

Application of Cellulosic Liquefaction Fuel (CLF) and Fatty Acid Methyl Ester (FAME) Blends for Diesel Engine

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ABSTRACT

A new bio-fuel i.e. the cellulosic liquefaction fuel (CLF) was developed for diesel engines. The cellulosic liquefaction fuel (CLF) was made from woods by the direct liquefaction process. CLF could not be completely mixed with diesel fuel, however CLF could be mixed with Fatty Acid Methyl Ester (FAME) and a diesel engine could be operated by CLF and FAME blends. In this study, CLF was divided into three fractions: 473 to 523 K (CLF1), 523 to 573 K (CLF2) and 573 K or more (CLF3) by fractional distillation in order to find CLF fraction which was suitable for diesel engine, and coconuts oil methyl ester (CME) was used as FAME. In the fuel droplet combustion tests, the combustion durations of CLFs were longer than those of diesel fuel and CME, and the combustion duration increased as the distillation temperature range rose, because CLF contained a lot of flame-resisting components like aromatic compounds. Each CLF fraction was mixed with CME to provide engine and tested weight mixing ratios of CLF in CME-CLF blends were 0, 5, 10 and 15 wt.%. All test fuels could be used for diesel engine, when the mixing ratio of CLF was up to 15 wt.%. The thermal efficiency of CLF1-CME blends is slightly higher than those of CLF2 and CLF3. Exhaust gas emissions increased as the mixing ratio of CLF increased because the ignitability of CLF was inferior. In the cold start test, crank angle at ignition delayed as the mixing ratio of CLF increased, however the ignition delay was improved as engine was warmed up. The crank angle at ignition became late in the order of CLF1, CLF2 and CLF3-CME blends, so that CLF1-CME blends showed good ignitability compared with other CLFs. Therefore, a low temperature distillation fraction of CLF is suitable for diesel engines.

INTRODUCTION

The depletion of petroleum fuels and air pollution emitted from diesel engines are very important problems and the green house effects caused by the carbon dioxide emission should be also solved. These are the matters to be settled at present, therefore many kinds of alternative fuel have been investigated and developed. The biomass fuels have been studied as one of attractive alternative fuels because the biomass such as wood and/or plants decrease the carbon dioxide from atmosphere and are renewable and sustainable energy source.⁽¹⁾⁽²⁾ Fatty acid methyl esters (FAME) which were made from plant oils and methanol have been already used as an alternative fuel for diesel engines. There are many kinds of FAMES based on vegetable oils, however most of vegetable oils are edible so that they should not be used for fuels of engines. The other hand, a lot of wood biomass is discharged as building scraps or wastes. A lot of lumber has been scraped, however very few investigations have been carried out to change these wood biomasses to the industrially available energy.⁽³⁾ In this study, an innovative conversion technology of cellulosic biomass to liquid fuel has been developed and a new bio-fuel i.e. the cellulosic liquefaction fuel (for short CLF) was produced.⁽⁴⁾ CLF is made from cellulose, hemi-cellulose and lignin contained in wood by the direct liquefaction process. Therefore, CLF is completely different from established bio-fuels such as FAMES. In the direct liquefaction process, the wood was crushed to small pieces and crushed wood was blended with the liquid solvent which was a distillate wood tar. The mixture of crushed wood and solvent was maintained at around 573 K for about 30 minuets, then woods were dissolved into the liquid, so that the CLF is liquefied wood itself

In this study, CLF was divided into three fractions: 473 to 523 K (CLF1), 523 to 573 K (CLF2) and 573 K or more (CLF3) by the fractional distillation and the purpose of this



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study is to elucidate distilled CLF fraction which was suitable for diesel engine combustion. To obtain the fundamental three CLF fraction properties, GC/MS (Gas Chromatograph/ Mass Spectrometry) analysis and the fuel droplet combustion test were carried out. For the feasibility of CLF applying as fuel for diesel engines, the ignition characteristics and performance of CLF were also experimentally clarified. An influence of three CLF fractions on engine performance was tested by the ordinary engine performance test using a four-stroke, direct fuel injection small diesel engine and the ignition characteristics of three CLF fractions were tested by the cold start and transient performance test.

When the neat CLF was supplied to diesel engine, the compression ignition did not occur, so that the neat CLF can not be used as a fuel for diesel engines. However the CLF could be burned by the appropriate ignition source such as a flame torch. CLF can not be completely mixed with normal diesel fuel at room temperature. Yamane et al. studied the wood-derived pyrolysis tar oil (WPO) for the alternative diesel fuel and WPO could be completely mixed with FAME.⁽³⁾ CLF in our study may have the similar features as WPO and it was found that CLF also could be mixed with FAME in any mixing ratios. In our previous study⁽²⁾, it was found that the coconuts oil methyl ester (CME) had good ignitability and it was expected that the ignitability of CLF was inferior, so that CME was chosen as FAME to mix with CLF. Therefore, to test CLF combustion characteristics by using actual diesel engine, each CLF fraction (CLF1, CLF2 and CLF3) was mixed with CME and the CLF-CME blends were used as test fuels. The weight mixing ratio of CLF in CLF-CME blends was varied for 0 to 15 wt.% in order to clarify the CLF combustion characteristics.

TEST FUEL PROPERTIES

Table 1 shows the GC/MS results and main ingredients of each CLF are also shown. These ingredients were estimated from molecular weight that was analyzed from result of GC/MS. CLF1 mainly includes guaiacols such as guaiacol, p-methylguaiacol and p-ethylguaiacol. CLF2 includes guaiacol and/or phenol such as p-methylguaiacol, p-ethylguaiacol and 2-methoxy-4-propyl-phenol. CLF3 which has a high and wide distillate temperature includes 2-furylmethanol, p-ethylguaiacol, 2-methoxy-4-propyl-phenol. As the distillation temperature of CLF increases, heavy molecule weight ingredients which have long retention time appear in each GC · MS result. However some ingredients such as guaiacol are commonly included in plural CLFs. This is because a large amount of guaiacol is included in CLF, so that it takes long period to evaporate guaiacol. All CLFs mainly consists of aromatic compounds i.e. guaiacol and phenol that are originated in cellulose and lignin. These aromatic compounds have steady molecular structure so that the ignition characteristic of CLF is inferior compared with that of diesel fuel and CME. Especially, the boiling point of CLF3 is higher than 573 K so that CLF3 hardly evaporates in combustion chamber of diesel engine and

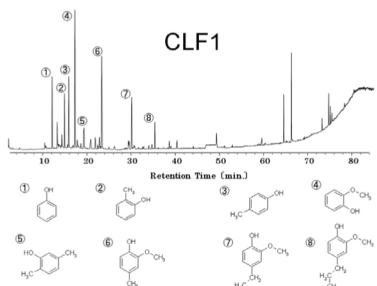
the ignitability of CLF3 may be much worse than CLF1 and CLF2.

Table 2 indicates the fuel specifications of diesel fuel, CME and three CLF fractions. The density of each CLF is slightly increased as the distillation temperature range increases because ingredients which have high boiling temperature and heavy weight are increased in CLF. However the density difference between CLF1 and CLF3 is only 3.3 % (densities of CLF1 and CLF3 are 1056 and 1091 kg/m³, respectively), so that three CLF fractions have almost the same density. As shown in table 2, other fuel specifications: calorific value and elements (carbon, hydrogen and oxygen atoms) of CLFs are similar to each other. Although the distillation temperature range is differed, no apparent property difference among three kinds of distillate CLF are shown. Therefore, it seems that three CLFs have almost the same physical properties. All CLFs contain a lot of oxygen atoms and mass fraction of oxygen is about 25 wt.%. This contained oxygen is much higher than that of FAME (for example 15 wt.% for CME). Therefore, it can be considered that CLF is effective to reduce soot and PM emission because of an oxygenated fuel. The mass fraction of hydrogen in CLF is smaller than those of diesel fuel and CME, and is about 8 wt.%. Therefore, H/C ratio of CLF is small than diesel fuel and CME, so that large amount of CO₂ will be emitted as compared with fossil fuel and FAME, when the same energy is provided. The calorific value of all CLFs is very low and is about 66 % of diesel fuel. The energy included in CLF is similar to coal because both coal and CLF are made from woods. Density of all CLFs is about 1.3 times larger than that of diesel fuel. These large density and low contained energy of CLF is caused by a large amount of oxygen atom included in CLF.

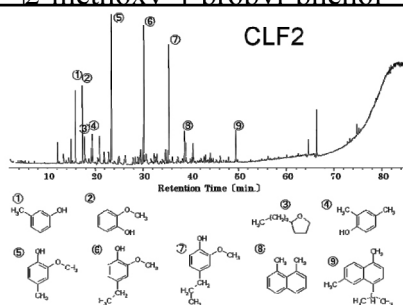
Figure 1 shows the fuel droplet combustion test results. In figure 1, the non-dimensional fuel droplet area is indicated as a function of the corrected time for neat three CLF fractions, diesel fuel and CME. The non-dimensional fuel droplet area was defined here as the ratio of fuel droplet projected area to initial fuel droplet projected area, and the corrected time was the time normalized by the initial fuel droplet projected area. In the fuel droplet combustion tests, fuel droplet with 1.0 mm of diameter was suspended by the silicon carbide fiber of diameter 15 µm and fuel was ignited by the heated nichrom wire. The droplet combustion processes were visualized with a shadowgraph method and images were taken by a digital high-speed camera (125 frames/s and shutter speed of 1/1000 s). The images were analyzed with an image processing system to obtain the fuel droplet projected area.

For all test fuels, the non-dimensional fuel droplet area gradually decreases as the time elapses due to combustion. All CLF can be completely burned until it burns itself out by the diffusion combustion. For all CLF fractions, the non-dimensional fuel droplet area decreases with fluctuating as compared with those of diesel fuel and CME. Especially, in the

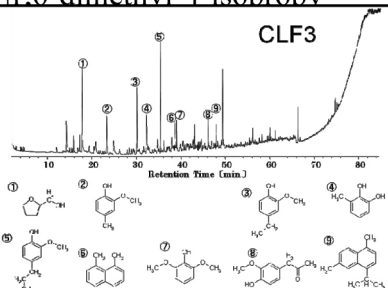
Table 1. Main ingredients of three CLF fractions



1	Phenol
2	o-cresol
3	p-cresol
4	Guaiacol
5	2,5-xvlenol
6	p-methylguaiacol
7	p-ethylguaiacol
8	2-methoxy-4-propyl-phenol



1	m-cresol
2	Guaiacol
3	2-n-butylfuran
4	2,4-xvlenol
5	p-methylguaiacol
6	p-ethylguaiacol
7	2-methoxy-4-propyl-phenol
8	1,8-dimethyl-naphthalene
9	1,6-dimethyl-4-isopropyl



1	2-furylmethanol
2	p-methylguaiacol
3	p-ethylguaiacol
4	6-methyl-catechol
5	2-methoxy-4-propyl-phenol
6	1,8-dimethyl-naphthalene
7	2,6-dimethoxyphenol
8	4-(2-oxo)-propylguaiacol
9	1,6-dimethyl-4-isopropyl

case of CLF3, the non-dimensional fuel droplet area steeply increases and then decreases at the corrected time about 0.5 s/mm². It seemed that the micro explosion occurred because CLF of high distillation temperature, CLF3, had a wide distillation range and included incombustibility components. The combustion duration of each CLF is slightly longer than those of diesel fuel and CME, however, combustion durations of CLF droplets are not so differ from that of diesel fuel. The combustion duration becomes slightly long in the order of CLF1, CLF2 and CLF3, because the distillation temperature range increases. For CLF1 and CLF2, almost the same tendency is shown in figure, however the combustion duration of CLF1 is shorter than that of CLF2 because the CLF1 which has low distillation temperature range is easy to evaporate. Therefore, the combustion duration of CLF slightly increases as the distillation temperature rises and the CLF of low distillation temperature range, i.e. CLF1, is most suitable for diffusion combustion because CLF1 has low boiling point and short combustion duration.

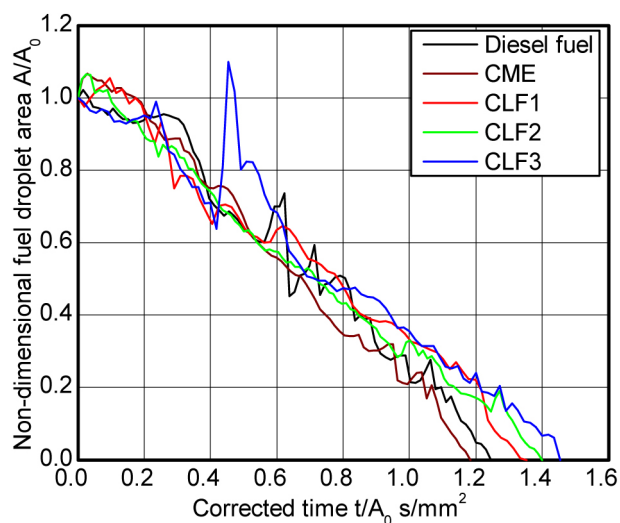


Fig. 1. Relationship between non-dimensional fuel droplet area and the corrected time

EXPERIMENTAL APPARATUS AND TEST PROCEDURE

TEST FUELS

Figure 2 shows the mixing condition of CLFs to CME or diesel fuel. In the mixing test, each CLF fraction is mixed with diesel fuel or CME in equal quantities 10 cm³ at room temperature. CLF-diesel fuel blends are in left bottles and CLF-CME blends are in right bottles in photographs. In the case of CLF-diesel fuel blends, CLF and diesel fuel is once mixed by vigorously stirring, however CLF and diesel fuel are gradually separated as the time elapses. CLF sinks to the bottom of the bottle and diesel fuel occupies the upper part of bottle because density of CLF is heavier than that of diesel fuel. Therefore, CLF in any