Automatic Control of NO Removal by Ozone Injection Method

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Abstract— NOx from diesel exhaust gases can be removed by the ozone injection method. In order to industrialize the system, it is necessary to develop the NO control system. In this study, we constructed a NO control system without using NOx sensors. The control system adopted two control methods; the ozone control and the discharge power control of ozone generator, and the control values were decided by using neural nets. The NO control experiments were carried out successfully by our system. Regarding the uncertainty of ozone generation characteristics by air condition, we have developed an automatic re-learning method of neural net.

Keywords— Silent discharge, Diesel engine, NOx removal, Ozone injection, Automatic control

1. Introduction

NOx and PM (Particulate Matters) exhausted from diesel engines are one of the causes of air pollution. So far, in order to reduce NOx and PM from exhaust gases, many researches have been carried out [1-3]. However, NOx reduction from diesel exhaust gases were very difficult because large amount of residual oxygen and PM are included in diesel exhaust gases. Especially, oxygen prevents the function of catalysis, which is successfully used for exhaust gases from gasoline engines. Alternatively, the plasma de-NOx technologies have been expected [4]. It is a technology that NO in exhaust gases is firstly oxidized to NO_2, then NO_2 is completely removed by a water scrubber. The technologies have progressed fairly till now [5-8]. Recently a problem of large energy consumption of plasma de-NOx was solved by use of water emulsion fuel or an application of EGR (Exhaust Gas Recirculation) technologies [9, 10]. In addition, a study to use a catalyst together with a discharge is performed [11, 12]. Now, we have come to the new stage. When we wish to apply this technology to the NOx removal of a diesel engine generating apparatus, a technology that controls NOx to a constant level independent on the output is needed. There were a very few reports of the automatic control technologies of plasma de-NOx. Therefore we have been studying the development of the NO automatic control systems, and so far we reported some results of researches of automatic control method of a NOx removal system. The first issue was an automatic NO control by discharge power control [13]. The second issue was a simultaneous control of discharge power and hydrocarbon addition [14, 15]. In this study, we investigated an automatic control method of ozone injection method.

In comparison with direct discharge method, the injection method has a merit that discharge device is not polluted by exhaust gas [16, 17]. As for the feed back control technology, it is the best way to watch the NO concentration with NOx sensor. Actually, the NO control system using a FTIR sensor is reported [18]. However, NOx sensors have problems such as high price and deterioration of sensitivity etc. Therefore in our laboratory we are developing a technology without using any NOx sensor. In case of the ozone injection method, we can adapt two methods. One method is a feedback control of discharge power and the second one is a feed back control of ozone. The discharge power feedback control method has a merit that it does not use any ozone meter. However, this method has a demerit that it can not control the NO concentration precisely, because an ozone generation characteristic changes by temperature and humidity of air. On the other hand, the ozone feedback control can control the NO concentration precisely if NO removal characteristic and ozone generation characteristic does not change. But, this method has a problem that the ozone meter is expensive. So, in this research, we actually investigated both methods. The control performances of the two methods were compared with each other. One of the features of this research is that, the control values of ozone and discharge power were decided by using a neural net. This method has an advantage that even when the ozone generation characteristic changed by environmental conditions such as humidity in air, the neural network can re-learn new ozone generation characteristics automatically. Therefore, this method can solve the week point of discharge power feedback control.

2. NO control system by ozone injection method

2.1 NOx removal and control system

Fig.1 shows the NO removal and control system used in this study. In this system, a 2.4kVA diesel engine was used. After exhaust gas (flow rate; 20m^3/h) was cooled to about 40C by a gas cooler, NO in the exhaust gas is oxidized to NO^2 by injecting ozone gas from an ozone generator. And, then NO^2 is completely removed by a water scrubber containing alkaline solution, though it is not described in the figure.

2.2 Control target and control method

This study is intended to control NO concentration in exhaust gas without using NOx sensor. Therefore, at first

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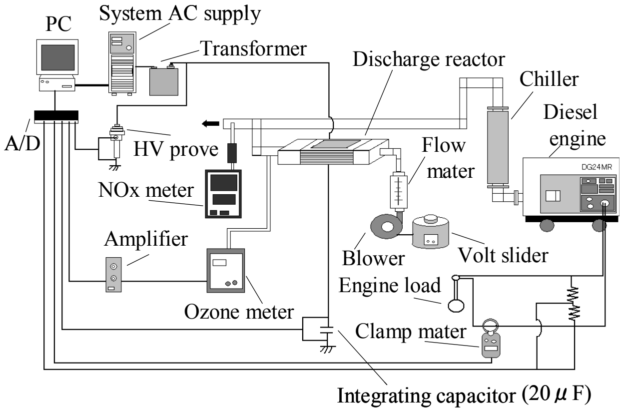

Fig. 1. NO control system

we have to know a relation between engine output power and NO concentration in exhaust gas. Fig.2 shows the relation between engine load and NO concentration in exhaust gas. By using this relation, the initial NO concentration of diesel exhaust gas can be presumed by measuring the load of engine. Next, NO contained in the diesel exhaust gas is oxidized to NO_2 by ozone gas injection (flow rate; $10m^3/h$). The relation between NO concentration and ozone concentration is shown in Fig.3, and the relation between discharge power and ozone concentration is shown in Fig.4 respectively. Using these relations, we can decide ozone concentration and discharge power that are necessary to control the NO concentration to specified values at any engine load. Therefore, in the ozone injection method, an ozone concentration or discharge power becomes the control target. And, by controlling these target values, we can control the NO concentration.

As already described, the ozone injection method has two control methods. When the controlled target is the ozone concentration, "Ozone feedback control" can be adopted. This is a method of observing and controlling the ozone concentration with an ozone meter. When the controlled target is the discharge power, "Discharge power feedback control" can be adopted. In this method, we used a computer program, which calculate the discharge power of barrier discharge from the area of Q-V Lissajous figure.

2.3 Determination of control values

In this system, the control values are decided by the same way, which we developed in the previous work. Namely each control value for NO control is decided by using a neural network. The neural net is a modeling of human brain, which consists of an input layer, hidden layers and an output layer. Each layer has several neurons and they are connected each other by linkage coefficients W_{xy}. The teacher data are given to the neurons of this input layer and to the output layer. Using the back propagation method, we repeat teaching until the neural net learn the teacher's data correctly. As a result, linkage coefficients W_{xy} between neurons are obtained. And, using these data, we can obtain the output data corresponding to any input data, including un-teaching one. Practically, when we wish to know the control value of ozone injection, we let the neural network of Fig. 5 (a) learn the experimental data that we showed in Fig.3. And, a set of linkage coefficient $W_{(1)}$ is obtained. In case of discharge power, the experimental data that we showed in Fig.4 is learned by the neural net of Fig. 5 (b). And, a set of linkage coefficient $W_{(2)}$ is obtained. The ozone concentration or the discharge power at an arbitrary engine output (load) and for the NO control value can be obtained by using these sets of linkage coefficients $W_{(1)}$ and $W_{(2)}$.

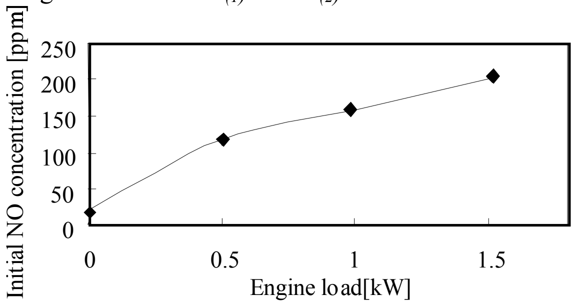

Fig. 2. Relation between engine load and initial NO concentration

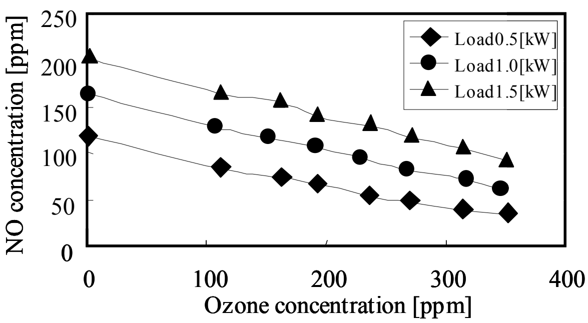

Fig. 3. NO concentration vs. ozone concentration

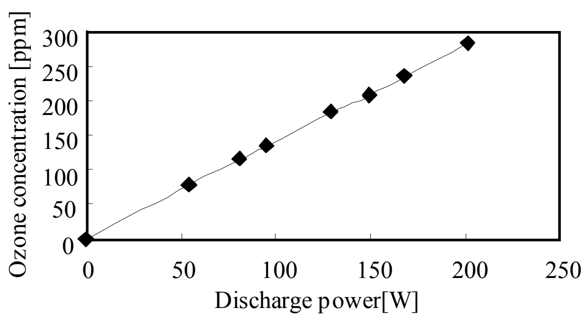

Fig.4. Relation between discharge power and ozone

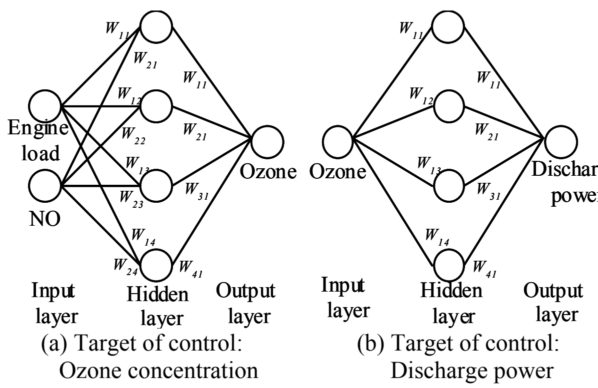

Fig. 5. Composition of neural network

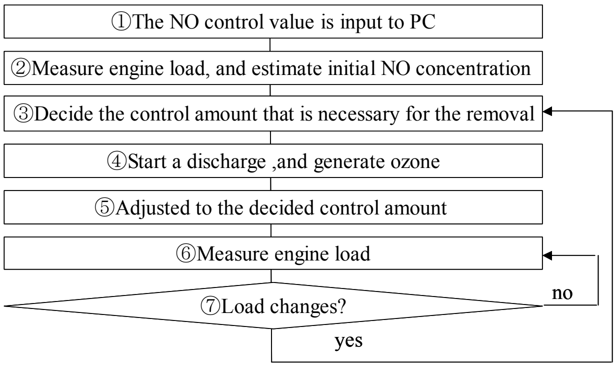

Fig. 6. Flow chart of the NO concentration control method

3. NO control experiments
3.1 Flow of the whole system

In this section, we test whether the NO removal control system works precisely or not. Fig.6 shows the flow of the NO concentration control program developed in this study. The flow of control program is explained as follows;

(1) At first, the NO control value is input in the input data form of PC in ①.

(2) Next in step ②, voltage and current of the engine output are measured. And at the same time, the electric power of the engine load is calculated by multiplying these data with PC. The initial NO concentration is presumed by using the relation shown in Fig. 2.

(3) In step ③, the ozone concentration, which is necessary to decrease the initial NO concentration to the NO control value, is calculated by the neural net of Fig. 5 (a). At the same time, the discharge power is calculated by the neural net of Fig. 5 (b).

(4) In step ④, discharge starts, and the controlled amount of ozone is injected into exhaust gas.

(5) In step ⑤, ozone concentration and discharge power are measured, and they are compared with the control values. If they do not agree, both ozone concentration and discharge power are controlled until the error margin becomes within 5%.

(6) In step ⑥, the engine load is measured again.

(7) In step ⑦, it is checked whether the load has changed. If engine load has changed, returning to the step ③, and new control values of the ozone concentration and the discharge power are calculated.

3.2 NO control experiments

The NO control experiments were carried out using the control program of Fig. 6 and the NO removal system shown in Fig.1. As an experimental condition, we set the NO control value as 120ppm, and we changed the engine load from 1kW to 1.5kW in the following sequence; 1→1.5→1.3→1.5→1kW. As for control method, we used both the discharge feedback control and the ozone feedback control methods. When we input NO control values into the PC program, requited ozone concentration C_{O3}[ppm] and discharge power P[W] are calculated by neural nets. And soon, the control begins. The NOx meter inserted in the exhaust gas line at down flow of ozone injection port measures NO concentration.

Figure 7 and Fig.8 show the measured values of the NO concentration by discharge power feedback control and the ozone feedback control respectively. At first, from Fig. 7, it is understood that independent of the engine load, NO concentration is controlled well to a value lower than control value. It is seen in the graph that discharge power is also controlled well to the order value. Next from Fig.8, it is seen that the ozone feed back control also can control the NO concentration precisely.

When we compare the discharge power feedback control with the ozone concentration feedback control, there are no distinct difference between the two. So we think that the discharge power feedback control without an expensive ozone meter is better. However, because the ozone generation characteristic is delicate to the temperature and humidity of air, the ozone concentration control will be better for precise control of NO concentration.

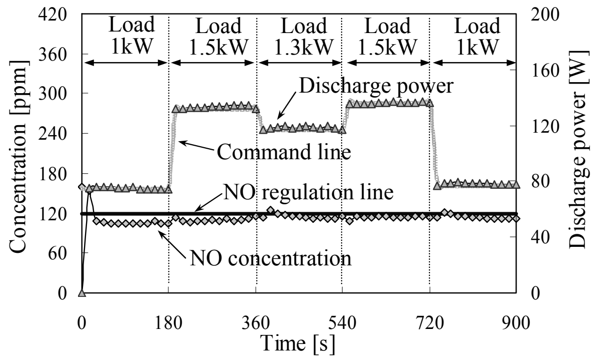

Fig. 7. Automatic control of the NO removal by discharge power feedback control

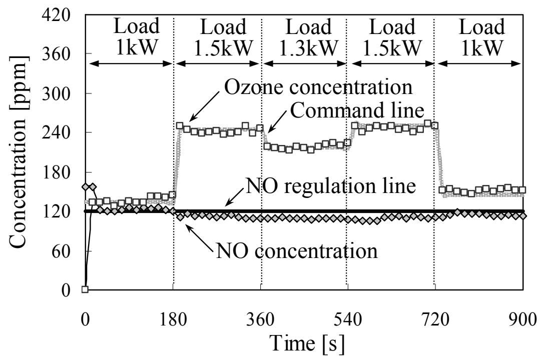

Fig. 8. Automatic control of the NO removal by Ozone feedback control

4. Problems and measures of discharge power control method
4.1 Problems of discharge power control method

As is well known, the ozone generation changes by the temperature and humidity of air. Therefore, precise NO control will not be possible only by discharge power control. However, if possible, it is desirable to controlNO precisely by only discharge power feedback control. In order to realize it, we decided to develop a system in which the ozone generation characteristics are automatically up dated, even when conditions have changed.

4.2 An automatic measurement system of ozone generation characteristic

Figure 9 shows an automatic measurement system of ozone generation characteristics. This system can measure ozone quantity at various discharge power. And the measured data are learned instantly by the neural net, and linkage coefficients can be updated to the latest one. The flow of the automatic measurement system is shown in Fig. 10, and it is explained as follows.

(1) In step ① of the flow, the voltage / frequency of a system AC power supply are set as 40V /50Hz.

(2) In step ②, the primary voltage/frequency is raised by 1.5V/10Hz pitch.

(3) In step ③, the discharge power is calculated by the discharge power measurement program.

(4)In step ④, the ozone concentration is measured by the ozone measurement program.

(5) The voltage and frequency are checked in step ⑤. If they exceed more than 55V/150Hz, go to step ⑥. If not, go to step ③.

(6) In step ⑥, the measurement results of ozone concentration and discharge power under various conditions are learned by the neural net of Fig. 5 (b).

(7) In step ⑦, a new set of linkage coefficients 2 is obtained.

Thus, the relation between the discharge power and the ozone concentration can be automatically revised.

4.3 Discharge feedback control using the automatic measurement system of ozone generation characteristics

We showed that the neural net can learn the new ozone generation characteristics automatically, even if the ozone generation characteristics have changed. Here, it will be verified whether this control system works accurately in experiments. The experimental system shown in Fig. 10 was used. The ozone concentration was set as constant value of 100ppm, and then the discharge was started. When 60 seconds had passed, we changed the humidity of air with a humidifier. Fig. 11 shows a change of the ozone concentration in this experiment. As can be seen in this figure, after 60 second from the start of control, the ozone concentration began to decrease from 100 to around 80ppm by the influence of humidity. Then, at around 80 second, the ozone automatic measurement system operated for about 50 seconds. It is seen that the ozone concentration increased from 60ppm to 290 ppm by the increase of discharge power. And during this period, the program got a new ozone generation characteristics. The neural net instantly re-learn these characteristics, and so after 140 second, the ozone concentration was controlled to 100ppm again. Thus, when we use this control method, even if we do not use ozone meter all the time, accurate control of ozone concentration can be performed by only a discharge power feedback control.

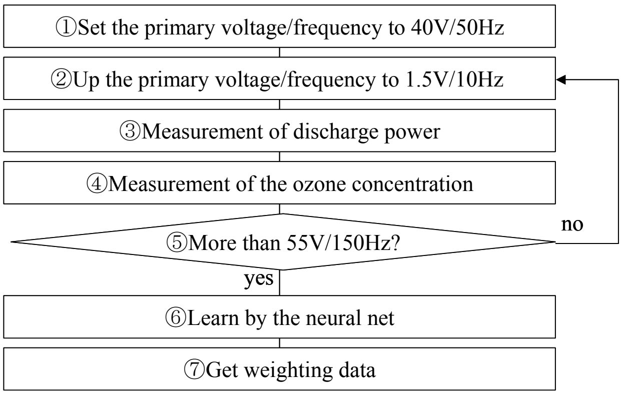

Fig. 9. Flow of automatic measuring system of the relation between discharge power and ozone concentration

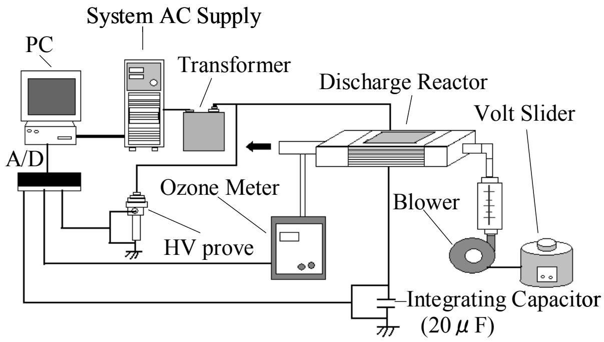

Fig. 10. Automatic measuring system of the relation between discharge power and ozone concentration

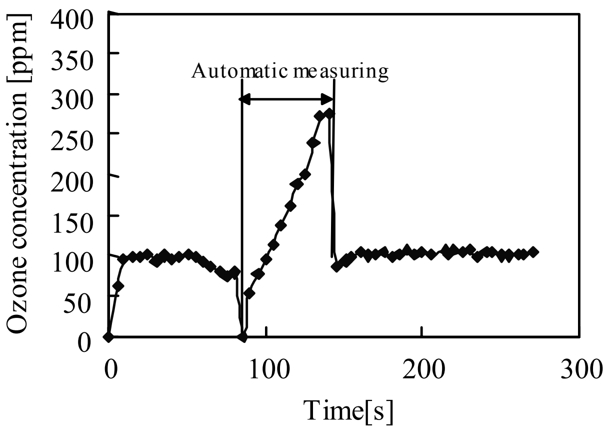

Fig. 11. Change in time of ozone concentration before, during and after the automatic ozone measuring system

5. Conclusion

In this study, we investigated two NO control methods of a NO removal system based on ozone injection and without NOx sensor. We actually constructed a NO control system of NOx removal system from diesel engine by ozone injection method. The system is consisted of engine load measuring system, discharge power measuring / controlling system, ozone measuring / controlling system and a NO control program using a neural net. We performed NO concentration control experiments of diesel engine exhaust gas by both ozone feedback method and discharge power feedback method. As a result, we obtained the following conclusions.

(1) It was successfully demonstrated that both control methods were able to control the NO concentration accurately.

(2) As for the problem that ozone generation characteristics changes with environmental conditions such as humidity, we developed a new method, with which we can let the latest ozone generation characteristics learn to the neural net again. Using this method, even if we do not use ozone meter all the time, the system can control the accurate ozone concentration only by discharge power feedback control.

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