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# A Study on the Deposit Formation in the Cylinder and Intake Valve of a S. I. Engine

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A spark ignition engine with port fuel injection (P.F.I.) system was used to accumulate cylinder head deposit (C.H.D.), intake valve deposit (I.V.D.), and piston top deposit (P.T.D.) on an engine dynamometer. In this study, the effect of base gasoline on I.V.D. was examined. The deposit forming tendency and the influence of the fuel component for decreasing deposits have been experimentally examined. The amount of I.V.D. has been observed to increase linearly with the engine operating time. It is also observed that the amount of valve deposit with newly blended gasoline is less than that with base gasoline.

**Key Words :** Intake Valve Deposit, Piston Top Deposit, Cylinder Head Deposit, Combustion Chamber Deposit, Gasoline, Engine Test Mode

## 1. Introduction

Thanks to the development of petroleum refinery technique fuel properties are changing to correspond with engine demands - octane number, adequate volatility, corrosion restraint, stability for catalytic converter, and suppression of evaporation gases. The compositions of deposit formed in an operating engine change according to fuel formulation, and the ingredients of gasoline additives should be reformulated to eliminate deposits. Since the middle of 1980's, when a large number of vehicles starting were equipped with P. F.I. (port fuel injection) system, combustion deposits resulted in loss of vehicle performance due to the problem of fuel injector plugging and fuel starvation caused by intake valve deposits (Bitting et al., 1987).

In order to determine the effect of deposits observed in BMW vehicles in 1984, engineers investigated it using the vehicle road test. Although the engine dynamometer procedure was developed to improve the repeatability of experimental conditions compared to the vehicle road test(Keller et al., 1992), the mechanism of intake valve deposit formation, the cleanness of fuel injector and relationship between many different engines were reported from this proceduce(Benson et al., 1986).

Kim et al. (1991) reported that the carbonaceous deposit is formed by thermo-chemical reaction in a valve tulip area because gasoline is sprayed directly onto the intake valve surface. According to Graham's work(Graham et al., 1992), the discharge coefficient decreases with increasing intake flow resistance caused by intake valve deposit and hence engine performance is lowered. Dry and carbonaceous valve deposits absorb fuel during the cold start phase of an engine driving cycle, resulting in a temporary leanness of air to fuel ratio(Keller et al., 1992). This resulted in rough idle. Base fuel formulation has been modified and additive technology has been mature enough to clean up the valve deposits. Now both of them are capable of controlling intake valve deposits, but they may increase deposit in the combustion chamber, the piston top and the cylinder liner.

In this study, the amount and formation trend

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of deposits were examined experimentally for a base gasoline and a newly blended gasoline using an engine equipped with the electronically controlled fuel injection system on an engine dynamometer.

## 2. Experimental Procedure

Engine test mode has been proposed to evaluate deposit-forming trend with a test fuel. Fuel characteristics affecting the amount of deposit have been evaluated with a engine dynamometer procedure. The engine dynamometer test and the vehicle road test are widely used methods for the study of deposit forming in automotive engines. In the vehicle road test known as 'BMW/SwRI mileage accumulation cycle'(Grant et al., 1992), the vehicle driven on the road for 10,000 miles consists of 10% in city, 20% in suburban and 70% in highway miles. But it takes a lot of time, and it is difficult to select a proper test course, and it has some problems with the controllability of experimental variables. Thus researchers developed the engine dynamometer procedure. The test should be well contrived to form the valve deposits.

In general, combustion deposit formation is affected by crankcase lubricant oil, gasoline components and valve surface temperature(Esaki et al., 1990). In this study, an engine operating mode is considered which will take into account many factors which contribute to deposit formation.

Combustion chamber deposit (C.C.D.) weights increase if oil consumption increases beyond limit (Cheng, 1993). In order to investigate the effect of the lubricant oil upon deposit, it is required that engine should be operated with a high intake manifold vacuum. This facilitates the procedure to observe the trend of oil flow into the valve tulip area from the valve deck through the stem guide. To observe this effect, the engine has to be operated at idling or at very light load.

In order to observe the fuel effect, engine should be operated under high load conditions to some extent that passes sufficient amount of fuel into the valve tulip area. The engine speed or load is increased, deposit formation is reduced(Shoppe et al., 1993). Therefore adequate engine speed and load are needed to observe the fuel influence. In general, engine speed is used from 2000 rpm to 4000 rpm, load is maintained at about 10% of engine's maximum output for the constant speed mode test.

Coolant temperature has been found to have great influence on the deposit formation. C.C.D. weights decreased with the increase of coolant temperature or surface temperature of the combustion chamber(Cheng S.S., 1996). In contrast, I.V.D. weights peaked at about 95℃ coolant temperature(Cheng S.S., 1992). Thus if coolant temperature is not selected for an experimental parameter, generally it is set about 90℃ which is the coolant temperature of the baseline engine condition.

Exhaust gas recirculation (E.G.R.) and blow-by gas are other important matters for deposit forming. In this study those are not adjusted to simulate the conditions of the road test vehicle for all of the tests.

The experimental conditions are as follows : 3000 rpm for 35 hours, intake vacuum of 58.8 kPa, engine dynamometer load of 23.5 N·m (about 7.4 kW) and coolant temperature of 90 ±2℃. This test mode is one of the standard method for deposit accumulation to evaluate the base gasoline in Chevron U.S.A. Production Company(Oronite Technology Group, 1992).

Some special facilities of laboratory were set up for the test because environmental conditions could affect a long term experiment. In order to make stable experimental surroundings, ventilation facilities, blower systems for engine air cooling, a large external fuel tank, a closed loop cooling system for an engine dynamometer, and constant temperature system for a dynamometer cell are equipped as additional apparatuses. Figure 1 shows an entire experimental system.

Before the test, the cylinder head is disassembled and cleaned, and new valves are mounted. The amount of valve deposit is measured using a digital balance before and after the test. After the experiment, the valves were taken apart from the test engine, then weighed and rinsed in n-Hexane to remove lubricant oil out of the deposit and weighed again. With these, we can clean up the

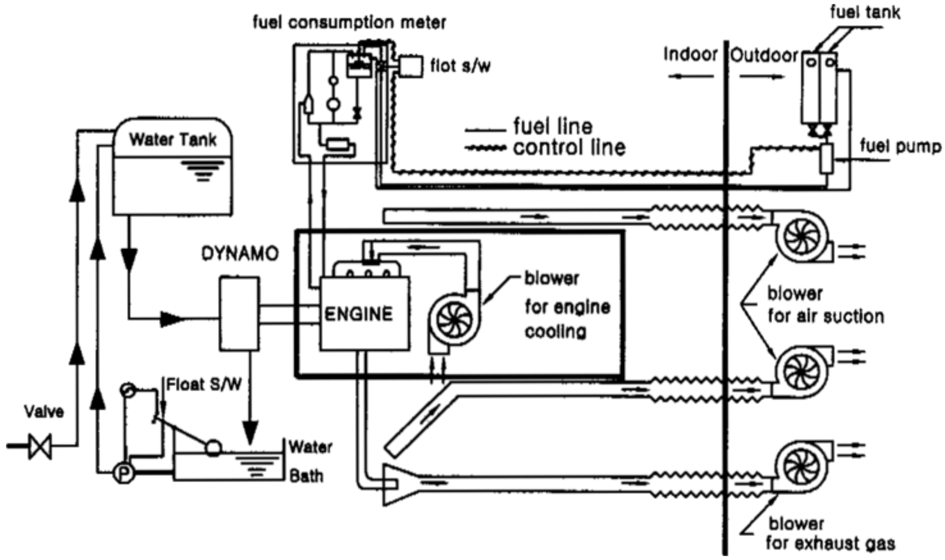



**Fig. 1** Schematic diagram of the experimental apparatus.

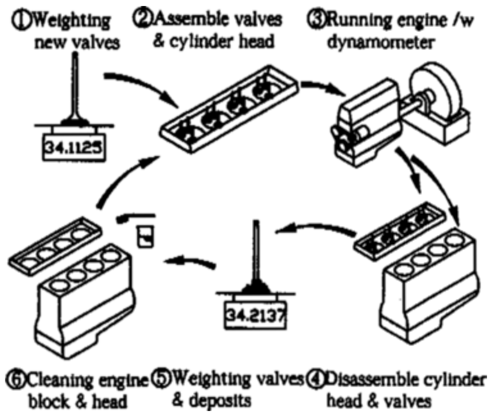



**Fig. 2** Schematic diagram of the test procedure.

lubricant oil out of valve deposits. Also we collected piston top deposits as well as cylinder head deposits and weighed them with the digital balance. We used a heavy paper and a masking tape to isolate the combustion chambers from each other and scraping the deposit. Intake valves and exhaust valve were left in the cylinder head to prevent the scraped deposits from falling into the port area. Using a threaded metal bar, the spark plug hole was plugged. This prevented deposits from escaping through the spark plug hole.

We photographed each valve, valve seat, combustion chamber, piston top with raw deposits. After oil was removed, we carried out research on deposit formation patterns. Figure 2 shows the experimental process.

**Table 1** Properties of the test fuel.

| | F1 Fuel | F2 Fuel | F3 Fuel | Commercial gasoline |
|---|---|---|---|---|
| T50(℃) | 91 | 91 | 91 | 94 |
| T90(℃) | 153 | 157 | 160 | 164 |
| Saturates(%) | 56 | 51 | 41 | 55 |
| Aromatics(%) | 34 | 34 | 39 | 35 |
| Olefins(%) | 10 | 15 | 20 | 10 |
| Gum(mg/100ml) | 1.4 | 1.2 | 1.1 | 0.8 |
| RON | 95 | 95 | 95 | 95 |
| Vapor Pressure(kPa) | 68 | 68.1 | 68.1 | 64.8 |
| Gravity(API) | 56.9 | 56.7 | 56.8 | 55.2 |

The base gasoline F1 fuel, F2 fuel and F3 fuel, which are differentiated in olefin content ratio were used in the experiment. In order to change the content of olifin in the test fuel, the volume of aromatics or saturates should be changed. Nishizaki et al. (1979) found that the combustion chamber deposits increased with aromatic content and mean molecular weight of the fuel. Because of the environmental regulations, the aromatic content could not be changed massively and in conse-

**Table 2** Specifications of an engine and dynamometer.

| Item | Specification |
|---|---|
| Engine | |
| Type | Water cooled 4 cylinder with port fuel injection |
| Bore x stroke | 75.5 * 83.5 (mm * mm) |
| Displacement | 1495cc |
| Compression ratio | 10.0 : 1 |
| Valve system | Over head single camshaft 12 valves (2intake/cylinder) |
| Max. output | 71 kW/5500 rpm |
| Engine Dynamometer | |
| Type | Eddy current type |
| Max. Absorbing Power | 130 kW |
| Max. Absorbing Torque | 340 N·m |

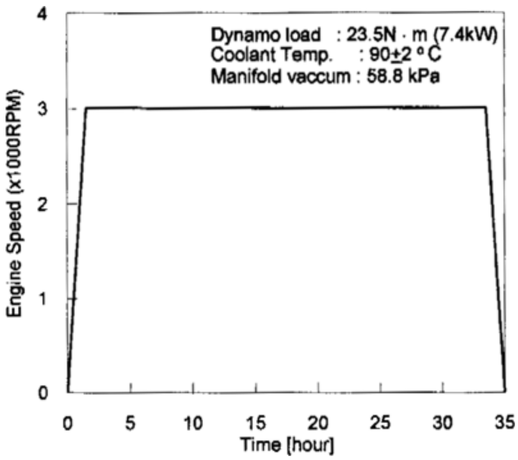



**Fig. 3** The engine test mode on an engine dynamometer.

quence, the saturate content was changed. Table 1 shows the characteristics of the test fuel. To prevent each fuel from mixing together, the remaining fuel is taken out of the fuel line and fuel tank.

The test engine is equipped with an electronically controlled fuel injection system, 1500 cc, 3 valves per cylinder and the maximum absorbing power of the dynamometer is 130 kW. Table 2 shows the specification of the test engine and the dynamometer. The test engine keeps constant operating condition during the experiment.

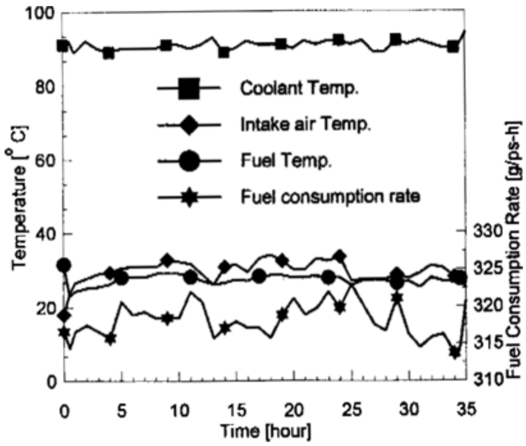
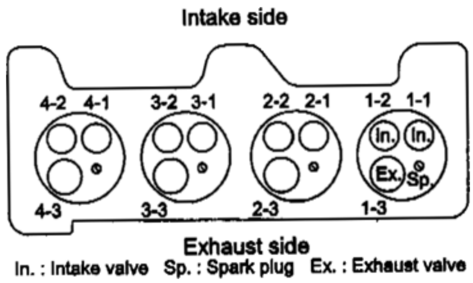
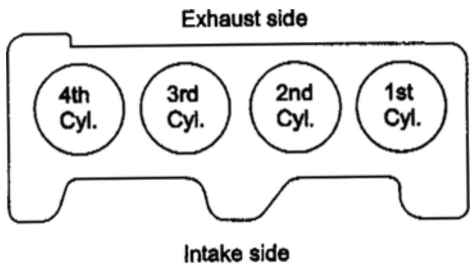



**Fig. 4** History of the engine running conditions.




(a) Cylinder head




(b) Cylinder block

**Fig. 5** Plane view of the cylinder block, head and valves.

Figure 3 shows the engine test mode. When the coolant temperature reached 90℃, the throttle valve was opened and the dynamometer was adjusted to the load which enables the engine to follow the mode. Figure 4 shows the measured data during engine runs and every item of experimental condition is authenticated to be kept constant. Figure 5 shows the valve position in the cylinder head and cylinder position in the engine

**Table 3** Test conditions and measured data.

| Exp. No. | Dur-ation (hour) | Fuel | IVD | PTD | CHD | Fuel Qnty. (liter) | Etc. |
|---|---|---|---|---|---|---|---|
| A | 18 | F1 | ● | | | 78 | |
| B | 30 | F1 | ● | ● | | 148 | |
| C | 35 | F1 | ● | ● | | 156 | |
| D | 35 | F1 | ● | ● | ● | 158 | |
| E | 35 | F1 | ● | ● | | 156 | * |
| F | 35 | F2 | ● | ● | ● | 157 | |
| G | 35 | F3 | ● | ● | ● | 155 | |

* : valve seals were not changed.

| | |
|---|---|
| Lubricant oil | 10W-40 API SH |
| Spark advance | MBT |
| Injection timing | ATDC 38° |
| Intake air temperature | 30±2℃ |

block. An experiment on F1 fuel is carried out under the same condition for different durations. The amount of deposits is measured after 18 hours (test A), 30 hours (test B) and 35 hours (test C, D & E) of engine running time. Test E is carried out without changing the valve stem seal, thus we can observe the deposit forming made by lubricant oil leaking through an aged valve stem seal. Test F and G are performed under the same condition using newly blended gasoline, F2 fuel and F3 fuel so that we can evaluate deposit formation to fuel composition. Table 3 is the specification of experimental condition.

## 3. Results And Discussions

Figure 6 shows the average amount of intake valve deposits for various test duration. An average amount of valve deposit measured in 18 hour test comes up to 50% of that measured in 35 hour test, which means that the quantity of deposit is directly affected by engine running time. That is, doubling engine operating time doubles the amount of deposit within the limited operation period in this study. In the test F using F2 fuel, the average amount of I.V.D. is similar to F1 fuel,

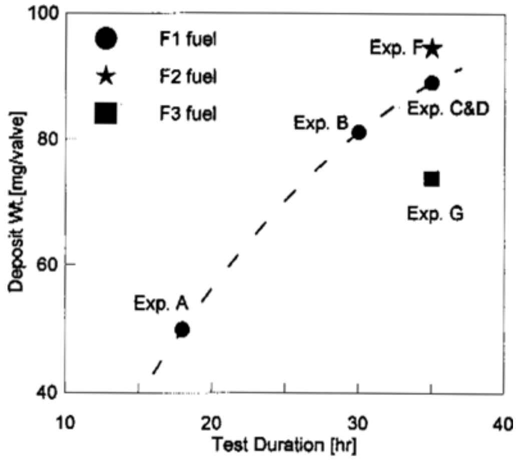



**Fig. 6** I.V.D. weights for various test duration.

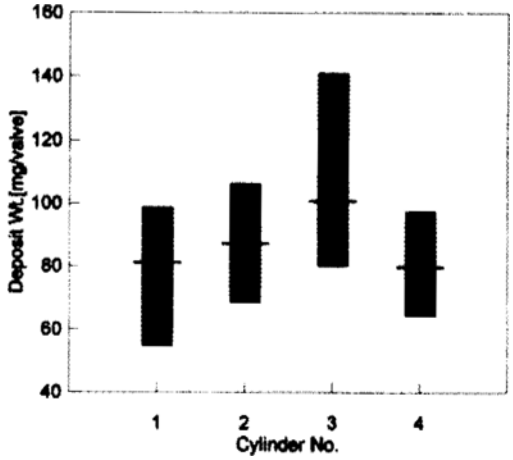



**Fig. 7** Difference of the average weights of I.V.D. for every cylinder.

but the test G with F3 fuel shows about 75% that of F1 fuel.

Figure 7 shows the difference of the average weights of I.V.D. for every cylinder. The amount of valve deposit around valves of the 1st and 2nd cylinder is about the average of all the valves, but the 3rd cylinder's valves have much more than others. Each cylinder has different amount of deposit is known in the experiment. It is regarded to be an effect of fuel distribution. The mass of air dispersed into each cylinder through the intake plenum is not equal in theory as well as in practice (Lee et al., 1996). Because of the different mass of aspirated air and its velocity, although the injectors spray the same amount of fuel into each

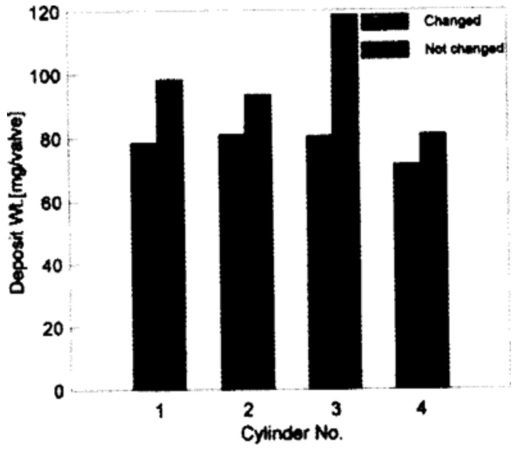



**Fig. 8** Comparison of I.V.D. for the aged valve seal with new one.

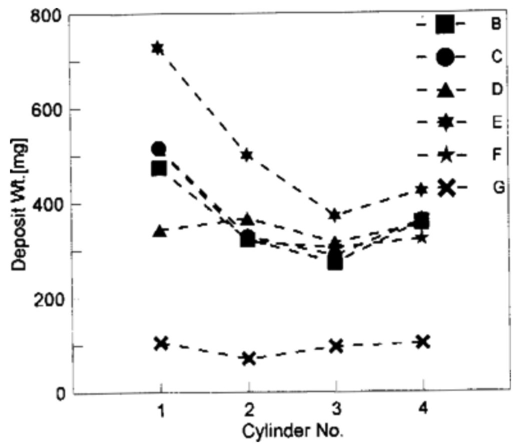



**Fig. 9** P.T.D. weights for every experiment.

cylinder, the quantity of fuel attached around the valves is not equal(Shin, 1997) which cause different mass of deposit. Also each valve in a cylinder has a different amount of deposit. It's due to the fact that aspirated air is not equally distributed into two ports inside the cylinder head.

For the purpose of knowing the effect of deposit caused by lubricant oil in test E, Fig. 8 shows the experimental results when the valve seal is not changed to new one. Every valve has more deposit than when it is not sealed with new one. It is because the aged valve seals allow lubricant oil to leak easily from the valve deck. Therefore we know the fact that replacing valve seal has an important effect on the valve deposit

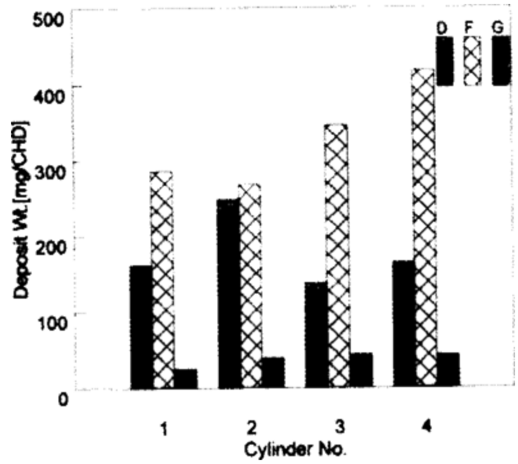



**Fig. 10** C.H.D. weight for each cylinder.

formation and the valve stem seals must be changed after valves are disassembled from the cylinder head.

Figure 9 shows the average amount of piston top deposit (P.T.D.) at each cylinder. The formation of deposit shows a similar tendency in every experiment. The tendency is that more than average deposits are observed in the 1st cylinder, average deposits are produced in the 2nd cylinder and the 3 rd cylinder has least. It is opposed to the tendency of I.V.D. formation. Especially the test E shows over 30-40% more deposits originated from the lubricant oil leaked from the aged valve seals. It is said that deposit by lubricant oil affects more P.T.D. than I.V.D. The amount of deposits in test G using F3 fuel is remarkable. This fuel contributes to decrease P.T.D. down to 30% that of F1 or F2 fuel.

Figure 10 shows Cylinder Head Deposit (C.H.D.) in each cylinder. Conspicuous formation tendency is not observed in each cylinder. It's similar to I.V.D. and P.T.D. However, in the test G using F3 fuel, the amount of C.H.D. is far less than F1 and F2 fuel.

Figure 11 shows the proportion of deposit formed at each cylinder in the test D. The quantity of total deposit produced in a cylinder differs from those of other cylinders. But the composition is unique. That is to say, the amount of I.V.D. in every cylinder is approximately 16% of the total.

Figure 12 shows the relation between the quan-

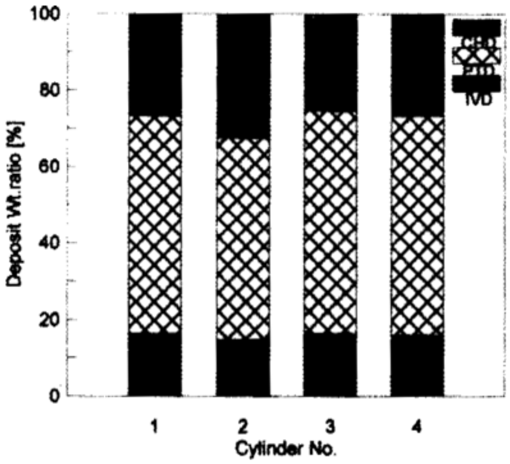



**Fig. 11** The composition of deposit formed in each cylinder.

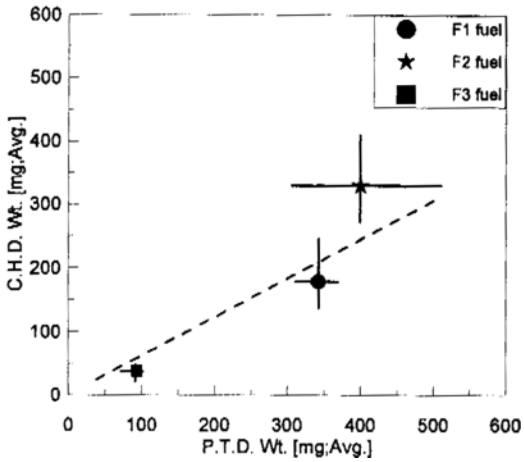



**Fig. 13** The relation between the amount of P.T.D. and C.H.D.

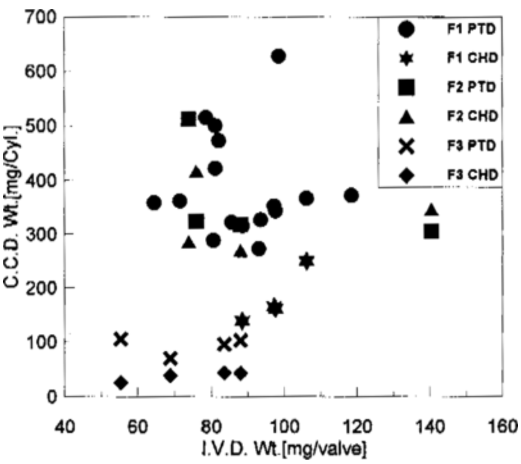



**Fig. 12** The relation between the amount of I.V.D. and C.C.D.

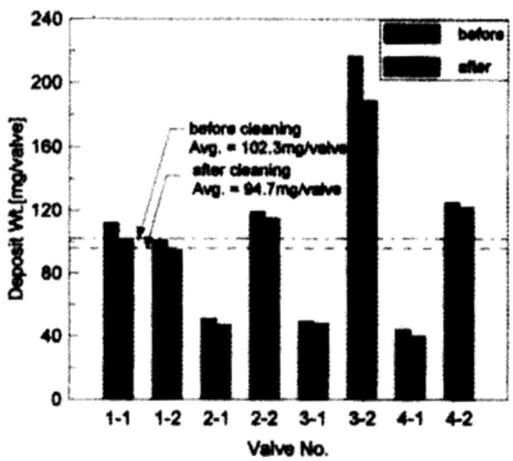



**Fig. 14** The intake valve cleaning by the n-Hexane.

tity of I.V.D. production and that of combustion chamber deposit (C.C.D.=P.T.D.+C.H.D.). No significant correlation is indicated between C.C.D. and I.V.D. F3 fuel is observed to cut down P.T.D. and C.H.D.. The regression plot in Fig. 13 shows a linear correlation between the P.T.D. and C.H.D.

Figure 14 shows the compared weight of intake valve before and after n-Hexane rinsing. The weights of valves are measured by the following procedure : After engine running, measure the weight of the intake valves separated from the cylinder head. And then, rinsing them in the n-Hexane and dry. In the final step, measure the valves again. On the average, 7.3% of the deposit weight is reduced on each valve. The lubricant oil is eliminated by the n-Hexane rinsing. Especially in the case of valve number 3-2, the deposit forming is higher than the others. After the n-Hexane cleaning, nearly 13% of the weight is reduced. That is, the amount of the lubricant oil soaked in the valve No. 3-2 is much more than in other valves.

Figures 15~17 show the I. V. D. production for changing the operation time in using F1 fuel. (respective test A, B, & D : valve No. 3-2) As the operation time extends to 18, 30 and 35 hours, the

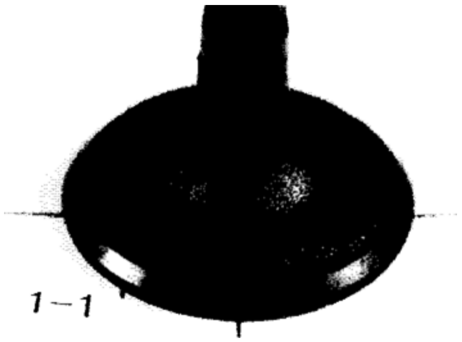



**Fig. 15** Intake valve after test A, valve No. 1-1 (I. V.D.−60 mg).

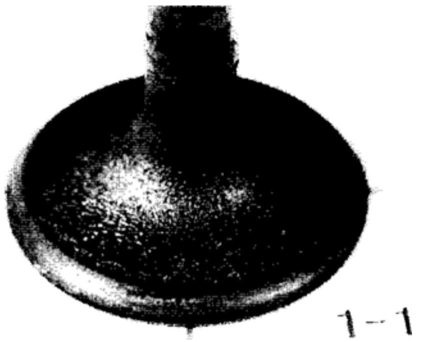



**Fig. 16** Intake valve after test B, valve No. 1-1 (I. V.D.=89 mg).

**Fig. 17** Intake valve after test D, valve No. 1-1 (I. V.D.=107 mg).

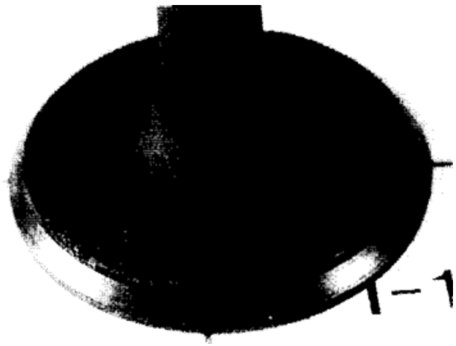



**Fig. 18** Intake valve after test G, valve No. 1-1 (I. V.D.−39 mg).

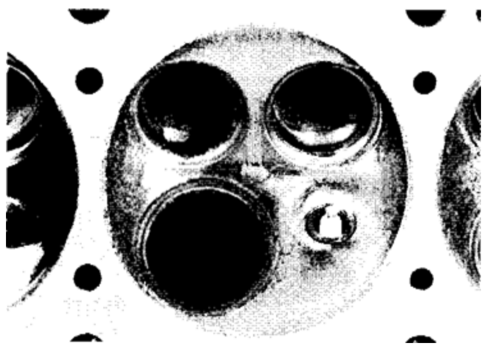


**Fig. 19** The 3rd cylinder head after test D (C.H.D. =137.9 mg).

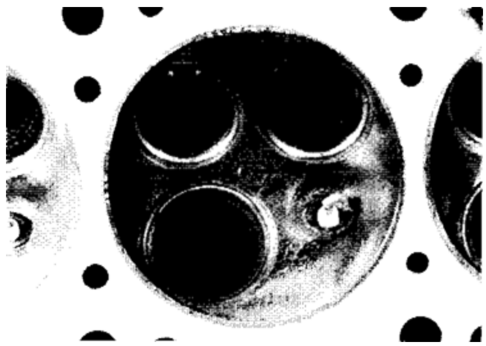


**Fig. 20** The 3rd cylinder head after test G (C.H.D. −42.9 mg).

production quantity increases to 60, 89, and 107 mg. As the operation time is lengthened, the amount of the lubricant oil that is flowing into the valve increase. As a result, the deposit has a shape of flowing lubricant oil at the neck of the valve. The overflowing deposit accumulates at the part of the valve tulip. Figure 18 shows that a little amount of the deposit (39 mg) can be observed in the No. 1-1 valve after test G using F3 fuel for 35 hours. Especially the deposit having the shape of flowing lubricant oil at the neck of the valve is not observed. It seems that the fuel reduces the deposit in that place. The same result is obtained for the case of F3 fuel.

Figure 19 shows the 3rd combustion chamber after test D using F1 fuel. The deposit is mainly

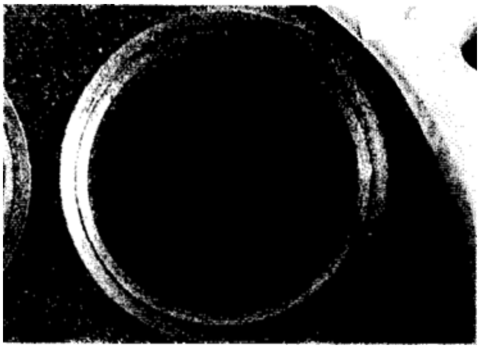


**Fig. 21** Intake valve seat after test D, valve No. 2-1.

**Fig. 22** Top of the 4th cylinder liner after test E.

observed in the edge of combustion chamber and boundary area where the inclined plane change into the rounded surface. The amount of deposit is 137.9 mg in this case. Figure 20 shows No. 3 combustion chamber after test G using F1 fuel. Deposit is equally distributed all around on the combustion chamber. In this case, the degree of the deposit is less than that in test D and the amount of deposit is much less than in the case of F1 fuel (42.9 mg). Figure 21 shows a valve seat after test D using F1 fuel. The dry deposit of this part and I. V. D. can induce the unstable idling due to temporary fuel starvation. The deposits temporarily absorb the fuel (Keller et al., 1992). In Fig. 22, the thickness of the deposit on the top of cylinder liner is about 0.5 mm. This part is the farthest area from the spark plug, and becomes the hot spot during heavy load operation, and can start abnormal combustion. Deposits of this part are commonly observed in all the tests.

## 4. Conclusions

In this study, the deposit forming tendency and the fuel for decreasing deposits are experimentally examined. The tests are performed on an engine dynamometer under the selected control mode using an engine equipped with an electronically controlled fuel injection system. The results are as follows:

(1) The amount of deposit production for the base fuel linearly increases with the running time, within the limited operation period in this study.

(2) Intake valve deposit is strongly influenced by the lubricant oil leakage from the valve deck through the aged valve seals.

(3) The amount of deposits during the test operation with F1 and F2 fuels are approximately equal, but the formation of P. T. D. and C. H. D. is remarkably decreased for the case of F3 fuel. Also there is a linear correlation between the P. T. D. and C. H. D..

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