ABSTRACT: The cold start performance and ignition characteristics of coconut-oil methyl ester (CME) were investigated by using a diesel engine. Diesel fuel and CME were mixed and the blended ratio of CME was changed. The tests were conducted at full load and 3000 min⁻¹. Diesel engine could be run stably with any mixing ratio of CME, however the power was slightly reduced with increasing CME mixing ratio. In cold start condition, when the mixing ratio of CME increased, the combustion chamber wall temperature rose quickly and the ignition timing was advanced. Therefore, CME had superior compression ignition characteristics in the cold start.

KEY WORDS: (Standardized) heat engine, compression ignition engine, BDF (Free) Coconut-oil Methyl Ester [A1]

1. INTRODUCTION

The depletion of petroleum fuels and air pollution caused by diesel engines are very important problems to be solved, therefore many kinds of alternative fuel have been investigated in recent. The biomass fuels have been recently studied as one of the alternative fuels for diesel engines because the biomass fuels like vegetable oils are renewable, sustainable and the sulfur free clean fuels. The biomass fuels have the potential to reduce the carbon dioxide in atmosphere and reduce smoke and hydrocarbon emissions as compared with the diesel fuel. There are many kinds of bio-diesel fuel based on vegetable oils such as sunflower-seed, rape-seed, soybeans, etc. and the fatty acid methyl ester (FAME) made from vegetable oils is also used as the bio-diesel fuel. Those bio-diesel fuels have different properties caused by the contents. The bio-diesel fuels are already used as mixing with petroleum based diesel fuel. For examples of bio-diesel fuel applications, B2 (2 % bio-diesel is blended with 98 % diesel fuel) is widely available in Minnesota, U.S.A., B5 is used in France and B20 is recommended by U.S. Environmental Protection Agency and the National Biodiesel Board, U.S.A. for use under the Automotive Motor Fuels Act 1988.

This study takes notice of coconut-oil methyl ester (CME). The CME is a biomass fuel and it is the fatty acid methyl ester that is made from coconut oil and methanol. The CME has following characteristics as the fuel for diesel engines. The viscosity and the cloud point of CME are lower than those of crude coconut oil, CME can be mixed with petroleum based diesel fuel in any mixing ratios, the diesel engine of this experimental setup can be operated by the neat CME and CME blended commercial diesel fuel for the short term usage, and the coconut oil contains a lot of short chain fatty acids compared with other biomass fuels so that the CME is hard to solidify at the normal temperature and is easy to evaporate in the cold start condition of diesel engine.

The performance of CME and diesel fuel blends was experimentally explored and the mixing ratio of CME was varied. In the previous study, it was confirmed that CME had a good ignitability, so that the improvement of the ignition characteristic of diesel engine with CME was attempted. The ignition characteristics were tested by the cold start test, and an influence

![Fig. 1 Configuration of test equipment.](image-url)
of CME on engine performance was tested by the ordinary engine performance test. For the comparative reason, both engine performance test and cold start test were conducted by using other two kinds of fatty acid methyl ester made from tallow (beef suet) and soybean, and both ignitability and engine performance were compared among three neat fatty acid methyl esters.

2. EXPERIMENTAL CONDITIONS

2.1 Experimental Apparatus

Fig. 1 shows the configuration of the test equipment and table 1 indicates specifications of test engine. The test engine was a four-stroke, single-cylinder, direct fuel injection, diesel engine. The cooling system was forced-air cooling and the displacement volume was 211 cm³. The compression ratio was about 19.9:1, when the measurement equipments were attached. The fuel injection timing was fixed and was always 14±1 deg. BTDC and fuel injection pressure was 20 MPa. The electric motor was horizontally connected to the engine to start the engine and to test the motoring condition. When the engine drove itself, the electric motor was acting as the dynamometer and absorbed the output power generated by the engine, and the electric power was transmitted to the electric inverter to control the engine revolution.

Fig. 2 shows the cross sectional view of re-entrant type combustion chamber and measurement points of cylinder pressure and mean combustion chamber wall temperature. The cylinder pressure was measured with a crystal pressure transducer. To detect the mean combustion chamber wall temperature, a K-type thermocouple with 1.0 mm of diameter was installed at the vicinity of the center of combustion chamber. The mean combustion chamber wall temperature in this study means the time average temperature at a certain point of combustion chamber wall and presents the cooling condition of air-cooled diesel engine. The exhaust gas temperature was measured by a K-type thermocouple with 1.0 mm of diameter and was measured in the center of exhaust pipe at a point adjacent to the exhaust manifold. The exhaust gas emissions; hydrocarbon, carbon monoxide and smoke concentrations were measured. All measurement equipments were connected to the data collection unit, so that data were collected and recorded continuously, automatically and simultaneously by the personal computer, therefore this system enabled to measure the transient response in the cold start test.

2.2 Test Fuels

The diesel fuel and CME were used for tests and CME was blended to diesel fuel in several mixing ratios. The diesel fuel used was JIS No. 2 grade and the mixing ratio of CME to diesel fuel in the blended fuel was changed as 0, 5, 10, 25, 50, 75 and 100 wt.%. Here, the mixing ratio of 0 wt.% means the pure diesel fuel and 100 wt.% means the neat CME.

Table 2 indicates fuel properties of diesel fuel and CME. The kinetic viscosity, specific gravity and the cold filter plugging point of CME were almost equal to those of diesel fuel, however the lower heating value of CME was about 89 % of diesel fuel. The CME contained a lot of oxygen atoms and included no sulfur.

Table 3 shows the elemental analysis results and lower heating value of three tested bio-fuels, tallow methyl ester (TME), soybean methyl ester (SME) and CME. The amount of oxygen atom contained in CME is largest among three fuels because the CME contains a lot of short chain fatty acid methyl esters. The

![Fig. 2 Cross sectional view of the combustion chamber and measurement points.](image-url)
lower heating values of three fatty acid methyl esters are almost equal to each other.

2.3 Test Procedures

Two kinds of experiment were conducted, and all tests were made under constant engine speed of 3000 min⁻¹ and the fuel injection volume was always at the full load fuel injection pump setting, 0.8 mm³/cycle. Two kinds of experiment were the performance test and the cold start test. An influence of CME on engine performance was examined by the performance test and an influence of CME on the ignition characteristics were examined by the cold start test.

In the performance test, the engine performance data; brake output power, fuel consumption and the exhaust gas emissions (smoke, hydrocarbon and carbon monoxide concentrations) were taken when the mean combustion chamber wall temperature became a steady state. The exhaust gas and lubrication oil temperatures were also measured.

In the test procedure of cold start test, the initial lubrication oil and mean combustion chamber wall temperatures were kept at 313 K or less. At first, the test engine was driven by the electrical motor until the engine revolution reached 3000 min⁻¹. At the moment, the mean combustion chamber wall temperature always reached about 523 K. Then, the fuel was started to inject at the full load setting and the engine firing operation began. The experimental term was started at the fuel injection commencement and was finished when the engine operating conditions was stabilized. To examine the influence of mixing ratio of CME in blended fuel on the ignition characteristics of the cold engine condition, the mean combustion chamber wall temperature, the exhaust gas temperature and indicator diagrams were continuously measured. These data were collected from the beginning of test until the mean combustion chamber wall temperature and exhaust gas temperature showed almost the steady values.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Results of the Performance Test

As the results of the performance test, engine output, temperatures and exhaust gas emissions are analyzed. The brake mean effective pressure and brake thermal efficiency are shown as a function of mixing ratio of CME in the blended fuel in fig. 3 and as a function of the energy content of supplied fuels in fig. 4. The brake mean effective pressure decreases as the mixing ratio of CME increases because the lower heating value of CME is about 89 % compared with that of diesel fuel. The brake thermal efficiency is slightly decreased as the mixing ratio of CME increases, however the brake thermal efficiency is not so affected by the mixing ratio of CME. This is because the ignition timing is slightly advanced by an increase of mixing ratio of CME.

![Fig. 3 Brake mean effective pressure and brake thermal efficiency as a function of mixing ratio of CME.](image3)

![Fig. 4 Brake mean effective pressure and brake thermal efficiency as a function of energy content of fuels.](image4)

![Fig. 5 Mean combustion chamber wall temperature and exhaust gas temperature as a function of mixing ratio of CME.](image5)

![Fig. 6 Smoke, hydrocarbon and carbon monoxide concentrations in exhaust gas as a function of mixing ratio of CME.](image6)
improvement of ignitability makes the thermal efficiency increase. The brake mean effective pressure and the brake thermal efficiency increase with the increasing the energy content of supplied fuels. This phenomenon is as same as that of the normal operating condition.

Fig. 5 shows mean combustion chamber wall temperature and exhaust gas temperature as a function of mixing ratio of CME in the blended fuel. The mean combustion chamber wall temperature is almost independent of the mixing ratio of CME, however the exhaust gas temperature decreases as the mixing ratio of CME increases. This is because the engine is forcibly cooled by the cooling air, so that the cylinder head is maintained at almost constant temperature. The exhaust gas temperature is reduced by the decrease of provided energy in the blended fuel.

Fig. 6 shows exhaust gas emissions (smoke, hydrocarbon and carbon monoxide concentrations) as a function of mixing ratio of CME in the blended fuel. The smoke, hydrocarbon and carbon monoxide concentrations decrease as the mixing ratio of CME increases. Especially, the smoke concentration is linearly decreases as the mixed CME increases. The smoke concentration and carbon monoxide concentration of neat CME are about 1/3 and hydrocarbon concentration of neat CME is about 1/2 as compared with those of diesel fuel. The reason why those exhaust gas emissions remarkably decrease is the oxygen atoms included in CME as show in table 3, therefore, the CME is very effective for the improvement of the exhaust gas emissions of diesel engines.

Table 4 shows the experimental results of engine performance test of three neat fatty acid methyl esters. The brake mean effective pressures are almost equal for three test fuels, however the brake mean effective pressure of CME is slightly low compared with other fuels. The mean combustion chamber wall temperature of CME is highest among three test fuels. The hydrocarbon emissions are almost equal among three test fuels, however the carbon monoxide and smoke concentrations of CME are remarkably lower than those of other fuels. This is because the amount of oxygen atom contained in CME is largest in three fuels as shown in table 3.

Therefore, it is confirmed that the diesel engine can be run stably with any mixing ratio of CME, and the CME can be used as the alternative fuel for diesel engines. The exhaust gas emission of CME is better than those of TME and SME. The CME has no negative influence on engine performance and reduces exhaust gas emissions.

3.2 Results of the Cold Start Test

As an influence of CME on the mean combustion chamber wall temperature and the exhaust gas temperature under the cold start condition, fig. 7 shows the mean combustion chamber wall temperature and exhaust gas temperature as a function of time after the commencement of fuel injection and fig. 8 shows the time constant of mean combustion chamber wall temperature and exhaust gas temperature rises as a function of mixing ratio of CME in the blended fuel. The time constant of mean combustion chamber wall temperature rise is 63.2 % of the time at which the mean combustion chamber wall temperature reaches the stabilized value for each mixing ratio of CME. The mean combustion chamber wall temperature increases and time constant of temperature rise decreases with increasing the mixing ratio of CME. When the CME is mixed with the diesel fuel, the mean

| Table 4 Engine performance |
|----------------------------|
| Pme MPa | TCE K | TEO K | EHC ppm | ECM % | ECO % | Ei % |
| TME | 0.66 | 856.0 | 822.8 | 21.7 | 0.24 | 38.0 |
| SME | 0.69 | 863.8 | 843.7 | 21.7 | 0.32 | 43.0 |
| CME | 0.62 | 873.2 | 789.0 | 25.0 | 0.10 | 18.3 |

Pme: Brake mean effective pressure
TCE: Mean combustion chamber wall temperature
TEO: Exhaust gas temperature
EHC: Hydrocarbon concentration
ECM: Carbon monoxide concentration
Ei: Smoke concentration

Fig. 7 Mean combustion chamber wall temperature and exhaust gas temperature as a function of time.

Fig. 8 Time constant of temperature-rise of mean combustion chamber wall temperature and exhaust gas temperature.
combustion chamber wall temperature rapidly reaches the steady condition even though the engine is in the cold condition. Therefore, the injected fuel is quickly vaporized and the cold start characteristic is improved by the mixing of CME. The exhaust gas temperature decreases with increasing the mixing ratio of CME at an arbitrary time because the energy content in supplied fuel is reduced. The time constant of exhaust gas temperature rise increases with increasing the mixing ratio of CME because of the slow exhaust gas temperature rising.

The combustion and ignition characteristics are analyzed from cylinder pressure records. Fig. 9 shows indicator diagrams obtained in the cold start test for several mixing ratios of CME in the blended fuel. The upper figure is measured at the immediately after the fuel injection commencement at which the mean combustion chamber wall temperature is about 523 K. The lower figure is measured at 773 K of mean combustion chamber wall temperature when the engine is running in the almost steady condition. The ignition is shifted to the early crank angle as the mixing ratio of CME in the blended fuel increases for both mean combustion chamber wall temperatures. In particular, the ignition timing is remarkably improved in the case of mean combustion chamber wall temperature at 523 K, however the ignitability improvement effect of CME disappears as the engine is warmed up. Therefore, the ignition characteristic in cold start is improved by the CME and the CME has a good ignition characteristic, because the coconut-oil mainly consists of the short chain saturated fatty acid such as lauric, myristic and palmitic\textsuperscript{(13)} Therefore, the cold start performance of diesel engines is remarkably improved by the mixing of CME.

The cylinder pressure and crank angle at ignition are analyzed from indicator diagrams and fig. 10 shows analyzed results as a function of mean combustion chamber wall temperature. In the upper figure, the cylinder pressure at ignition increases as the mean combustion chamber wall temperature increases because, as shown in lower figure, the ignition timing becomes early and approaches to the top dead center. The injected fuel is easily evaporated and ignited by the high temperature air in the combustion chamber, therefore, an increase of combustion chamber wall temperature is good for the improvement of ignition. The cylinder pressure at ignition increases and the crank angle at ignition is shifted to the early crank angle with increasing the mixing ratio of CME. Especially, when the mean combustion chamber wall temperature is still low condition, at 523 K, the crank angle at ignition of neat CME is 3 deg. earlier than that of pure diesel fuel. This is because CME mainly consists of relatively short carbon chain fatty acid methyl esters that have relatively low boiling points. Therefore, evaporation is enhanced for the mixing ratio of CME 75 wt.% and neat CME, and the ignition timing is hardly affected by the mean combustion chamber wall temperature. The ignition point of CME is lower than that of the diesel fuel, so that the ignition characteristics are improved by CME. Therefore, the mixing of CME to diesel fuel is very suitable to improve the ignitability and the CME can avoid the diesel knock in the cold start condition.

The maximum combustion pressure and the crank angle at maximum combustion pressure are analyzed from indicator diagrams and fig. 11 shows results as a function of mean combustion chamber wall temperature. The maximum combustion pressure increases and the crank angle at maximum combustion pressure is shifted to the early crank angle as the mean combustion chamber wall temperature increases. As the mixing ratio of CME increases, the crank angle at maximum combustion pressure is always shifted to the early crank angle at any mean combustion chamber wall temperature. The maximum combustion pressure increases as the mixing ratio of CME increases when the mean combustion chamber wall temperature is up to about 773 K. It is assured that the ignition timing becomes early by the mixing of CME to diesel fuel and the diffusion

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**Fig. 10** Cylinder pressure at ignition and crank angle at ignition as a function of mean combustion chamber wall temperature.

**Fig. 9** Indicator diagrams at mean combustion chamber wall temperature of 523 K and 773 K.
combustion is improved. In the case of neat CME, the maximum combustion pressure at low mean combustion chamber wall temperature shows very high value in spite of the low content energy in fuel and the maximum combustion pressure is hardly influenced by the mean combustion chamber wall temperature. When the mean combustion chamber wall temperature is at about 873 K, however, the maximum combustion pressure decreases as the mixing ratio of CME increases although the crank angle at ignition is still slightly improved. This is because the energy in supplied fuel is reduced due to the lower heating value of CME.

Fig. 12 shows the indicator diagrams obtained in the cold start test for three kinds of neat fatty acid methyl ester: TME, SME and CME. The upper and lower figures show indicator diagrams measured at the mean combustion chamber wall temperature of 523 and 773 K, respectively. In upper figure, for the cold start condition, the ignition timings of both CME and TME are earlier than those of SME and diesel fuel, because the TME also includes a lot of short chain saturated fatty acid methyl ester(3), therefore both CME and TME have a superior ignitability compared with SME. However, the ignition improvement effect is not observed when the engine has been warmed up. Therefore, the CME is an excellent biomass fuel for diesel engines because the CME has superior ignitability in the cold condition and reduces exhaust gas emissions.

4. CONCLUSIONS

(1) The brake mean effective pressure decreases as the mixing ratio of CME increases because the lower heating value of CME is about 89 % of diesel fuel. However, the brake thermal efficiency is hardly affected by the mixing ratio of CME in the diesel fuel and CME blends.

(2) The smoke, hydrocarbon and carbon monoxide concentrations decrease as the mixing ratio of CME increases in blended fuel. The CME is effective to reduce smoke, hydrocarbon and carbon monoxide emissions because CME includes a lot of oxygen atoms.

(3) The cylinder pressure at ignition increases and the crank angle at ignition is shifted to the early crank angle with increasing the mixing ratio of CME in the blended fuel when the engine is in the cold condition. However, the ignition improvement effect gradually disappears as the engine is warmed up.

(4) The maximum combustion pressure increases as the mixing ratio of CME in the blended fuel increases and the diffusion combustion is improved. When the engine is in the steady condition, the maximum combustion pressure decreases as the mixing ratio of CME increases because of the reduction of energy in provided fuel.

(5) The CME has the superior compression ignition characteristics and reduces exhaust gas emissions and the diesel engine can be run stably with any mixing ratio of CME to diesel fuel, therefore the CME is good alternative fuel for diesel engines.

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