Influence of Combustion Design for Waste Plastic Decomposition Oil
(An Attempt to Use Waste Plastic Decomposition Oil in DDF Engine)

Kenichi ENDOH*[1], Katsuhiko TAKEDA*[2] and Keiichiro SANO*[3]

*1 Graduate School of Engineering, Kanto Gakuin University
1-50-1 Mutsuura-higashi, Kanazawa-ku, Yokohama 236-8501, JAPAN
m1141004@kanto-gakuin.ac.jp

*2 Division of Mechanical Engineering, Department of Science and Engineering,
College of Science and Engineering, Kanto Gakuin University
1-50-1 Mutsuura-higashi, Kanazawa-ku, Yokohama 236-8501, JAPAN
takeda@kanto-gakuin.ac.jp

*3 College of Human and Environmental Studies, Kanto Gakuin University
1-50-1 Mutsuura-higashi, Kanazawa-ku, Yokohama 236-8501, JAPAN
keisano@kanto-gakuin.ac.jp

Abstract

A feasibility study was conducted on improving combustion and exhaust emission of waste plastic decomposition oil (WPDO) by applying diesel dual fuel (DDF) engine from combustion design perspective. In Japan, about 10 million tons plastic is discarded every year, and it is increasing. Since the energy efficiency of material recycling is not high, thermal recycling is recommended in Japan. However, incineration power plant needs more energy and transportation costs. On the other hand, the Japanese packaging company began to pilot use WPDO in their factory because it has possibility of high efficiency. However, they use WPDO mixing with heavy oil 50%. Mixing with heavy oil causes much exhaust emission, especially carbon dioxide (CO_2) emission. In addition, natural gas is expected to reduce the amount of CO_2 emission. Moreover, it is expected from the advantage of large supply quantity at low cost by the Shale gas. Furthermore, DDF engine which using a Diesel cycle with natural gas attracts expectation for high efficiency natural gas engine, it is anticipated as an engine that can improve the fuel consumption of the natural gas engine. Therefore, the CO_2 emission can reduce by using DDF engine. Consequently, the experimental study was conducted on applying WPDO to DDF engine. The test engine was produced by improving conventional diesel engine. A gas mixer was set on the intake pipe in order to charge natural gas. This engine can suck mixture of air and natural gas. Then this mixture is ignited by the fuel injection after compression. WPDO is used this fuel injection. DDF combustion using WPDO is investigate that it can get the stable operation. Moreover, particulate matter (PM) can get significant reduction. In addition, it can be confirmed that CO_2 and nitrogen oxides (NOx) are reduced.

Keywords: waste plastic decomposition oil, diesel dual fuel engine, cetane number, natural gas, CO_2

1 Introduction

Plastic is used many products around the world, then it is necessary for current life. About 10 million tons plastic is discarded every year in Japan, and it is continue to increase. Thermal recycling of the waste plastic is recommended in Japan, since the energy efficiency of material recycling is not high. However, thermal recycling with incineration power plant needs more energy and transportation costs. On the other hand, using waste plastic decomposition oil (WPDO) to the diesel engine generator in the factory discarding the plastic has possibility of high efficiency. Therfore, the Japanese packaging company began to pilot use WPDO in their factory. However, they use WPDO mixing with heavy oil 50%. Mixing with heavy oil causes much exhaust emission, especially carbon dioxide (CO_2) emission.

The natural gas is anticipated to reduce the amount of CO_2 emission. Furthermore, it is expected from the advantage of large supply quantity at low cost by the Shale gas [1]. Moreover, diesel dual fuel (DDF) engine which using a Diesel cycle with natural gas attracts expectation for high efficiency natural gas engine [2]. DDF engine sucks mixture of air and natural gas. Then this mixture is ignited by the fuel injection after compression. Therefore, DDF engine can be operated with a Diesel cycle, and then it can make high efficiency. Consequently, DDF engine is anticipated as an engine that can improve the fuel consumption of the natural gas engine, and furthermore it can reduce CO_2 emission [3], [5]. Accordingly, the experimental study was conducted on applying WPDO to DDF engine. This study was made on improving combustion and exhaust emission of WPDO by applying DDF engine from combustion design perspective. This paper describes the influence of combustion design for waste plastic decomposition oil.

2 Properties of test fuels

In this study, the properties of test fuels were investigated before the engine performance test in order to confirm the characteristics of WPDO. Therefore, gas oil (JIS #2) was measured for the reference.

Figure 1 gives the measured density and kinematic viscosity of test fuels. Density was measured by the

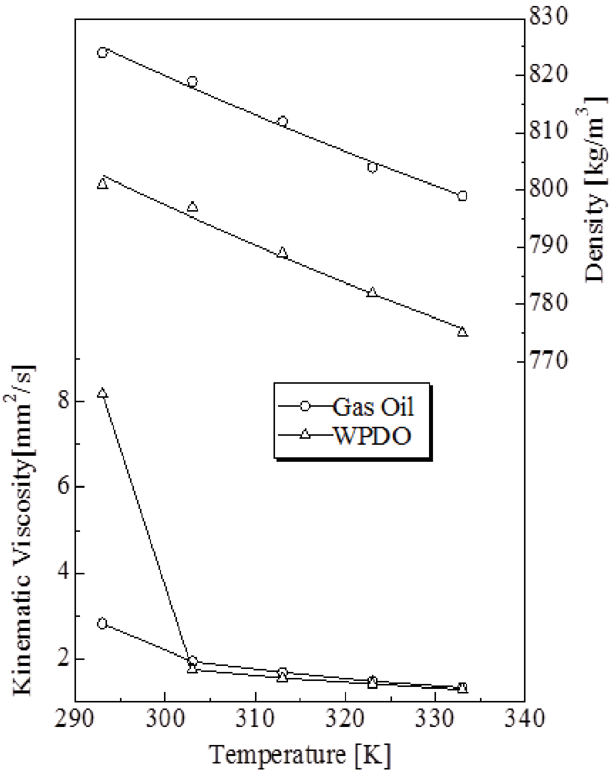

Fig. 1 Density and kinematic viscosity

Table 1 Properties of gas oil and WPDO

	Gas Oil (JIS #2)	WPDO
Density [kg/m^3(@303K)]	819	797
Kinematic Viscosity [mm^2/s(@303K)]	1.95	1.76
Pour Point [K]	265.5	267.5
Cetane Number	59	56
Lower Calorific Value [MJ/kg]	43.0	43.4

float test, and viscosity was measured by using the viscometer (A&D; VM-10A-L). In addition, **Table 1** shows difference of the properties comparing WPDO and gas oil.

From **Fig. 1**, it can be found that density of WPDO is lower than that of gas oil. The energy density is important for vehcle fuel, however WPDO is considered for generator fuel. Besides, the difference of density is not much, therefore it does not have to apprehend. From **Fig. 1**, although kinematic viscosity of WPDO is seen to be similar to that of gas oil from 303[K] to 333[K], there is difference at 293[K]. Kinematic viscosity of gas oil is 2.83[mm^2/s(@293K)], but WPDO is 8.17[mm^2/s(@293K)]. Therefore, it can be seen that WPDO has higher coefficient of viscosity than that of gas oil. Consequently, WPDO has to pay attention to fuel temperature unless at high atmosphere temperature. The higher kinematic viscosity make longer ignition delay, since fuel spray particle diameter is bigger. Moreover, from **Table 1** cetane number of WPDO is lower than that of gas oil. Therefore, ignition delay of WPDO will be longer than that of gas oil when WPDO is used under 300[K].

3 Engine performance test

3.1 Experimental apparatus and method

The engine performance test was carried out in order to declare the difference of diesel operation and DDF operation. **Figure 2** presents the engine performance test apparatus. The engine used in this study was produced by improving conventional water-cooled single cylinder direct injection diesel engine. A gas mixer was set on the intake pipe in order to charge natural gas. This engine can suck mixture of air and natural gas. Then this mixture is ignited by the fuel injection after compression. WPDO is used this fuel injection. The base engine specifications are shown in **Table 2**. Then, the experiment was performed under the following conditions:

The engine was set five step loads by the dynamometer. These loads were selected up to the continuous horse power of the test engine. DDF engine was conducted experiments with two operation patterns. The first one is an operation in which adjusting output by injected WPDO amount. It is named the DDF-WPDO boost. The second one is an operation in which adjusting output by charge natural gas amount. It is named the DDF-NG boost. Both of DDF operation and diesel operation have same drive conditions such as same fuel injection timing or same fuel injection pressure. There is only difference on the suction air which contains the natural gas and air mixture or only air.

The pressure and temperature also the amount of intake air, cylinder pressure and crank angle, exhaust gas temperature, they were measured and recorded with the data logger. Exhaust gas was sampled directly from the exhaust pipe in order to measure the particulate matter (PM) precisely by the opacity meter (HORIBA; MEXA-600SW). Also, exhaust emissions such as carbon monoxide (CO), CO_2, total hydro carbon (THC) and nitrogen oxides (NOx) were precisely measured from directly sampled exhaust gas by using the exhaust

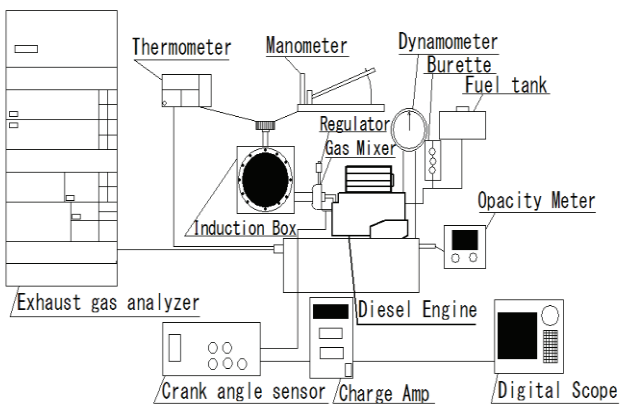

Fig. 2 Experimental apparatus

Table 2 Engine specifications

Model	NF19-SK
Bore×Stroke[mm]	110×106 [mm]
Displacement Volume	1007 [cc]
Compression ratio	16.3
Maximum Output	14 [kW]@2400rpm
Rated Output [kW/rpm]	12[kW]@2200rpm
Fuel injection time	BTDC17.5° [deg]
Fuel Pump	Plunger type
Combustion Chamber	Direct Injection

gas analyzer (HORIBA; MEXA-9100D). In addition, engine performance such as brake specific fuel consumption (BSFC) was investigated. The all of measurements was precisely measured at each five loads while the steady state condition at 1800 rpm. Finally, combustion of each fuels were analyzed from recorded cylinder pressure and crank angle.

3.2 Results and discussions

The cylinder pressure and heat release rate at the highest load are shown in **Fig. 3**. Crank angle is set on the vertical axes and cylinder pressure and heat release rate are on the horizontal axes in this figure. **Figure 4** gives the engine performance test results of each fuel. Exhaust emissions and BSFC are on the vertical axes and the shaft horse power is set on the horizontal axes in this figure.

From **Fig. 3**, it can be found that ignition delay of WPDO is longer than that of gas oil. This cause is from higher kinematic viscosity because the atmosphere temperature was under 300[K], as mentioned above. From **Fig. 3**, it can be seen that ignition timing of both DDF operation is dependent on that of WPDO. Also, it can be seen that heat release rate of both DDF operation is confirmed to be higher than that of diesel operation. Therfore, it can be said that DDF operation ignites by injected WPDO and natural gas mixture is burned with premixed combustion, because DDF can get same ignition timing with WPDO and DDF can get higher heat release rate. In addition, it can be said that main combustion of DDF operation is premixed combustion from natural gas.

From **Fig. 4**, it can be seen that NOx emission of both DDF operation is confirmed to be increased higher than that of diesel operation only at high load. Also, it can be found that DDF-NG boost is slightly lower than DDF-WPDO boost. This can be considered that higher premixed combustion from WPDO self causes higher combustion temperature at high load, since injection amount is much at high load. Therefore, DDF-NG boost is slightly lower since injection amount is less than DDF-WPDO boost. Conversely, NOx of both DDF operation is lower than that of gas oil at low and middle load. This can be consider that DDF operation can get

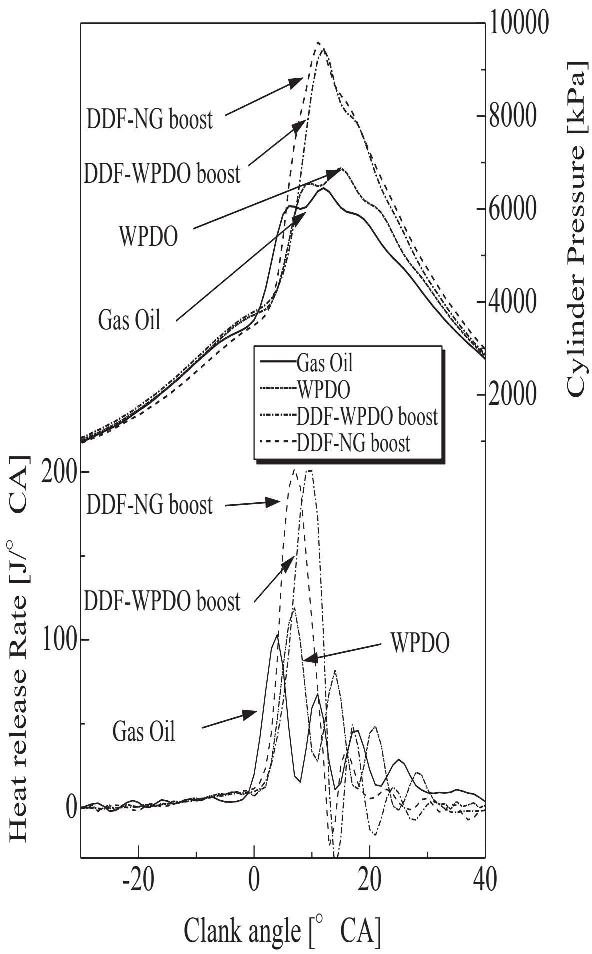

Fig. 3 Cylinder pressure and heat release rate at the highest load

homogeneous premixtre gas, since main combustion of DDF operation is premixed combustion from natural gas, besides amount of injected liquid fuel is little at low and middle load. Therefore, NOx emission is reduced lower than that of gas oil.

THC and CO emission of both DDF operation are confirmed to be increased higher than that of WPDO at low load. Ignitability is deteriorated by WPDO because it has low cetane number and high kinematic viscosity. In addition, intake air is reduced since natural gas is the gas fuel having large volume. Then amount of oxygen in the air-fuel mixture is reduced, and then THC and CO are increased because of incomplete combustion. However, most of the THC is a low-grade hydrocarbon such as methane. Therefore, it can be reduced lightly by the oxidation catalyst.

PM emission of both DDF operate are comfirmed to be reduced significantly lower than that of WPDO. It is considered that diffusion combustion pireod is shortened by the prolonged premixed combustion because DDF combustion has two-stage premixed combustion from natural gas and liquid fuel [6]. Moreover, the carbon content of natural gas is little and natural gas is difficult to make PM. Therefore, PM is reduced drastically by DDF combustion.

CO_2 emission of both DDF operation are confirmed to be reduced lower than that of diesel operation.

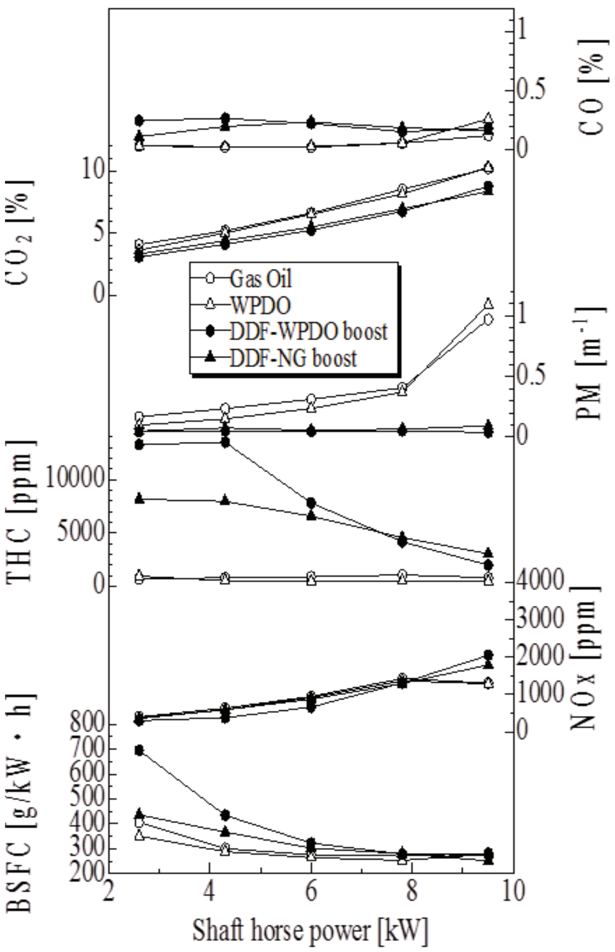

Fig. 4 Engine performance test results

In adittion, it can be found that CO_2 emission of DDF-NG boost is slightly lower than that of DDF-WPDO boost. This cause can be considered that the main component of natural gas is methane which has small C/H ratio [7]. Therefore, CO_2 emission of DDF-NG boost is slightly lower than that of DDF-WPDO boost, since DDF-NG boost burned much natural gas. Consequently, CO_2 emission can be reduced significantly by DDF combustion especially DDF-NG boost.

BSFC of both DDF operation are worse than that of diesel operation at low load. This can be considered that unburned natural gas makes worse BSFC, since the amount of injected WPDO is little at low load. However, it can be seen that BSFC of both DDF is very close to gas oil at high load. In addition, DDF-NG boost can improve BSFC. WPDO is considerd for the generator fuel, and the generator can drive one point load. Moreover, CO_2 emission is reduced as mentioned above. Therefore, BSFC of WPDO does not have to apprehend, and it can be said that WPDO has possibility for generator fuel, particularly DDF-NG boost operation has a feasibility.

Thus, combustion design which changings the diesel combustion to DDF combustion can change the exhaust emissions and engine performance. It can be said that combustion design based on applying WPDO to DDF engine can reduce CO_2 emission.

4 Conclusions

In this paper, the experimental study was conducted on applying WPDO to DDF engine. This study was made on improving combustion and exhaust emission of WPDO by applying DDF engine from combustion design perspective. The fuel properties were measured before the engine performance test. Then, diesel operation and both DDF operation were investigated with engine. The main conclusions can be summarized as follows:

1) Kinematic viscosity of WPDO is higher than that of gas oil at low temperature. Therefore, WPDO has to pay attention to fuel temperature unless at high atmosphere temperature.
2) PM emission of both DDF combustion is significantly reduced lower than that of diesel combustion.
3) Although NOx emission of both DDF combustion is higher at the highest load, it is confirmed to be reduced lower than that of diesel combustion at another load.
4) CO_2 emission of both DDF combustion is reduced lower than that of diesel combustion, particularly DDF-NG boost can reduce lower.
5) BSFC of both DDF operation is very close to gas oil at high load, especially DDF-NG boost can improve BSFC. DDF-NG boost operation has a feasibility for generator.

References

[1] T. FJITA, K.IHARA,　Shale revolution, NTS Press, (2014), pp.1-17.
[2] R. YOSHIDA, Element technology trend of clean diesel development, NTS Press, (2008), pp.425-435.
[3] Y. YAMASAKI, Y. NOGUCHI, N. FUJIWARA, S. KANEKO, "Study on Diesel Engine with Biomass Producer Gas", Journal of JIE, vol. 92, No. 10, (2013), pp.957-963.
[4] K. ISOJIMA, The most advanced of Liquid fuel technology, CMC Press, (2007), pp. 16-26.
[5] The Japan Institute of Energy, All of the natural gas, Corona Press, (2008), pp. 5-14.
[6] N. FUKUTANI, E. TOMITA, N. KAWAHARA, K. MARUYAMA, T. KOMODA, "Combustion and Exhaust Characteristics in the Supercharged Engine Ignited with Gas Oil Fueled by Pyrolysis Gas Generared from Biomass", JSME(B), vol. 73, No. 730, (2007), pp.65-72.
[7] H. HIROYASU, The internal combustion engine, Nissin Press, (2008), pp.165-167.

Received on September 30, 2013
Accepted on January 29, 201