

Study of Base Number Estimation Method for Engine Oil Deterioration Monitoring System

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ABSTRACT

In this research project, technology for estimating the base number (BN) deterioration, used as an index for judging engine oil deterioration, was developed. A detailed investigation using an NOx bubbling unit was carried out, and as a result it was found that the speed at which the BN falls is determined mainly by heat and NOx. In addition, a detailed analysis was carried out, and it was found that the reduction speed can be expressed using the differential rate law. A study of the possibility of estimating reduction of the BN in an actual engine was carried out using a BN deterioration equation. The results of this study showed that it was possible to adequately estimate the BN deterioration. This indicated that it is possible to estimate the reduction of the BN on-board by the engine control unit (ECU).

1. Introduction

Engine oil cleans, cools and inhibits rust and corrosion, in addition to its functions as a lubricant for various engine parts, and a sealant for the combustion gas. Although all of these functions are important, reduction of its detergent properties (detergency) in particular can result in sludge and deposits inside the engine, which can lead to serious issues such as oil circuit blockages. Engine oil additives that are closely related to detergency include the metallic detergents represented by salicylates. These detergents offer resistance to high temperatures and are said to be indispensable for minimizing deposits on hot parts of the engine, such as those near the piston and lubricated parts of the turbocharger^{(1),(3)}. These detergents also protect the engine by neutralizing organic acids, generated as a result of fuel combustion, and the nitric acid that is

generated as a byproduct of NOx in the blow-by gas⁽²⁾. The base number (BN) indicates the amount of basic substances contained in engine oil, and is a representative index of the amount of residual basic metallic detergent. The BN is also used as an index of the oil's ability to neutralize acid, and is an important indicator of the degree of deterioration of engine oil. However, even if the BN is used as an index of the useable life of the oil, special equipment is necessary to quantitatively measure the BN. For this reason, it is hard for an automobile user to know when to replace the oil using the BN as an index. The main aim of this research was to devise a method of estimating the degree of deterioration of the BN by utilizing data acquired from an engine sensor, such as the engine water temperature sensor, without having to actually measure the BN. Another aim was to utilize this data to study the feasibility of using an on-board BN deterioration detection system.

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2. Relationship between BN and Oil Deterioration

2.1. Relationship between BN and High Temperature Deposits

The BN is often used as an index of oil deterioration. In this research, a validation was carried out concerning the effect of BN on minimizing deposits, using the hot tube test (JPI-5S-55-99) and an engine test. The hot tube test involves passing a mixture of oil and air through a heated glass tube, and evaluating the deposits formed inside the glass tube. Figure 1 shows an outline diagram of the hot tube test. Its effectiveness in minimizing deposits was evaluated by investigating the relationship between the deposit generation temperature and the BN. In the hot tube test, the deposit generation temperature was defined as follows: First, the oil under evaluation was tested at various temperatures; the deposit amounts at each temperature were then measured. The amount of deposits versus temperature was plotted, and the calibration curve method was used to estimate the deposit generation temperature. Also a test using an actual engine with fresh oil was conducted. Mid-way through the test the engine was disassembled and the deposits on the piston were then visually confirmed. The BN at this time was

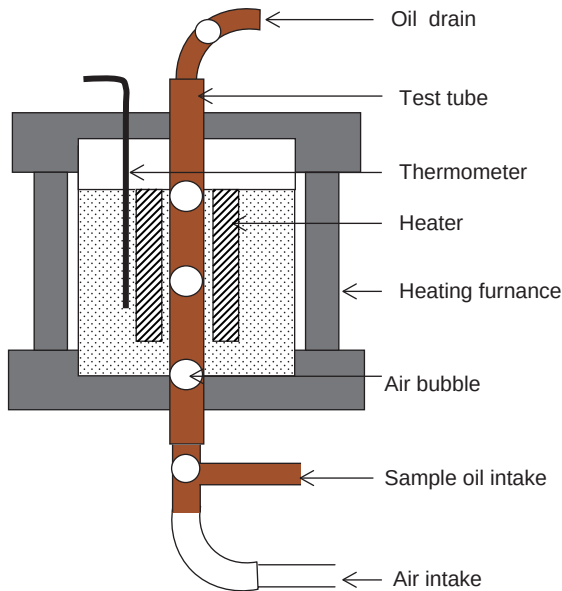


Fig. 1 Hot tube test device

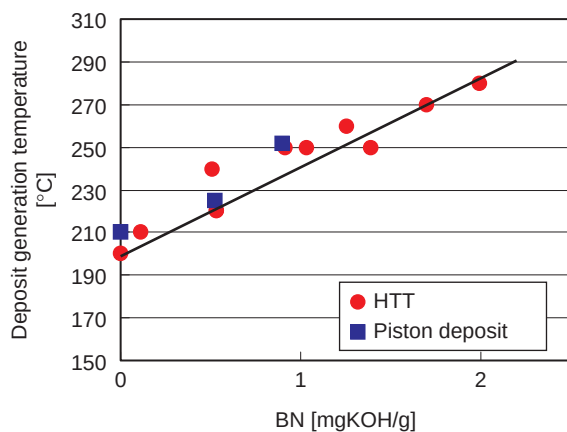


Fig. 2 Relationship between BN and deposit generation temperature

Table 1 Sample lists for deposit temperature preparation

Sample no.	Mileage [km]	BN [mgKOH/g]	Oil	Test
1	4337	2	Honda genuine	Hot tube test
2	4470	1.39	↑	↑
3	5000	1.70	↑	↑
4	6892	0.53	↑	↑
5	7985	0.11	↑	↑
6	9156	2.3	↑	↑
7	10301	3.2	↑	↑
8	12274	3.4	↑	↑
9	13585	1.7	↑	↑
10	16175	1.7	↑	↑
11	18616	1.5	↑	↑
12	25032	0	↑	↑
13	—	0	↑	Engine
14	—	0.52	↑	↑
15	—	0.9	↑	↑

measured to examine the relationship between the deposits and piston temperature. A previously measured value was used as the piston temperature. The oil used is shown in Table 1.

As shown in Fig. 2, a strong correlation between the BN and the deposit generation temperature was seen. A metallic detergent blended with oil basically has the same structure as that of alkaline soap. When the alkali concentration of alkaline soap falls, its effectiveness weakens. It is thought that the detergency of engine oil also weakens as a result of the reduction of the BN, and that this is the reason the deposit generation temperature falls when the BN is reduced. Thus, it can be seen that there is a clear relationship between the BN and high temperature deposits. Generally, the usable range of the BN is between 0.5 and 1.0 mgKOH/g, although this will vary depending on the performance of the engine oil. The present research results indicate that the deposit generation temperature within the usable range of the BN is around 230 °C to 250 °C. This coincides roughly with the maximum temperature of the engine parts which need lubricating oil, and can be considered appropriate as a limit value.

2.2. Relationship between the BN and Metal Wear

Figure 3 shows the relationship between the BN and the metal content of the oil. All of the oil used in the analysis was collected

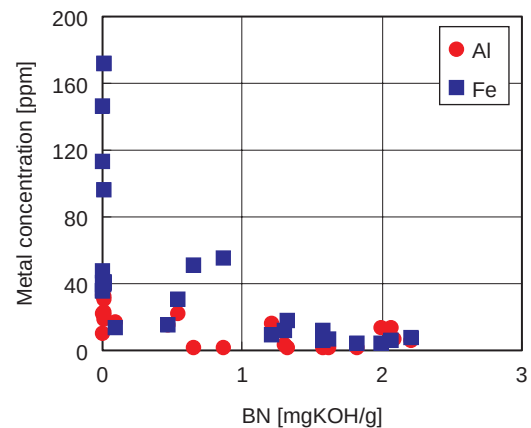


Fig. 3 Relationship between BN and metal concentration

Table 2 Sample lists for metal concentration research

Sample no.	Mileage [km]	BN [mgKOH/g]
1	1931	1.58
2	2000	1.58
3	2000	2.06
4	2982	1.82
5	3000	1.99
6	4000	1.21
7	4280	2.21
8	4532	1.30
9	5000	0.54
10	5038	1.62
11	6001	1.32
12	6371	2.08
13	7833	0.00
14	7895	0.09
15	8983	0.65
16	9182	0.00
17	9200	0.47
18	10552	0.01
19	10901	0.01
20	13937	0.01
21	15000	0.00
22	15648	0.01
23	15825	0.86
24	20000	0.00
25	24630	0.01

from users, and had been used for different travel distances and travel times, and under different conditions. The oil used in the analysis is shown in Table 2. It can be seen that when the BN falls, the metal concentration in the oil tends to rise. This is thought to be that when the BN falls, its ability to neutralize acid is reduced, and as the oil becomes highly acidic, metal dissolves in it. It can thus be said that the BN is an important index of oil deterioration from the viewpoint of metal corrosion and wear.

3. Derivation of an Equation for Calculating the BN Deterioration Rate Based on Empirical Values

3.1. Cause of Deterioration of the BN

Of the factors responsible for the reduction of the BN, the first is the neutralization reaction due to acidic matter generated by oxidation in the oil itself. The second is an external factor such as NO_x, SO_x or an organic acid generated during combustion when the engine is running. It is thought that these acidic matters mix with the oil^{(4),(5)} and react with basic substances such as detergents, causing the BN to fall. The third factor is the occurrence of pyrolysis at high-temperature parts, such as the piston, which causes the BN to fall. To analyze the effect of each external factor, a deterioration test of the engine oil was carried out using an NO_x bubbling test. Figure 4 shows an outline of the NO_x bubbling test apparatus. NO_x gas, fuel composition and water content were used as the external deterioration factors. The test conditions are shown in Table 3. NO gas was used to represent NO_x as investigations of NO_x composition in the crankcase showed that it consisted mostly of NO. NO gas was mixed with air and the mixture blown into the oil. The air was first blown through water to adequately moisturize it, and then mixed with the NO gas. The fuel component used was the residue formed by distilling white gasoline at 150 °C. This procedure collects relatively large molecules so as to simulate the

Table 3 NO_x bubbling test conditions

	Test condition
NO _x (ppm)	0 to 2776
Water	Steam with air
White gas (wt%)	5
Oil temp (°C)	25, 80, 150
Oil 1	Honda genuine-1
Oil 2	Honda genuine-2
Oil 3	Special

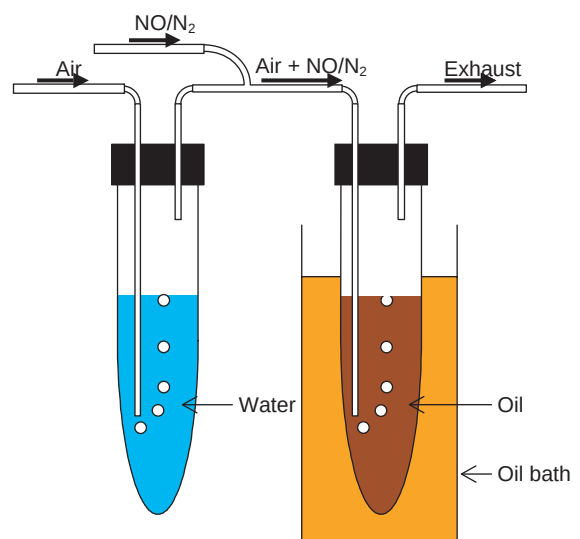
actual unburnt fuel, as well as to oxidize the fuel to a certain extent to simulate the condition of unburnt fuel. The SO_x component depends greatly upon the actual fuel, and in this research the use of sulfur-free fuel was assumed so SO_x was not taken into consideration. The method of measuring the BN is described under JIS and ASTM guidelines, and all BNs used in this report were measured using the hydrochloric acid method based on the method described in JIS K 2501.

3.2. Deterioration of the BN due to Heat

The following are conceivable causes of a reduction in the BN when heat alone is applied to the engine oil.

- (1) Alteration and pyrolysis of the basic additive itself
- (2) A reaction that neutralizes the carboxylic acid generated by the oxidation of the engine oil itself
- (3) Generation of acid due to the oxidation of the engine oil additives (e.g. generation of sulfuric acid due to the oxidation of additives containing sulfur)

NO_x and other causes of deterioration were removed from the engine oil by passing it through an NO_x bubbling apparatus, and the BN deterioration rate when only heat and air blown through the engine oil was investigated. The BN deterioration rate was analyzed, and an attempt was made to indicate the rate as a BN deterioration rate equation. The differential method⁽⁶⁾ was used as the analysis method. As shown in Fig. 5, the order of reaction was estimated to be approximately 2, based on analysis. Here, if it is assumed that the order of reaction with respect to the BN is 2, a deterioration rate equation is defined as Eq. (1).

Fig. 4 NO_x bubbling device

$$-\frac{d[BN]_{Heat}}{dt} = k_1[BN]^2 \quad (1)$$

When the temperature dependence of the BN deterioration rate is measured, and an Arrhenius plot of the deterioration rate coefficient k_1 is made, a linear relationship is obtained as shown in Fig. 6, so it is considered that the BN deterioration rate is that of an Arrhenius type.

3.3. Deterioration of the BN by NOx

As shown in Fig. 7, when NOx is blown into the engine oil, the BN deterioration rate increases. Because the BN deteriorates even when NOx is not blown through the engine oil, it is natural to assume that the deterioration rate term due to NOx can be treated as an independent term in Eq. (1). Here, if the deterioration rate term due to NOx is defined as A_{nox} , the following equation can be assumed.

$$-\frac{d[BN]_{Heat,NOx}}{dt} = k_1[BN]^2 + A_{nox} \quad (2)$$

The second term of Eq. (2) can be obtained empirically by performing tests with and without NOx, respectively, and obtaining the difference between the resulting deterioration rates. Figure 8 shows the relationship between A_{nox} and BN. As a result of these tests, it was found that A_{nox} increases proportionally to the BN. Here, it can be seen that the inclination of A_{nox} has increased due to

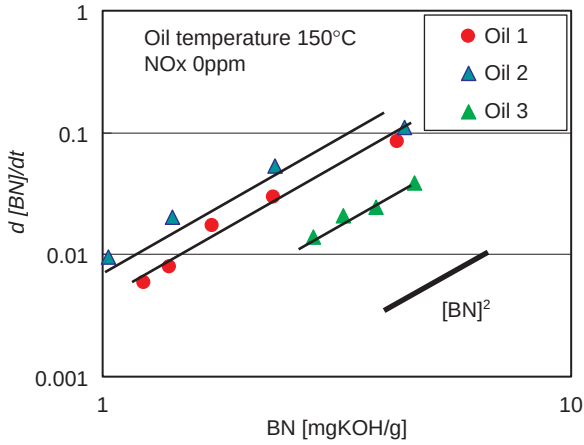


Fig. 5 BN dependence of BN deterioration velocity

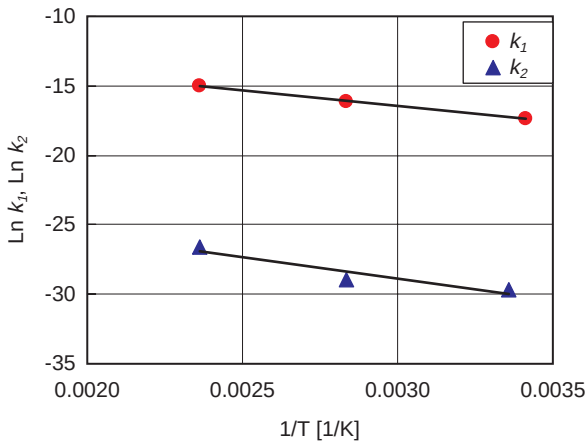


Fig. 6 Arrhenius plot for reaction rate constant k_1 , k_2

the NOx concentration. Figure 9 shows the magnitude of the inclination versus the NOx concentration. It was found that the inclination of A_{nox} is proportional to the square of NOx. In other words, it can be said that A_{nox} is proportional to the BN, and is also proportional to the square of NOx. From the above relationship, it can be considered that if the proportional constant is defined as k_2 , A_{nox} can be represented by Eq. (3).

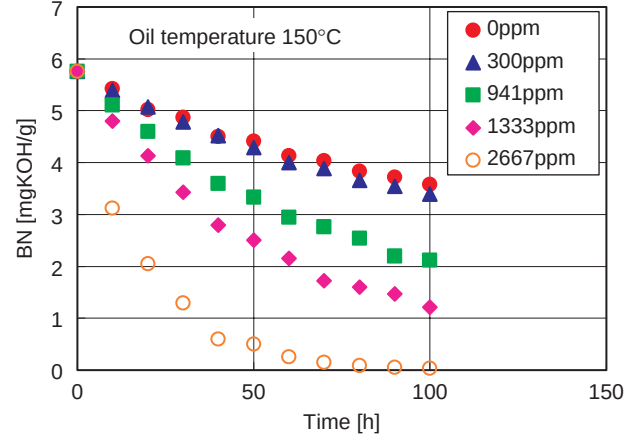


Fig. 7 NOx-dependence of BN degradation rate

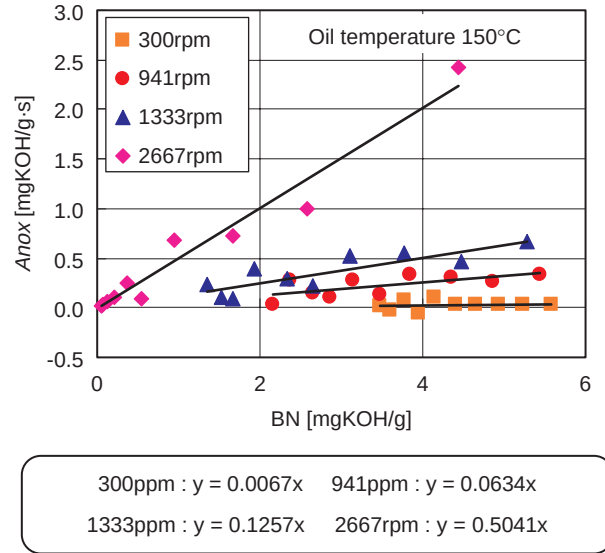


Fig. 8 BN dependence of A_{nox}

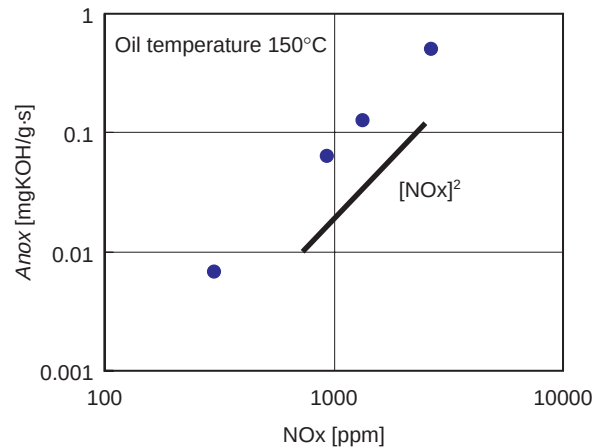


Fig. 9 NOx dependence of A_{nox}

$$A_{nox} = k_2[BN][NOx]^2 \quad (3)$$

In addition, it was found that A_{nox} is also dependant on temperature. In other words, the proportional constant k_2 depends upon temperature, and similar to k_1 , an Arrhenius plot of k_2 produced a linear relationship, as shown in Fig. 5.

3.4. Deterioration of the BN due to the Fuel Composition and Water Content

It is said that generally oil deterioration is greatly affected by unburnt fuel and the water content. It is well known that the existence of water in the engine oil accelerates the dissolution of NOx ions in the oil^{(4),(5)}, and it is thought that it also has a large effect on the reduction of the BN as well. When the oil temperature is low, unburnt fuel is liable to become mixed with the oil⁽⁷⁾. As a result, it is thought that organic acid due to unburnt fuel is liable to be produced, affecting the reduction of the BN. To validate this assumption, the effect of water content and fuel were studied in this research. As a result, it was found that the effects of water content and fuel were either nil or negligible, as shown in Fig. 10. It is thought that the fuel oxidized becomes an organic acid. The organic acid reacts with the base component in the oil to generate a salt, and is neutralized. Generally, an organic acid is weakly acidic compared to hydrochloric acid, for example, and in the BN measurement using the hydrochloric acid method, the salt itself is titrated. Consequently, it is thought that almost none of the organic acid contributes to the deterioration of the BN. Previously, regarding the effect of water content, the existence of water resulted in the precipitation of needle crystals from an Mg-type detergent, causing the BN to drop markedly. This issue has been solved as a result of progress made in additive technology. Also, it was thought that the addition of water would cause the amount of NOx in the oil to increase, which in turn would cause the BN to fall, but no such effect was found in tests performed during this research. There is a report stating that if there is a certain amount of water in the oil, the amount of NOx that dissolves in oil will become a rate controlling factor⁽⁴⁾; it is conceivable that this was an influencing factor.

From the results of the above tests, it is possible to express the BN deterioration rate using the following general equation (k_1 and k_2 are Arrhenius type deterioration rate coefficients).

$$-\frac{d[BN]}{dt} = k_1[BN]^2 + k_2[BN][NOx]^2 \quad (4)$$

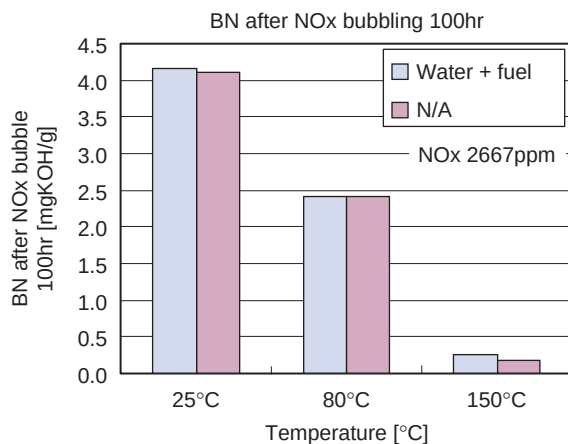


Fig. 10 Water and fuel influence on BN degradation

4. Validation of BN Deterioration in an Actual Vehicle

4.1. Deterioration Rate Equation for Validation using an Actual Vehicle

Using deterioration rate Eq. (4) for the BN obtained from the results of oil tests, a validation test was carried out to see if it was also possible to indicate the BN deterioration due to engine operation. The oil temperature and NOx, which constitute necessary information for carrying out a validation on a vehicle, were measured or estimated using the following method.

(1) Oil temperature

The oil temperature was measured at the oil drain bolt using a thermocouple.

(2) NOx

The concentration of NOx inside the crankcase, which is considered to come into contact with the oil most frequently, was used as a reference for the NOx. Because it is difficult to measure NOx inside the crankshaft of an actual engine using an on-board device, the NOx concentration was estimated from the driving conditions.

When Eq. (4) is applied to an actual engine, the values of contact efficiency between air or NOx and oil are dependent on whether an oil test or an engine test is carried out, so it was difficult to conceive that the deterioration rate coefficient obtained from the oil test could be used as is. Accordingly, the oil was allowed to deteriorate in an actual engine, and the contact efficiency coefficient η was applied to Eq. (4) so that it matched the BN data obtained in this case.

$$\frac{d[BN]}{dt} = \eta \times (k_1[BN]^2 + k_2[BN][NOx]^2) \quad (5)$$

4.2. Results of Validation using an Actual Vehicle, and Estimated Accuracy

Honda genuine oil was used for the vehicle validation. Eq. (5) was used to calculate the BN, and each coefficient used was set for use with Honda genuine oil. Figure 11 shows the correlation between the measured BN analysis values and the value of the BN obtained from calculation, in each mode. The measured values agreed well with the simulation values, indicating that it was possible in practice to estimate the BN without issue.

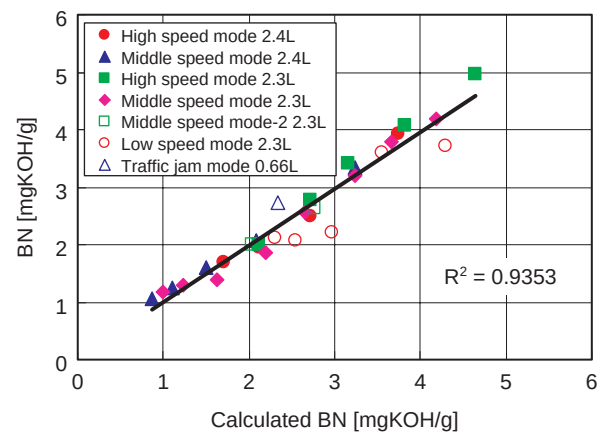


Fig. 11 Correlation between calculation results and actual BN measurement values

5. Considerations

The BN deterioration rate equation proposed in this research was derived from the results of tests using various types of engine oil. For this reason, although there was some apprehension concerning cases where the equation was applied to various kinds of oil on the market, it was found that it could be used with all of the oils tested to present, and so the equation is considered to be highly versatile. It is thought that this is because the basic phenomenon of the deterioration mechanism remains unchanged even when the type of additive or chemical structure that indicates the BN changes. It is known that the deterioration rate coefficient and the BN concentration of the engine oil differ significantly with the type of engine oil, thus affecting the life of the oil. When using the deterioration rate equation to detect the BN deterioration on board, it is desirable to determine the composition for each kind of engine oil and to incorporate the results into the deterioration rate coefficient, as well as to set the BN working limit value for each kind of oil used. Conceivable methods of setting the BN deterioration rate coefficient and the working limit value include methods in which the user enters the kind of oil used manually, or developing a sensor for automatically identifying the kind of oil used. It is also desirable to specify the kind of oil to use, which is frequently being done these days by the European automobile manufacturers. By using a combination of these methods, the BN estimation accuracy should increase, enabling the oil replacement intervals to be increased, and also enabling the construction of a highly effective system for users.

6. Conclusion

In this research, the effectiveness of methods of estimating the deterioration of the BN, which can be used as an index of engine oil deterioration, was determined. Oil tests were carried out, and a detailed analysis was performed. As a result, it was found that there was regularity in the deterioration of the BN, and a general equation describing the rate of BN deterioration was proposed. Use of this equation to calculate the BN deterioration in an actual vehicle showed that the BN deterioration could be adequately estimated using this method. This indicates that it is possible to realize an on-board type BN deterioration estimation system using the abovementioned algorithm.

Acknowledgements

The authors wish to express their sincere gratitude to Showa Shell Sekiyu K.K. and Shell Global Solutions for their kind cooperation in this research.

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