Springer

Journal of Mechanical Science and Technology

Journal of Mechanical Science and Technology 22 (2008) 2526~2533

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0903-x

Investigation of variations of lubricating oil diluted by post-injected fuel for the regeneration of CDPF and its effects on engine wear †

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(Manuscript Received April 7, 2008; Revised July 14, 2008; Accepted September 1, 2008)

Abstract

The purpose of the present study was to investigate the effects of oil diluted by post-injected fuel for CDPF regeneration on engine wear and to find out the characteristic variation of diluted oil according to operating conditions. Experimental studies were made on a 2700 cc, 5 cylinder engine with an after-treatment system. Fuel content in oil increased according to the increase in the duration of post injection. A fuel dilution chart was made to predict the existing fuel content in used oil. The oil analysis method using this chart was validated through the comparison of the results analyzed by GC. The oil contamination by the post-injected fuel caused the quantity of blow-by gas and engine wear to increase and main gallery pressure to decrease.

Keywords: Fuel dilution; Diesel particulate filter; Diesel oxidation catalyst; Particulate matter; Post injection; Passive regeneration; Active regeneration; Catalyzed Diesel Particulate Filter (CDPF)

1. Introduction

Recently, with the increasing global interest in environmental pollution, particulate matters and NOx exhausted from diesel passenger cars have been recognized to be the main reason for air pollution in a metropolis, and the exhaust emission standards are becoming gradually stricter. Many researchers are endeavoring to develop various technologies to reduce tremendously harmful exhaust gas from diesel engines and to meet more and more stringent exhaust emission requirements. The solution can be largely classified into two groups: One is to improve fuel quality with additives or engine combustion system itself, and the other is to use a diesel particulate filter as after-treatment.

In particular, after-treatment technologies can be divided into diesel particulate filters and diesel oxidation catalysts. The classification of diesel filter systems is based on the principle of filter regeneration. The majority of diesel filter systems are not disposable but regenerating ones using the thermal regeneration that has particulate matters oxidized to produce gaseous products. Regenerating particulate filter systems are again classified largely into three types such as passive, active and passive-active combination type. First, in passive filter systems, the soot oxidation temperature is lowered to a level to allow auto-regeneration during regular vehicle operation. However, when fuel additives or catalyzed traps are not considered during regular vehicle operation, the exhaust gas temperature itself is too low to sustain auto-regeneration in a filter trap. This difficulty may be overcome by either 1) decreasing the required soot combustion temperature to a level which is reached during regular engine operation, or 2) increasing the temperature of the trapped soot to a point where it starts oxidation. Second, active filter systems can actively trigger regeneration by raising the tempera-

† This paper was recommended for publication in revised form by Associate Editor Kyoung Doug Min

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ture of soot trapped in the filter by using outside energy sources. Two obvious energy sources are the fuel and the electricity that include post fuel injection, additional fuel burners, electrical spark, etc. The third type of system utilizes the combination of passive and active regeneration, where a catalyst-based filter is also equipped with some kind of an active regeneration system [1].

Active regeneration filter systems are much more complex than passive ones and waste more energy to fulfill the required temperature for regeneration, while the passive filters are quite simple and the approach is more attractive. However, a vehicle duty cycle heavily affects the regeneration of passive systems. If an engine is operated for a long time at low loads such as idling or slow city driving, soot will be overloaded in a filter trap and critical problems on the filter durability may result from the excessive oxidation rate of collected soot [2]. One of merits of the passive system is that it allows the trapped soot to be oxidized by using diesel oxidation catalysts even under general vehicle operating conditions. A catalyst is added in fuel as additives or is directly coated onto the surface of a filter trap.

Active systems increase the temperature of a filter trap by heating exhaust gas flow fully or partially using either electric heaters or fuel burners. In addition, it is possible to increase the exhaust gas temperature by using preheating catalysts through applying engine management like common rail post injection. Except for this, there are other engine management methods such as fuel injection timing, injection rate, intake throttling, and EGR (Exhaust Gas Recirculation) [3, 4].

The after-treatment system used in the present study belongs to the active-passive combination filter systems, and the diesel oxidation catalyst is placed upstream of the diesel particulate filter substrate. For the conditions of low-load and low-speed, the exhaust gas temperature is in the level of 200~300℃. It is impossible to oxidize the collected soot at this temperature in which temperature condition of about 600℃ is required to oxidize the trapped soot perfectly and rapidly. In the present study, the common rail post injection is used to solve this hurdle. Post-injected fuel reacts with DOC(diesel oxidation catalyst) and plays a main role in an increase in the upstream gas temperature of CDPF(catalyzed diesel particulate filter) as roughly 600℃. This allows the trapped soot in CDPF to actively start the oxidation reaction. For high-load and high-speed, the exhaust gas temperature is about 700~800℃, which is sufficient to regenerate the filter with much less fuel post injection. Therefore, this combination type of the after-treatment system can reduce particulate matters below the restriction level for all operating conditions.

However, some of post-injected fuel is adsorbed on the oil film of a cylinder wall and causes the lubricating oil to be diluted. This research is an experimental study to investigate the characteristic variation of fuel diluted oil according to the operating conditions and its influences on the wear of engine components.

2. Experimental conditions

This test was performed using a 2700 cc, 5 cylinder engine, and Table 1 shows the specifications of the engine. The properties of fuel and lubricating oil are summarized in Table 2 and Table 3. Fig. 1 indicates the distillation characteristic of typical diesel fuel, and Fig. 2 shows the operating mode for durability. The durability test is conducted for 500 hours using this operating mode that is basically composed of 22 hours (called as one cycle). The main gallery pressure and the quantity of blow-by gas are measured to monitor the transient engine wear without the engine disassembly every 100 hours. Fig. 3 depicts the mechanism of oil dilution by the post-injected fuel. The main procedure of the mixing of the post-injected fuel with the oil is as follows:

(1) The thickness of oil film on cylinder liner is maintained by piston motion that causes recirculation phenomena in the upper part of the oil film. Because injection timing is retarded by post injection, some of post-injected fuel escapes from piston bowl and some of this escaped fuel is directly adsorbed to the oil film.

(2) Here, the reciprocating motion of a piston has not only new oil from the sump supplied to the liner but also the previous oil having a fuel component returned to the sump in terms of scraping down the oil film.

(3) Oil dilution also occurs while the blow-by gas is passing through the ring pack of a piston [5-7].

Under normal operation, the main functions of oil film are to prevent wear by keeping metal surfaces and their asperities separated, to provide sealing from combustion products, and to transfer heat from the engine for cooling. When excessive fuel dilution occurs, the oil viscosity dramatically goes down and the strength of oil film becomes considerably weaker.

Table 1. Test engine specifications.

Engine type	4-stroke, 5-cylinder
Displacement	2700 cc
Bore	86 mm
Stroke	92 mm
Number of valves	20
Valve arrangement	DOHC
Compression ratio	18:1
Fuel injection type	CRDI
Number of injectors	5

Table 2. Test fuel specifications.

Items	Result
Fuel type	Diesel
Density (at 15℃, g/㎤)	0.8334
Cetane number	58.6
Ignition point(℃)	82.0
Kinematic viscosity (at 40℃, cSt)	3.245

Table 3. Test oil specifications.

Test oil		
Viscosity grade		10W40
Density (at 15℃, g/㎤)		0.8651
Flash point(℃)		227
Viscosity	40℃, cSt	100.70
	100℃, cSt	15.19
Viscosity index		159

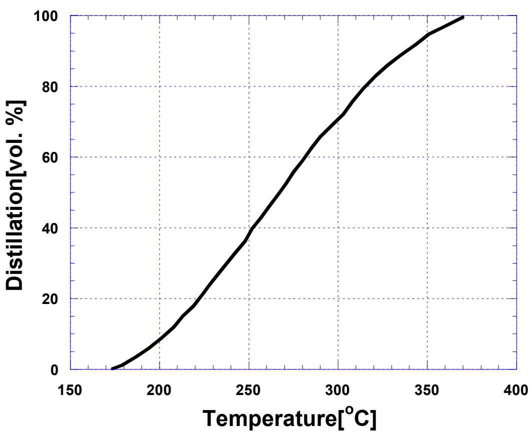

Fig. 1. Typical distillation curve of diesel fuel.

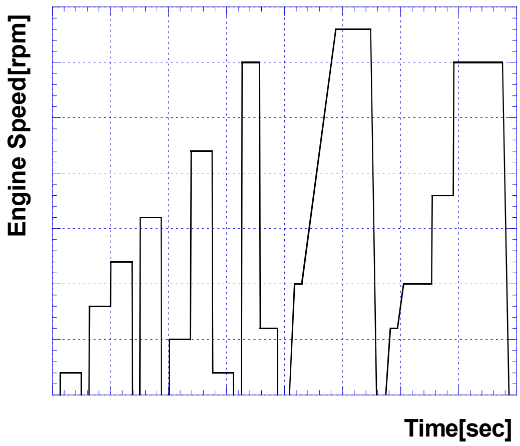

Fig. 2. Durability test cycle condition.

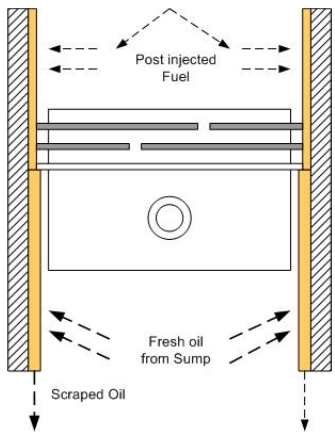

Fig. 3. Main oil dilution mechanism.

These may allow an increase in wear and that can lead to engine failure.

Besides these problems, the excessive fuel dilution can represent a drop in oil pressure, weakness in lubricant detergency, acceleration in lubricant oxidation, formation of varnish, and some acid. All of the problems mentioned above have a bad effect upon the lubricant effectiveness.

An oil analysis can provide information on the quantity of wear metals and the variation of oil properties. This also allows serious problems to be identified long before engine breakdown. Representative parameters of the oil analysis include viscosity, coolant, water, fuel dilution, insolubles, TAN (total acid number), TBN (total base number), wear metals, etc.

Viscosity that denotes the resistance to flow is one of the most important properties of lubricant. Oil viscosity can be increased due to oxidation, presence of contaminants, or evaporation of light components. It can be decreased by oil shearing or fuel dilution. Ethylene glycol, the major component of antifreeze coolant, can come into the oil due to the use of a defective gasket or a cracked head/block. It reacts quickly in a hot engine and generates varnish and sludge. The water present in the oil is due to condensation from low temperature engine operation or from a leak in the cooling system. The suspended material present in the oil is due to presence of soot from diesel combustion and contamination from airborne dust, dirt, or sand.

TAN indicates the quantity of base required to neutralize all the acidic constituents presented in the oil. It can be known that how oxidized the oil has become from this quantity. TAN will increase when the oil is oxidized or the acidic contaminants are produced in the oil. An increase in TAN results in the increase of wear, viscosity, metal corrosion, and oxidation. New oil normally has a low level of acids because some additives in it are acidic inherently. TAN level increases according to operating time and conditions.

Alkaline of base additives is to neutralize acidic products. When the oil change interval is exceeded, the ability of this additive to neutralize acids will drastically fall because there is a limit to this ability. In contrast to TAN, the highest TBN is expressed in new oil. The level of TBN indicates the capability of the additives to neutralize such acids. It is known that when TBN is reduced to the half of its original value, the exchange of oil is desirable. Since Zinc(Zn), Phosphor(P), Calcium(Ca), Magnesium(Mg), and Molybdenum(Mo) are the components of additives, they do not increase or decrease. TBN is an important parameter that determines whether these additives remain effective or not. High levels of Ferrum(Fe) and Copper(Cu) indicate increases in the wear of crankshafts, valves, cylinder liner, and bearings. Table 4 shows the warning levels of important oil analysis items that are normally recommended by oil manufacturers.

Checking the viscosity in these parameters is the fastest and the most convenient tool to monitor the characteristic variation of oil. Also, this method makes qualitative prediction of the fuel quantity diluted in the oil possible. Fig. 4 shows the viscosity variation curves of the sample oils that have different viscosity grades according to the fuel percent included. In the present research, the curve marked with 'Test' is used to predict the fuel content included in oil. The unit of viscosity is cSt, and the reference temperature is 40℃.

Table 4. Oil analysis items and warning levels.

Oil Analysis Items	Warning Level
Viscosity	25% change of new oil viscosity [cSt@40℃]
	15% change of new oil viscosity [cSt@100℃]
Water	0.1%
Dilution	5%
Insolubles	0.5%
TAN	5
TBN	3~4
Fe	100 ppm
Cu	20 ppm
Si	20 ppm

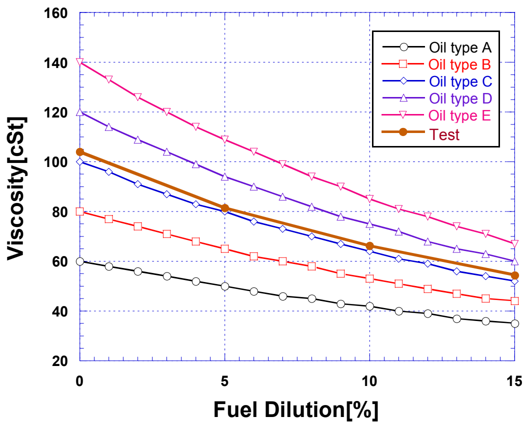

Fig. 4. Fuel dilution chart for predicting fuel contents [%] using oil viscosity.

3. Results and discussion

Common rail post injection used in the present research is controlled by ECU according to the mass of collected soot, the pressure drop between the upstream and downstream of CDPF and temperature conditions. Post-injected fuel quantity depends on engine speed and load. The higher speed and load represent the less quantity of post-injected fuel. First, to monitor the rate of fuel dilution according to the post injection time, this test was performed on an operating mode that requires a relatively large amount of post-injected fuel. Post injection was executed for two hours and we kept engine speed and load at

Table 5. Test conditions.

Sampling No.	Operating Mode	Post Injection	Operating Time [hr]
1	1500 rpm 90 Nm	Yes	0
2			0.5
3			1
4			1.5
5			2
6	Durability Test Cycle	No	5
7			10
8			15
9			20

1500 rpm and 90Nm, respectively. After this period, the test condition was changed to a durability test mode to examine the characteristic variation of diluted oil. Used oil was sampled for oil analysis every 30 minutes to execute post injection and every 5 hours for durability test mode. With respect to total experimental time and oil consumption, the sampling volume was determined as 150 cc. Upper test conditions are summarized in Table 5.

Post injection itself has little effect on increasing the exhaust gas temperature, and this cannot satisfy the required temperature (about 600℃) to start active oxidation reaction of soot. This technical hurdle could be solved by having the exhaust gas passed through DOC. Fig. 5 shows the temperature difference between the inlet and the outlet of the DOC. The post-injected fuel that is transmitted to the DOC plays a main role in increasing the exhaust gas temperature since it acts as an outside energy source for the filter regeneration. The temperature increase at the outlet of the DOC represents that the post-injected fuel in the exhaust gas reacts actively with the catalyst in the DOC.

In general, a GC (gas chromatography) analysis is known as the most accurate method for measuring the fuel content diluted in oil. While this chemical analysis has some drawbacks, such as complexity in measurement, time-consuming procedure, and expensive test machine, the fuel quantity prediction using oil viscosity can not only provide nearly the same qualitative result as the results of such a GC analysis, but also represents a considerable advantage in experimental time and cost.

Fig. 6 shows the prediction results of fuel quantity according to experimental schemes. Fuel quantity

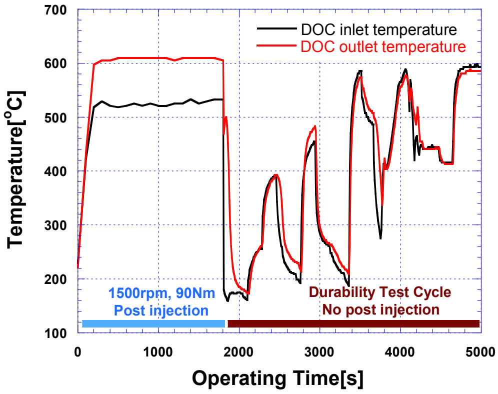

Fig. 5. Temperature traces in the DOC inlet/outlet on the operating condition and time.

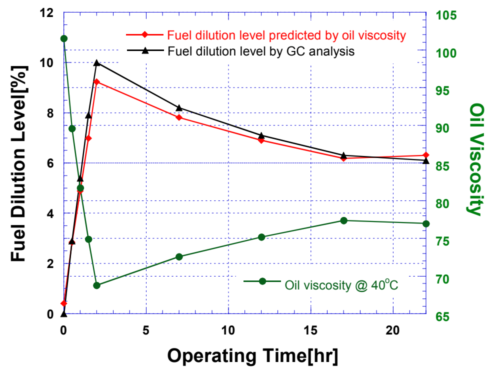

Fig. 6. Comparison of the oil dilution level (fuel %) in accordance with the oil analysis method.

prediction results using oil viscosity are in good agreement with the results from the analysis of GC. In Fig. 6, after two hours of the post injection, the oil viscosity decreased 34% compared to the new oil viscosity (104.03 cSt @ 40℃). This viscosity is above the recommended limit level (25% change of the new oil viscosity at 40℃) for oil drain. Also, the quantity of fuel dilution is much more than the general limit value (5%) for oil exchange. Therefore, we can recognize that oil contamination becomes severe due to the post-injected fuel. In particular, during the durability test mode, oil viscosity shows a rapid increase in the early stage and down to a steady state after 17 hours. This is in contrast to the general viscosity behavior that shows a decrease in the early state of operation. The causes of this phenomenon include the volatilization of fuel diluted in oil, oxidation of oil, formation of varnish, sludge, etc.

Since a serious decrease in oil viscosity results in drastic weakening of oil film strength, it causes overheating at metal parts that should be kept separated. It allows an increase in engine wear that can lead to engine failure. For that reason, an engine durability test was performed to examine the influence of fuel dilution on engine components.

Oil for a durability test was prepared to simulate the fuel dilution phenomenon by post injection. The oil blended (initial viscosity: 57 cSt @ 40℃) with 15% diesel fuel and 85% oil was used to simulate test conditions harder than the general fuel dilution limit (5%). For the durability test, the frequencies of oil sampling and drain intervals were determined by every 10 cycles and 20 cycles, respectively, for considering oil consumption and oil volume extracted for one sampling (300 cc).

Fig. 7 shows experimental results obtained by using the blended oil. The main reason in the increase of oil viscosity (decrease of fuel content) before oil drain is due to the volatilization of fuel diluted in oil. This is related to the distillation characteristics of the diesel fuel shown in Fig. 1. The temperature of lubricating oil is controlled by the engine cooling system and it remains constant. Therefore, more volatile fuel components are vaporized as the oil temperature increases. As the operating time elapses, evaporation rates go down gradually. Fig. 7 also shows that the maximum and the minimum of average fuel content are relatively steady as 14.42% and 8.14%, respectively. The initial fuel content does not reach to 15% because of the oil remaining in the total lubricating system after oil exchange. The minimum fuel content (8.14%) no longer decreased because the fuel distillation temperature showed the range between 170℃ and 370℃. After all, only a few parts that are directly exposed to combustion, such as cylinder wall and piston ring pack, satisfy the temperature condition to evaporate the fuel. As shown in Fig. 1, the temperature that distillates the fuel completely is approximately 370℃ or higher. Because the temperature condition of the combustion chamber and engine system is restricted by the cooling system, the evaporation of all fuel diluted in oil is limited.

Also, as the time goes into the second half (10 to 20 cycles), the active fuel evaporation appearing in the first half (0 to 10 cycles) was diminished. In the first half, the main influence of the oil viscosity increase might be the fuel evaporation, but, in the second half, the oxidation of oil and the formation of varnish and sludge.

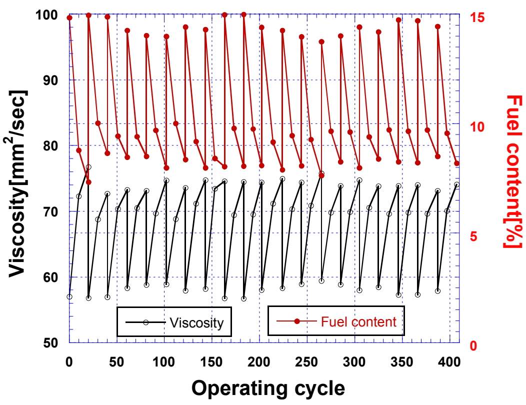

Fig. 7. Fuel content and viscosity variation curves of the fuel diluted oil in accordance with engine durability test cycles.

High speed rotating parts and large weight transmitted areas need good oil properties to prevent the metal contacts and to lubricate these engine components efficiently. We inspected the turbocharger, piston ring pack, and bearings to estimate the effects of the fuel dilution on engine system, and we found no problems caused by the fuel dilution. In a comparison of the experimental results to normal oil, increases in the wears of piston ring pack and bearings showed a little despite the drastic decrease in oil viscosity.

Since the load from the combustion pressure is transmitted to the connecting rod big end bearings, the lubrication performance around these parts is very important. However, the oil contaminated by the fuel dilution helps their wear that is predominant in the inspection of all engine components. Also, we could observe signs of overheating on some of crankshaft journal bearings. However, the whole wear appeared not to be bad compared to the experimental results using typical oil without such fuel dilution.

The variation of the main gallery pressure and the quantity of blow-by gas is very sensitive to the leakage of a lubricating system due to the piston rings and the oil viscosity. Therefore, these two parameters were measured to compare the experimental results using the fuel diluted oil with those using typical oil. Figs. 8 and 9 show variations of the main gallery pressure and the quantity of blow-by gas. When 15% fuel diluted oil is used, an increase in the wear of piston ring pack allows some of the compressed gas mixture on the top of the pistons in the cylinder to leak past and escape into the crankcase. The increase of blow-by gas can be explained by the wear of the piston rings. In addition, not only the wear of the total

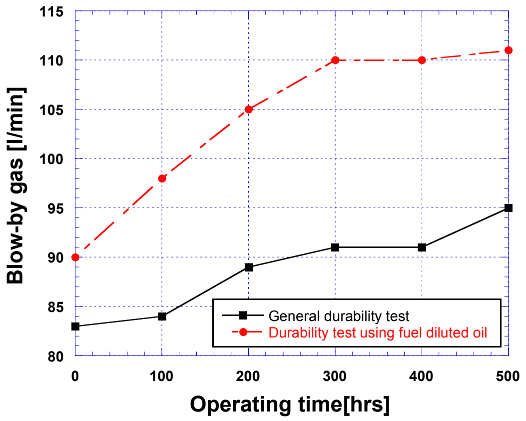

Fig. 8. The quantity of blow-by gas in the comparison of the test results using 15% fuel diluted oil and pure oil.

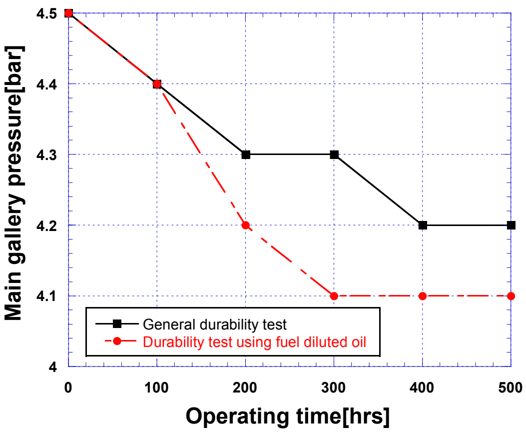

Fig. 9. The main gallery pressure in the comparison of the test results using 15% fuel diluted oil and pure oil.

engine system but also the low oil viscosity due to the oil dilution played a major role in the decrease of the main gallery pressure. Compared to the wear of the engine components related to the camshaft and the crankshaft, the piston rings wear more to cause the increase of the amount of blow-by gas.

4. Conclusions

The purpose of the present study was to investigate the effects of oil diluted by post-injected fuel for CDPF regeneration on engine wear and to find the characteristic variation of diluted oil according to the operating conditions. Experiments were performed on a 2700 cc, 5 cylinder engine with an after-treatment system of an active-passive combination type. The results can be summarized as follows.

(1) In order to evaluate the variation of fuel content in the oil diluted by post-injected fuel, we made fuel dilution prediction curves. Validations of the experimental scheme using these curves were made through a comparison of the chemical analysis results by using the GC method.

(2) In the engine test using the oil mixed with 15% fuel, it was found that about half of the fuel diluted was evaporated in the operation. The rest that was not evaporated was considered to cause the acceleration of oil oxidation and the formation of varnish and sludge.

(3) From the results of the durability test using the oil mixed with 15% fuel, it was found that the maximum and the minimum of average fuel content were relatively steady with 14.42% and 8.14%, respectively. The initial fuel content did not reach to 15% because of remaining oil after drain. The minimum fuel content (8.14%) no longer decreased because the fuel distillation temperature was between 170℃ and 370℃.

(4) The low viscosity due to the oil dilution had bad influence on keeping the strength of oil film and the metal parts separated, and therefore it increased the wear of piston ring pack and bearings. However, the total engine wear appeared not to be serious considering the oil viscosity prepared to represent a severe operating condition that could occur in the CDPF system using the post injection for the regeneration of filters.

(5) Compared to the experimental results using normal oil without fuel dilution, the quantity of blow-by gas increased due to the wear of the piston rings, and the main gallery pressure decreased due to the wear of the total engine system with the oil viscosity lowered by the fuel dilution.

Acknowledgment

This research was financially supported in part by the Ministry of Knowledge Economy(MKE) and Korea Industrial Technology Foundation(KOTEF) through the Human Resource Training Project for Strategic Technology.

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