

Evaluation of NO_x Production Rate in Diesel Combustion Based on Measurement of Time Histories of NO_x Concentrations and Flame Temperature

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ABSTRACT

In this study, we evaluated NO_x production rates of diesel combustions occurred in a constant volume chamber of a rapid compression machine in order to investigate relationship between flame behaviors and NO_x emissions. A total gas sampling device was used to measure the NO_x concentration in total gases existing in the chamber at a designated time. An EINO_x (Emission Index of NO_x) production rate was evaluated on the time history of NO_x concentration. Temporal temperature distributions in the chamber were measured with a high speed 2-color thermometry. Gas oil (JIS #2) was used as the fuel. The EINO_x production rate increases with increasing injection pressure through temperature rises in flames due to enhanced mixing of fuel vapor with ambient air. An increase in the ambient pressure causes overlaps between flames formed around the nozzle, which reduces the flame temperature. Nevertheless, high reactant concentrations resulting from the elevated ambient pressure slightly increase the net EINO_x production rate. A reduction of number of injection holes decreases the total surface area of flames formed in the chamber, and then decreasing the EINO_x production rate. In this study, the EINO_x production rate was modeled in terms of the ambient air density, flame volume and reaction rate coefficient of an elementary reaction in the Zel'dovich mechanism. There is a correlation between the results obtained from the prediction model and the EINO_x production rate even though a large derivation remains in the result obtained under the high ambient pressure condition.

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INTRODUCTION

To date, the reduction of NO_x and soot emissions from commercial diesel engines are required in order to meet severe regulations on the exhaust gas. In general, a reduction of NO_x emission induces an increase in soot emission level, which is called 'trade-off relation' [1]. Many previous studies [2, 3, 4, 5, 6, 7] aimed at improving exhaust characteristics including NO_x and soot emissions, in which the effects of injection pressure, boost pressure, number of injection holes and exhaust gas recirculation (EGR) on the emissions were investigated. EGR is a useful means of reducing the NO_x emission even though increasing the soot emission [3,4]. In contrast, increases in injection pressure and boost pressure reduce the soot emission level [2, 3, 4, 5, 6]. Thus, a combination of high injection pressure, EGR and high boost pressure allows for the reduction of both NO_x and soot emissions [3,4] through the optimization of combustion behavior in a chamber. Therefore, further understanding of combustion phenomena occurred in chambers is needed for the control of emissions.

In this study, we focus on the reduction of NO_x emission. Dec and Canaan [8] visualized NO_x concentration distributions in combustion chambers by planar laser-induced fluorescence measurements. In view of the conceptual model [9], the authors concluded that NO_x is formed in thin sheet-like diffusion flames appearing at the periphery of fuel spray. The results obtained from numerical simulations based on multi-zone models [10] demonstrated that NO_x formation occurs in regions with high temperatures, which implies the high sensitivity of NO_x formation to the local flame temperature.

Dec and Canaan [8] also revealed that two third of quantity of NO_x emission is formed at a combustion period, and the remaining one third is formed at the following post-combustion period. The NO_x production at the combustion period should be well controlled by some methods regarding injection pressure, EGR, boost pressure and injector nozzle configuration. In contrast, as pointed out by Dec and Canaan [8], the NO_x formation at the post-combustion period is significantly affected by operation conditions including the

engine speed and compression ratio through temperature variations of post-combustion gases. These significant influences of operating conditions eventually hide the effects of the combustion control on the NO_x emission level. Therefore, the accurate verification of the combustion control methods requires information of NO_x production rate at the combustion period.

For further understanding of relation between NO_x formations and flame behaviors appearing in combustion chambers, we evaluated EINO_x production rates based on time histories of NO_x concentration obtained from dumping measurements [11, 12, 13]. In addition, temporal measurements of temperature distribution in a combustion chamber were made for the purpose of flame observation. In this work, the effects of injection pressure, boost pressure and nozzle configuration on the EINO_x production rate and flame behavior were demonstrated. Finally, we found a simple correlation between flame behaviors and NO_x production rates by use of a model for predicting EINO_x production rate in terms of flame volume, reaction rate coefficient and ambient air density.

EXPERIMENTAL METHODOLOGY

In order to reproduce flame behaviors in combustion chambers of diesel engines, we used a constant volume chamber incorporated in a free-piston type rapid compression machine (RCM). Figure 1 shows schematics of experimental apparatus consisting of RCM, combustion chamber and measurement system based on a 2-color thermometry. The detailed explanation of the apparatus was described in previous studies [12, 13]. The combustion chamber has a disc shape with a diameter of 60 mm and a width of 20 mm. An electrically driven common rail injector is mounted on the base surface of the chamber while an optical window made of polycarbonate is mounted on the other base.

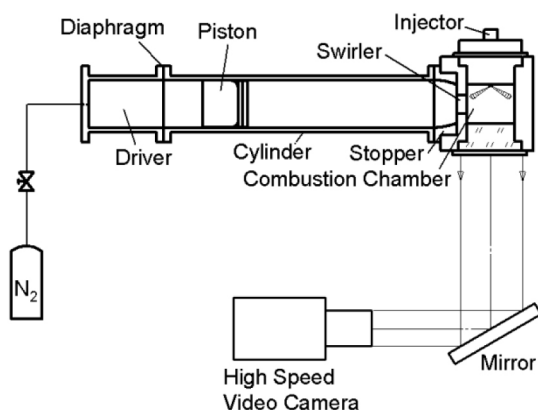


Figure 1. Schematics of experimental setup.

The air accumulated in the cylinder is compressed by the moving piston, and subsequently enters the combustion chamber through a swirler connecting the lateral side of the chamber. The swirler with a size of 14 mm × 16 mm provides a rotational flow in the chamber with an azimuthal velocity of 19 m/s, which is measured at a radial position of 20 mm from the chamber center. The temperature of air existing in the cylinder before compression was adjusted at a designated value by a heater. In order to realize a boost condition, the air in the cylinder was pressurized by a high pressure bottle. The temporal variations of the pressure in the chamber were measured by a piezoelectric pressure transducer (Kistler, 601A).

When measuring a time history of NO_x concentration in the chamber, a total gas sampling device was mounted on the base of the combustion chamber instead of the optical window as shown in Fig. 2. The device consists of an expansion chamber, punching probe and throat connecting the combustion chamber. Diaphragm made of polymer sheets with a thickness of 0.18 mm is inserted at the entrance of the throat. The expansion chamber has a volume of 2000 cm³ filled with an inert gas of nitrogen. Thereby, the combustion gases in the expansion chamber are diluted with the inert gas. At a designated time, the puncturing probe is actuated by an air cylinder, and then ruptures the diaphragm. Thereafter, combustion pressure is rapidly reduced by half in a short time of less than 0.7 ms, which freezes combustion reactions being occurred in the gases. The NO_x concentration in the diluted combustion gas was measured by a gas analyzer (Yanaco, ECL-77A) within a relative error of 0.2 %. In addition, we also measured the CO₂ concentration by an analyzer (J-Science Lab., GC7000) within an error of 0.6 % to estimate emission index of NO_x (EINO_x). The concentration of each species in the combustion gas before dilution was evaluated based on the mass ratio of combustion gas to diluent.

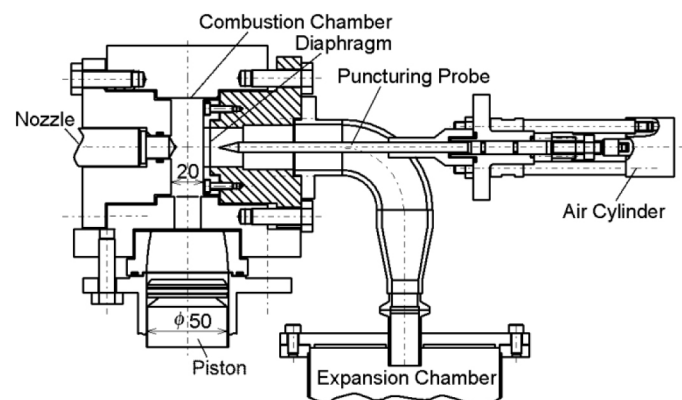


Figure 2. Schematics of total gas sampling device.

In order to measure temporal evolutions of temperature distributions in the combustion chamber, we used a 2-color thermometry system (Mitsui Photonics, Thermera HS) with a high speed camera (Vision Research, PHANTOM V310). Light emitted from a flame is detected by the camera through the optical window and mirror as shown in Fig. 1. According to a radiation theory proposed in a previous study [14], temperature distributions were evaluated on the intensities of light emissions at wavelengths of 536 nm and 611 nm. A processing software provides a value of temperature as 8-bit data in the range from 2023 K to 2973 K, and accordingly the temperature resolution is 4 K. The detectable wavelengths are higher than those of chemiluminescent emissions originated from blue flame, and thereby the measured temperatures can be regarded as those in luminous flames. This means that the flame behaviors obtained from temporal variations of temperature distribution correspond to those in sooty diffusion flames. During the experiment trials, the shutter speed and frame rate were maintained at 0.4 μ s and 20000 fps, respectively. The spatial resolution of the evaluated temperature distribution is 0.02 mm / pixel.

Table 1. Experimental conditions for temperature distribution measurements.

Combustion Chamber Diameter $\times$ Width	60 mm $\times$ 20 mm
Compression Ratio	18:1
Swirl Velocity	19 m/s
Fuel	JIS#2
Fuel Quantity	0.05 mL
Ambient Temperature	850 K
Fuel Injector Nozzle Hole Number (N_h), Diameter (D_h)	Nozzle A: $N_h = 8$, $D_h = 0.112$ mm Nozzle B: $N_h = 4$, $D_h = 0.158$ mm
Ambient Pressure	4 MPa, 8 MPa
Fuel Injection Pressure	100 MPa, 160 MPa

Table 2. Experimental conditions for NOx measurements.

Case	Nozzle	Ambient Pressure P_a MPa	Injection Pressure P_i MPa
1	Nozzle A	4	100
2	Nozzle A	4	160
3	Nozzle A	8	100
4	Nozzle B	4	100

The experimental conditions applied during temperature measurements are summarized in Table 1. Commercial gas oil in Japan (JIS #2) was used as the fuel, and the injection quantity is a constant of 0.05 mL for all the trials. Ambient conditions at fuel injection timings were adjusted by the selection of compression ratio, temperature and pressure in the cylinder air. The ambient temperature at the injection timing was set to 850 K within ± 15 K. The ambient pressure (P_a) was 4 MPa under standard condition and increased up to 8 MPa to simulate boost conditions. The fuel injection pressure (P_i) was varied from 100 MPa to 160 MPa. Because of a constant fuel

quantity, injection period is shortened with increasing injection pressure. In this study, we used two types of injector nozzles having either 8 holes (Nozzle A) or 4 holes (Nozzle B). Both nozzles have the same total area of injection holes, and thereby, the hole diameter of Nozzle B is enlarged from 0.112 mm to 0.158 mm. The spray angle is 140 degree. The dumping NOx measurements with the total gas sampling device were made for four cases described in Table 2. Case 1 is the base condition, and comparison between results for Case 1 and other cases exhibits the effects of injection pressure, ambient pressure and nozzle configuration.

In the previous studies [3][4], the authors focused on combined effects of several factors (e.g. EGR ratio and boost pressure [3], EGR ratio and injection pressure[3][4]) for reducing NOx and soot emissions. On the other hand, we investigated the individual effects of injection pressure, boost pressure and nozzle configuration. In other words, we cannot elucidate the combined effects of these factors in this work. In addition, any experiments regarding EGR, which is a prevailing method for reducing NOx emission, were not made in this study.

Therefore, one may think that the four experimental conditions listed in Table 2 are too few to model the NOx production rate. Modeling of the NOx production rate would require additional dumping NOx measurements under other conditions allowing for the investigations of EGR and combined effects, which is one of our future works.

RESULTS AND DISCUSSION

NOx Production Rate

Figure 3 shows the temporal variations of EINOx defined as the following equation [15],

$$EINOx = \frac{W_{NOx} X_{NOx} \cdot 1000}{(12.01 + 1.008y)(X_{CO2} - X_{CO2,0})} \quad (1)$$

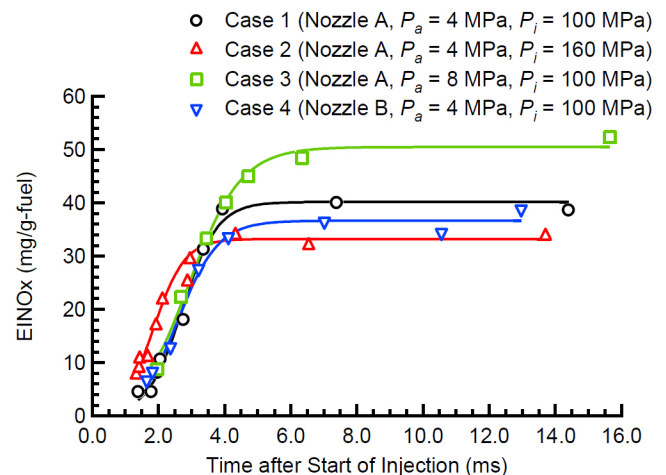


Figure 3. Time histories of EINOx.

Here, X_{NOx} and X_{CO_2} are NOx and CO₂ concentrations measured with the total sampling device, respectively. γ is a H/C ratio (mol / mol) of 1.95 in the fuel used. W_{NOx} denotes the reference molecular weight of NOx. In this study, the weight of NO (= 30) was selected as the reference value. $X_{CO_2,0}$ is CO₂ concentration in the ambient air, and is assumed to be zero in the present analysis. EINOx represents the mass ratio of NOx formed in the chamber to burned fuel.

As shown in Fig. 3, the EINOx value under each condition linearly increases during a duration time from 1.0 ms to 4.0 ms after start of injection, and then approaches to a constant. The steady-state value of EINOx under the high ambient pressure condition (Case 3) is higher than that at the base condition (Case 1). On the other hand, the use of Nozzle B ($N_h = 4$, $D_h = 0.158$ mm, Case 4) and the high pressure injection (Case 2) reduces the steady state value of EINOx. In Case 2, the timing when EINOx starts to increase is earlier than other cases.

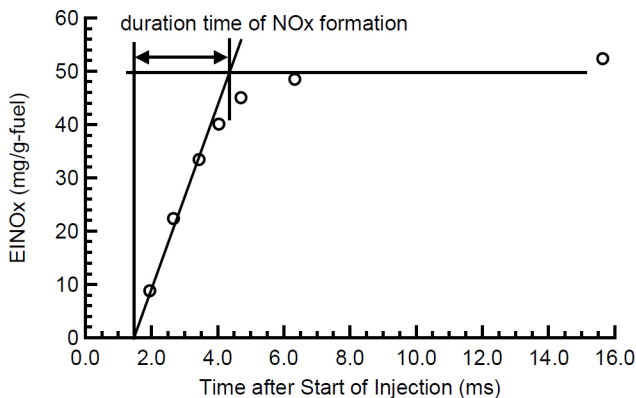


Figure 4. Schematics of determination of EINOx production rate and duration time of NOx formation.

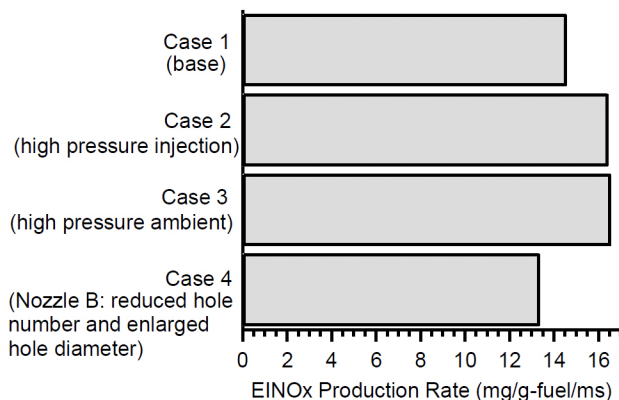


Figure 5. EINOx production rates evaluated with the procedure shown in Fig. 4.

We evaluated the NOx production rate and the duration time based on the time history of EINOx. An EINOx variation at an early stage of NOx formation is approximated to be a linear function, the gradient of which defines the corresponding EINOx production rate. Assuming that the end of NOx formation duration is a time when the approximated line crosses with a line of steady-state EINOx value, we can estimate the duration time of NOx formation as shown in Fig. 4.

Figures 5 and 6 are EINOx production rates and duration times evaluated on the above procedure, respectively. As the injection pressure is increased, the EINOx production rate increases while the duration time drastically decreases, eventually resulting in the lower NOx emission than the base condition. An increase in the ambient pressure increases both EINOx production rate and the duration time. The EINOx in this case therefore is higher than other cases. The use of Nozzle B ($N_h = 4$, $D_h = 0.158$ mm) decreases the production rate while maintaining the duration time. The decrease in the production rate slightly decreases the NOx emission level as a result.

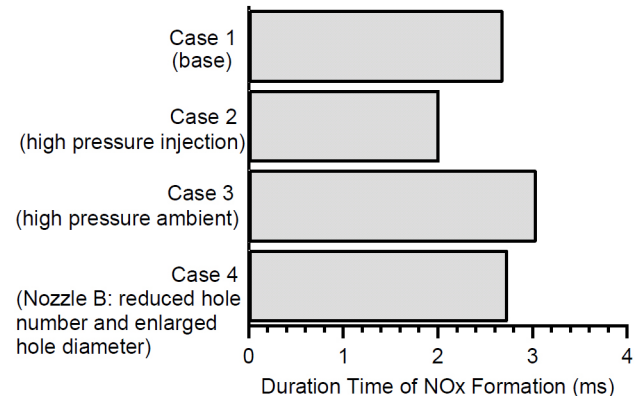


Figure 6. Duration times of NOx formation.

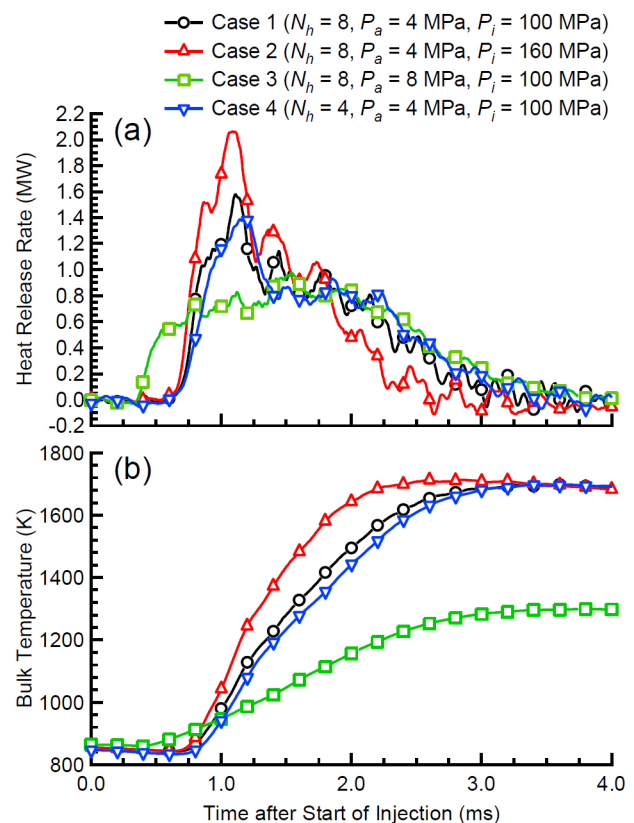


Figure 7. Temporal variations of heat release rate (a) and bulk temperature (b) evaluated based on the pressure measured in the combustion chamber.