to be uniform. Heat generation due to chemical reaction is approximated by the Arrhenius law. Semenov’s theory of spontaneous ignition is expressed in Eq. (1)

$$\frac{P_c^2}{T_c^4} = \left(\frac{hSR^3}{\Delta H V k_2 X_A^2 E}\right) e^{\frac{E}{RT_c}} \tag{1}$$

Eq. (1) can be written in the logarithmic form and expressed in Eq. (2)

$$\ln\left(\frac{P_c}{T_c^2}\right) = \ln\left(\frac{hSR^3}{\Delta H V k_2 X_A^2 E}\right)^{\frac{1}{2}} + \frac{E}{2RT_c} \tag{2}$$

Where P_c is critical pressure, T_c is critical temperature, h is heat transfer coefficient, S is surface area of the walls of the vessel, R is universal gas constant, ΔH is thermal energy release of the reactions, V is the volume of the vessel, k_2 is the pre-exponential, X_A is the mole fraction of the species A, E is activation energy.

In this study, however, Semenov's theory of spontaneous ignition is applied to predict the spontaneous ignition of ethanol with improver in CI engine conditions. The ethanol with improver is considered a homogeneous fuel and is injected immediately into the combustion chamber. Mole fraction of mixture (X_A, from Eq. (1)) can be defined as

$$X_A = \frac{n_f}{n_f + n_a} \tag{3}$$

where n_f is the mole of fuel and n_a is the mole of air. n_f in Eq. (3) can be defined as

$$n_f = n_E + n_I \tag{4}$$

where n_E is the mole of ethanol and n_I is the mole of improver. By substituting Eq. (4) into Eq. (3), one obtains

$$X_A = \frac{n_E + n_I}{n_E + n_I + n_a} = \frac{\frac{m_E}{M_E} + \frac{m_I}{M_I}}{\frac{m_E}{M_E} + \frac{m_I}{M_I} + \frac{m_a}{M_a}} \tag{5}$$

where m_E is the mass of ethanol, m_I is the mass of improver, m_a is the mass of air, M_E is the molecular weight of ethanol, M_I is the molecular weight of improver, M_a is the molecular weight of air. The variables in this study are improver concentration (Y_I) and equivalence ratio (ϕ). They are defined by Eqs. (6) and (7), respectively,

$$Y_I = \frac{m_I}{m_f} = \frac{m_I}{m_I + m_E} \tag{6}$$

$$\emptyset = \frac{\frac{m_f}{m_a}}{\left(\frac{m_f}{m_a}\right)_{stoi}} \tag{7}$$

where Y_I is the mass concentration of improver, m_f is the mass of fuel and ϕ is the equivalence ratio. By substituting Eqs. (6) and (7) into Eq. (5), one obtains

$$X_A = 1 - \frac{\frac{1}{M_a}}{\frac{(1-Y_I)\,\emptyset\,(m_f/m_a)_{stoi}}{M_E} + \frac{Y_I\,\emptyset\,(m_f/m_a)_{stoi}}{M_I} + \frac{1}{M_a}} \tag{8}$$

Eq. (1) and Eq. (8) are combined for predicting the spontaneous ignition of ethanol with improver. The critical pressure and temperature are estimated from common diesel engine (for compression ratio 18) by polytropic process, written as Eq. (9)

$$\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^n, \quad \frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{n-1} \tag{9}$$

where n is the polytropic index, P_1 and T_1 are the air pressure and temperature at beginning of compression process, P_2 and T_2 are the air pressure and temperature at the end of compression process (critical condition), V_1/V_2 is the compression ratio. In this study, n is assumed to be 1.30 [9]. P_1 and T_1 are set to 1 atm and 298 K, respectively.

The heat transfer coefficient (h) is estimated by Eq. (10) [10].

$$\frac{h_e b}{k_g} = 10.4\left[\frac{Gb}{\mu_g}\right]^{0.75} \tag{10}$$

Where b is the bore, μ_g is the dynamic viscosity, k_g is the thermal conductivity, G is determined from mass flow rate divided by piston area

$$G = \frac{\dot{m}_a}{A_p} \qquad (11)$$

Fig. 1 shows prediction results of ethanol with bio-diesel as improver in CI engine for compression ratio 18.

From Fig. 1, the pure ethanol (Y_I = 0) can be ignited at mole fraction (X_A) about 0.025. Increased improver in ethanol (Y_I) reduces the mole fraction for ignition. This means the addition of improver will improve the ignition of fuel. Bio-diesel has a higher heating value than ethanol. It produces higher heat when reacting with air. Hence, the heat generation term in Semenov's theory of ethanol with bio-diesel is higher than pure ethanol, resulting in reduction of mole fraction for ethanol with improver.

A variation of equivalence ratio of ethanol blended with bio-diesel is shown in Fig. 2. Pure ethanol ignites at equivalence ratio of about 0.4, whereas pure bio-diesel ignites at equivalence ratio of about 0.6. Although the bio-diesel can ignite at lower mole fraction as compared with ethanol (Fig. 1), it ignites at a higher equivalence ratio. Bio-diesel has higher molecular weight than ethanol, resulting in a higher equivalence ratio.

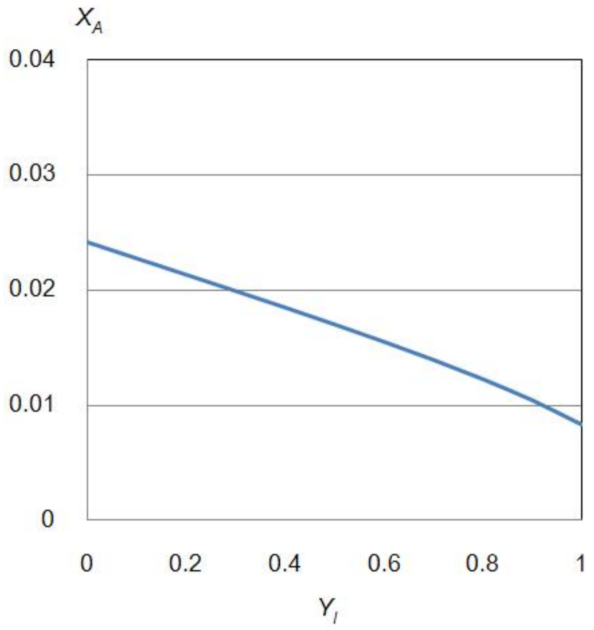

Fig. 1 Prediction of spontaneous ignition of ethanol with bio-diesel as improver in CI condition

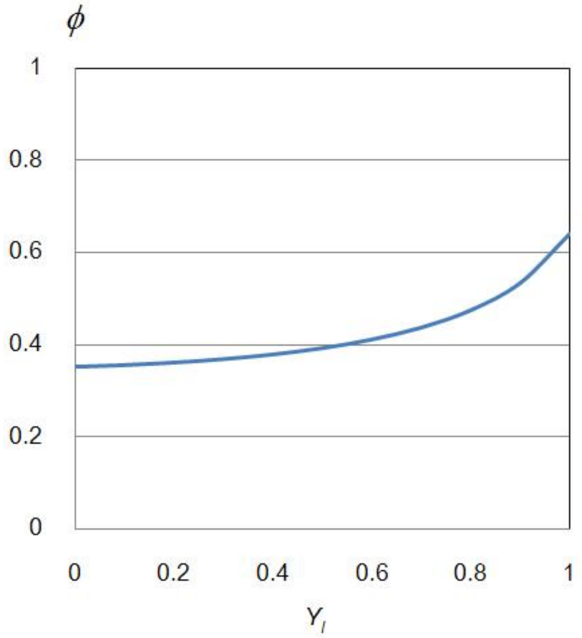

Fig. 2 Equivalence ratio of ethanol with bio-diesel as improver at startability condition

3. Experimental results

Experiments were performed in a single-cylinder, 4-stroke, water-cooled, DI diesel engine. The engine was modified to increase compression ratio from 18:1 to 23:1 and 28:1 by reducing the volume of the combustion chamber on the piston. Table. 1 shows the technical data of the engine

Table. 1 Engine specifications [11]

Description	Values
Bore x Stroke (mm)	97 x 96
Displacement (cm^3)	709
Max. power (kW)	10.3
Max. torque (kg-m)	5.0
Compression ratio	18 : 1 23 : 1 28: 1

The engine was tested in a controlled room divided into two zones by a plastic curtain. Both zones were air conditioned to maintain air temperature at 25ºC. The experiment apparatus is shown in Fig. 3.

K-type thermocouples measured the engine temperature, i.e. cooling water and oil temperatures. Temperature data were recorded with data logger Keyence Thermo NR-TH08 [12]. Temperature, humidity, and barometric pressure data were recorded by a 3 channel data logger, TR-73U Thermo Recorder [13]. They were installed for measuring engine room temperature (T_1), intake air temperature (T_2) and outside air temperature (T_3).

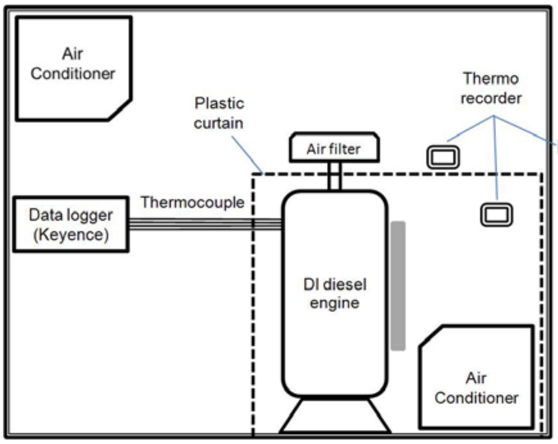

Fig. 3 Schematic diagram of the experiment

The engine and fuel tank were soaked in the room until the room temperature, cooling water and oil temperature varied within 25±1ºC at least 1 hour before starting, as shown in Fig. 4. The fuel injection rate was set to maximum for all cases.

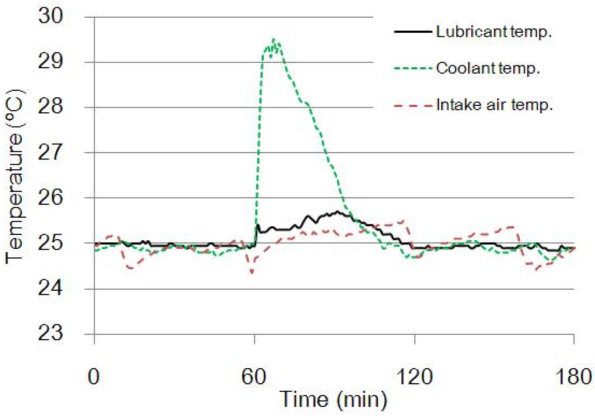

Fig. 4 Temperature profile

The engine was then started by motor for five seconds. If the engine run continuously for one minute, it was defined as “engine runs after starting”. The experiment was repeated three times in each case. When “runs after starting” was achieved, the cooling water and oil temperature was then cooled down to 25±1ºC for about 1 hour in preparation for the next test.

When the improver concentration was increased to 30% for the startability test with compression ratio 18, the engine did not start. Hence, there are no results of startability for compression ratio of 18.

Table. 2 shows the results of engine startability for bio-diesel. The engine started with ethanol and bio-diesel at improver concentration of 18% and 17% with higher compression ratio of 23 and 28, respectively. It is noted that the sign "X" means the engine does not run after starting and "√" means the engine runs after starting.

Results of startability test from Table. 2 are compared with Semenov's theory. Fig. 5 shows the minimum equivalence ratio with spontaneous ignition occurring for compression ratio of 18, 23 and 28.

The higher compression ratio enhances the ignitability of fuel. The fuel ignites at a lower equivalence ratio due to higher pressure and temperature. There are two plots in Fig. 5, BD23 and BD28, which are the result of the startability test of ethanol with bio-diesel as improver for compression ratio 23 and 28, respectively. BD23 ignites at an equivalence ratio of about 0.4 while Semenov's theory predicts at about 0.2. BD28 also ignites at equivalence ratio of about 0.4 while Semenov's theory predicts about 0.1. The difference between Semenov's theory and experimental results may be due to the definition, "engine runs after starting". For improver concentrations of less than 17%, the ignition of fuel can be observed, but it is not enough for the engine to run continuously. Cylinder pressure data are required for studying fuel ignition in detail.

Table. 2 Results of startability test for bio-diesel

Improver concentrations (%)	CR 23:1	CR 28:1
10	X	X
11	X	X
12	X	X
13	X	X
14	X	X
15	X	X
16	X	X
17	X	√
18	√	√
19	√	

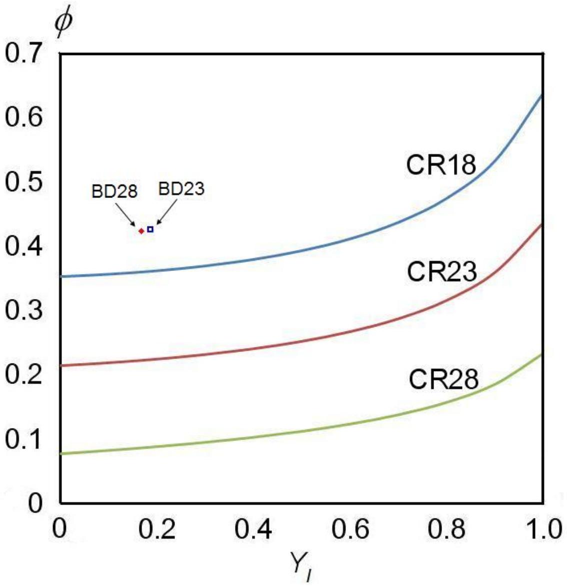

Fig. 5 Results of Semenov's theory and experiment

4. Conclusions

Semenov's theory of a spontaneous ignition is derived in terms of equivalence ratio (ϕ) and improver concentrations (Y_I). Increased improver in ethanol (Y_I) reduces the mole fraction of fuel to ignite. This means that adding improver will improve the ignition of fuel. Although bio-diesel can ignite at lower mole fraction compared with ethanol, it ignites at higher equivalence ratios due to its higher molecular weight.

The higher compression ratio enhances the ignition of fuel. Fuel can ignite at lower equivalence ratios due to higher pressure and temperature. Semenov's theory underestimates the startability of the engine by a factor of 2 to 4, as compared with the experiment results.

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