

The Effect of the Induction of Nitrogen Oxides on Natural Gas HCCI Combustion

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ABSTRACT

The main aim of this study is to investigate the effect of NO and NO₂ on the combustion characteristics such as pressure development and combustion phasing in natural gas HCCI engine. A secondary aim is to demonstrate a method of obtaining a significant sensitizing effect on methane oxidation reaction from small amounts of NOx. Experiments were conducted using a rapid compression-expansion machine that was constructed from a single-cylinder diesel engine.

First, the sensitizing effect of NO and NO₂ on the HCCI combustion of natural gas was investigated in a case where NOx was uniformly mixed into a charge. Obtained results show that the auto-ignition timing is significantly advanced and an acute heat release is promoted by adding either NO or NO₂.

Second, the effect of non-uniform mixing of NOx into an air-fuel mixture was investigated according to our expectation that the existence of local spots with high NOx concentrations can assist auto-ignition more effectively than the same amount of NOx homogeneously distributed. Obtained results show that when NO and air-fuel mixture are individually inducted into a cylinder, by retarding the NO induction timing to suppress the progress of mixing, combustion phasing is advanced and higher combustion pressure is obtained with keeping the inducted NO amount constant.

CITATION: Kawasaki, K., Kubo, S., Yamane, K., and Kondo, C., "The Effect of the Induction of Nitrogen Oxides on Natural Gas HCCI Combustion," *SAE Int. J. Fuels Lubr.* 7(3):2014, doi:10.4271/2014-01-2697.

INTRODUCTION

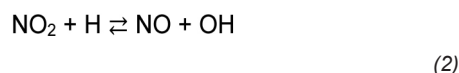
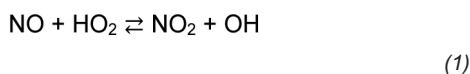
A homogeneous charge compression ignition (HCCI) engine fuelled by natural gas is an attractive power source because of its potential to produce high thermal-efficiency and low emissions of nitrogen oxides (NOx). A natural gas HCCI engine is, therefore, expected to be a new power-source for combined heat and power (CHP) systems, especially for the purpose of achieving a high electricity/heat ratio.

However, the high auto-ignition temperature of methane, which is approximately 1000 K, makes it difficult to promote and control the auto-ignition of a natural gas mixture. Therefore, in addition to a high compression ratio of about 20:1, an ignition-assist technique such as charge heating is required to initiate oxidation reaction at the desired crank-angle timing [1, 2, 3, 4, 5]. Recent studies on a natural gas HCCI engine have reported that charge heating using internal exhaust gas recirculation (EGR), also referred to as burnt gas trapping, is effective in the combustion control of a HCCI engine [6, 7, 8, 9, 10]. The authors have shown that internal EGR based on valve timing control is effective in improving HCCI combustion in previous

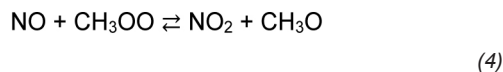
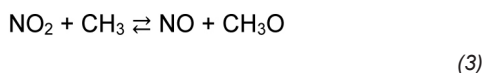
studies [11][12]. In particular, the benefits of a rebreathing technique in which hot exhaust-gas is charged from an exhaust port during the induction stroke have been demonstrated [12].

The principal purpose for applying internal EGR to a natural gas HCCI engine is to raise the temperature of a charge by using the heat of the exhaust gas. It is known, however, that NOx in an exhaust gas such as nitric oxide (NO) and nitrogen dioxide (NO₂) have a chemical sensitizing effect of a methane oxidation reaction. Thus, NOx in a mixture inducted by EGR also may play an important role in promoting auto-ignition.

The chemical impact of NOx on methane oxidation has been studied previously in a flow reactor [13, 14, 15, 16, 17], a jet-stirred reactor [18], and a rapid compression machine [19]. According to these kinetic studies, the presence of NO and NO₂ can promote a methane oxidation reaction based on the so-called NO/NO₂ recycling mechanism in which NOx and hydrocarbons are mutually sensitizing their oxidation. In this mechanism, the formation of important radicals such as OH, reactions such as OH is promoted via the following reactions:



Methane oxidation is also directly accelerated by NO and NO₂ via formation of a methoxy radical as follows:



These sensitizing effects have been experimentally observed under a wide range of pressures, temperatures and fuel concentrations.

The primary purpose of this experimental work is to reveal the effect of NO and NO₂ on the combustion characteristics such as pressure development and combustion phasing in natural gas HCCI engine. A secondary purpose is to demonstrate a method of obtaining a significant sensitizing effect from a small amount of NOx. All experiments were conducted using a rapid compression expansion machine (RCEM) to eliminate the effect of residual gas from a previous combustion cycle. First, the sensitizing effect of NO and NO₂ on the HCCI combustion of natural gas was investigated in a case where NOx was uniformly mixed into a charge. Second, the effect of the non-uniform mixing of NOx into an air-fuel mixture was investigated according to our expectation that the existence of local spots with high NOx concentrations can assist auto-ignition more effectively than the same amount of NOx homogeneously distributed.

EXPERIMENTAL SETUP AND METHOD

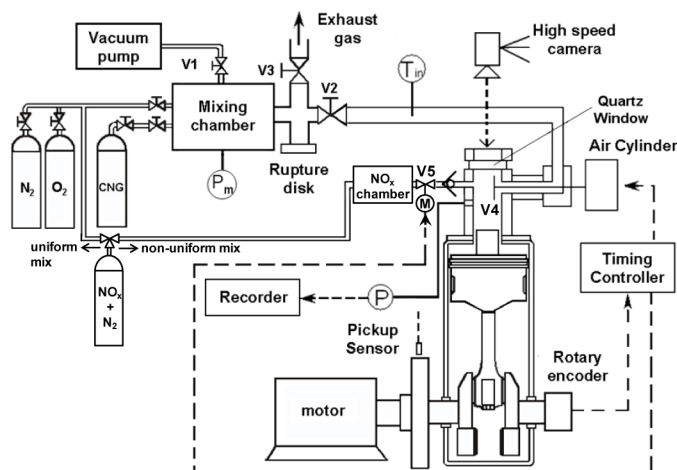


Figure 1. Layout of experimental apparatus

The experiments were conducted on an RCEM, which was constructed from a single-cylinder diesel engine (YANMAR NFD-170, bore=102 mm, stroke =105 mm). Figure 1 shows the layout of the experimental apparatus. A RCEM mainly consists of a modified engine, a mixing chamber, and an electric motor for driving the crankshaft. The air-fuel mixture created in the mixing chamber is compressed to be auto-ignited in the combustion chamber by closing the intake/exhaust valve (V4) which is actuated by an air-cylinder. The inside of the combustion chamber can be observed through an optical window (diameter 30 mm) in the top of the cylinder head.

In this study, NOx was mixed into an air-fuel mixture in two ways. The first one was uniform mixing into a mixture. The second one was non-uniform mixing by inducing NOx directly into the engine cylinder from an additional small chamber of 31 mm³ (referred to as the NOx chamber) connected to the engine cylinder. Each experiment was carried out according to the following procedures.

A. Uniform mixing

- A1. After all valves (V1-V4), except for drain valve V3, are opened, the entire system is evacuated to a pressure of 1.5 kPa. Then, the valves of the mixing chamber (V1, V2) are closed. Note that the NOx chamber is disconnected.
- A2. The mixing chamber is filled with N₂, O₂, compressed natural gas (CNG), and NOx to form a uniform mixture with a prescribed gas-composition and total pressure. Then, V2 is opened so that the mixture is spread throughout the system.
- A3. The piston is driven by an electric motor to move the mixture back and forth between the mixing chamber and the combustion chamber, while the mixture temperature is elevated by electric heaters attached to the mixing chamber and the intake pipe.
- A4. When the temperature at the inlet of the combustion chamber T_{in} reaches a prescribed value, intake/exhaust valve V4 is closed at around BDC (bottom dead center), so that the mixture is compressed and auto-ignited. After the combustion, the piston continues to move for a while with keeping V4 and drain valve V3 open.

B. Non-uniform mixing

- B1. After the entire machine including the NOx chamber is evacuated in the same manner as A1), the mixing chamber and NOx chamber are closed.
- B2. The mixing chamber is filled with N₂, O₂, and CNG. Then, V2 is opened so that the mixture is spread throughout the machine. The NOx chamber is filled with NOx diluted with N₂ at a total pressure of 0.87 MPa.
- B3. T_{in} is elevated in the same manner as A3), while the inside of the NOx chamber is also kept at T_{in} by an electric heater.

B4. When T_{in} reaches a prescribed value, V5 (solenoid valve) is opened during the intake stroke to inject NOx into the combustion chamber. Then, V4 is closed at around BDC to compress the in-cylinder gas.

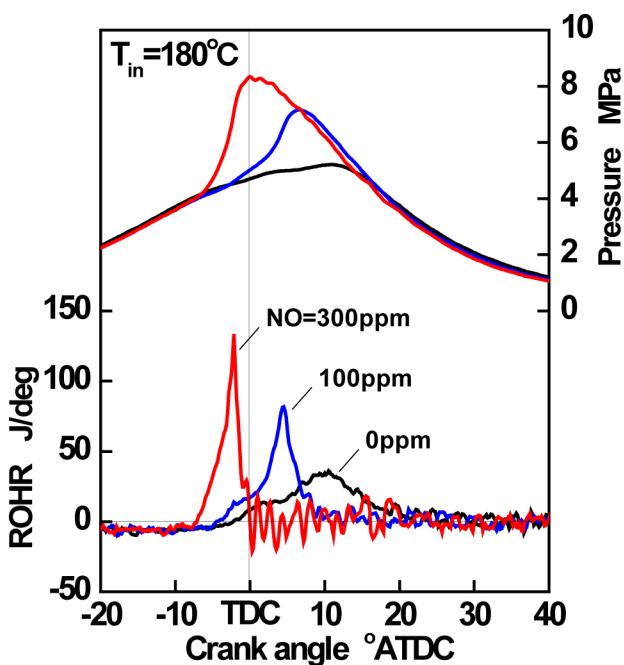
In the case of non-uniform mixing, the induction timing of NO θ_{NO} at which V5 is opened is varied to control the mix between the air-fuel mixture and the NOx. As θ_{NO} is retarded, the mixing period inside the cylinder is shortened so that a larger heterogeneity may remain during the compression stroke.

The engine revolution speed was 600 rpm throughout the experiments. The intake/exhaust-valve was closed at 140° BTDC to obtain the maximum charging efficiency. The effective compression ratio which was determined as the ratio of the volume at intake-valve close timing to the clearance volume was 22.3, while the geometrical compression ratio was 24.2. The CNG used was a standard natural gas which consisted of methane 85vol% and propane 15vol%. NO and NO₂ were supplied from a standard gas (approximately 1000 ppm diluted with N₂). Water at 80°C was circulated around the cylinder liner to keep the wall temperature constant.

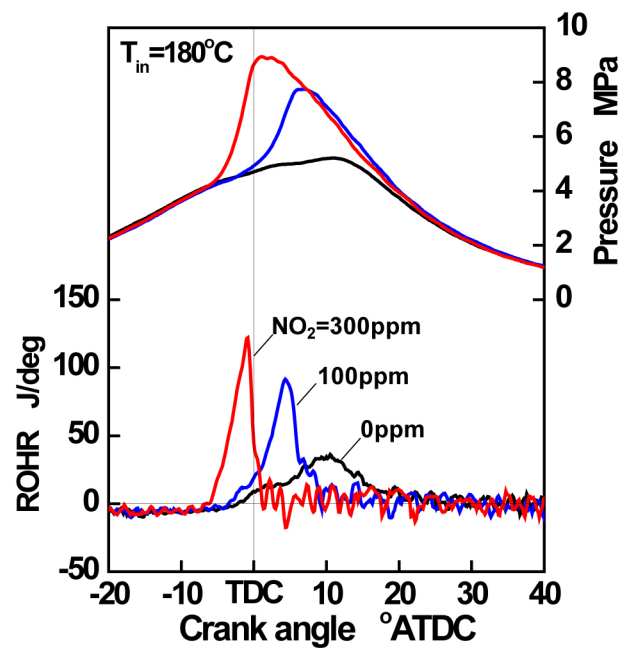
RESULTS AND DISCUSSIONS

The Effect of Nox Addition on Combustion

First, the effect of the presence of nitrogen oxides on natural gas HCCI combustion was investigated. NO and NO₂ were uniformly mixed into a natural gas mixture. The NOx concentration was varied between 0 ppm and 300 ppm in the mixing chamber while keeping the equivalence ratio at 0.45.



a. Effect of NO



b. Effect of NO₂

Figure 2. (cont.) In-cylinder pressure and ROHR with crank angle for different NOx concentrations

Figure 2 shows in-cylinder pressure and rate of heat release (ROHR) with crank angle for different NO and NO₂ concentrations. The effects of NO and NO₂ are compared in Fig. 3 by showing the maximum pressure p_{max} and MFB50 (the timing when the mass fraction of burned fuel reaches 50%), which are calculated from the results of Fig. 2 as a function of NOx concentration. The inlet gas temperature T_{in} is kept at 180°C. Note that measurements were done 5 times for each experimental condition. The pressure and ROHR in Fig. 2 are moderate one-cycle data of each condition, while p_{max} and MFB50 are averages of 5 cycles.

Figure 2 shows that auto-ignition timing is significantly advanced and acute heat release is promoted by adding either NO or NO₂. As a result, the MFB50 is advanced and the maximum pressure is increased as shown in Fig. 3. Furthermore, Fig. 3 indicates that NO and NO₂ have almost the same effect on HCCI combustion. This result corresponds to the NO/NO₂ recycling mechanism in which fuel oxidation is enhanced by radical production through NO oxidation and NO₂ deoxidation reactions.

Next, we evaluate the effect of NOx addition by comparing it with the effect of the increase in intake gas temperature. Figure 4 show the results for $T_{in} = 180^\circ\text{C}$ and 220°C with NOx concentrations between 0 ppm and 300 ppm. For example, the MFB50 for NO = 200 ppm with $T_{in} = 180^\circ\text{C}$ is approximately 0°ATDC , which is almost the same as that for NO = 0 ppm with $T_{in} = 220^\circ\text{C}$. This result implies that the combustion enhancement obtained by adding 200 ppm of NO is almost equivalent to that achieved by raising the intake-gas temperature by 40°C .

Figure 2.