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Reduction of NO in a Spark Ignition Engine with Fuel-Injection System

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The possibility to reduce nitric oxide emission was examined by a dual combustion chamber spark ignition engine with fuel-injection systems. This type of engine enables the combustion process to be controlled by the chamber configuration and the mixture state, both of which are important factors to affect NO formation in a spark ignition engine. The engine was operated in various arrangements of the prechamber and injection nozzle at various fuel injection timings, and variations of the mixture state were experimentally related to NO emission and engine performances.

Models to calculate NO formation in engine cycles are also proposed to support experimental data. The models can be applied not only to a homogeneous charge of an ordinary spark ignition engine but also to a nonhomogeneous or stratified charge associated with such an engine with fuel-injection systems.

1. Introduction

Nitric oxide formation in high temperature combustion gases is affected by the gas compositions and their temperature-time history. In order to reduce NO formation in spark ignition engines, therefore, the condition of fuel-air mixture and the combustion process should be adequately controlled. From this point of view, a concept of stratified charge engine arises.

With a dual chamber stratified charge engine remodeled from a two-cycle gasoline engine, it was found that the engine could be operated even at idling with a minimum cycle-to-cycle variation, and clean exhaust gases were attained as compared with a conventional carburetted two-cycle engine[1), 2)].

The engine is characterized by both the combustion chamber which is divided by an orifice into main chamber and prechamber and the mixture formation by direct fuel-injection into the cylinder. The torch from the prechamber, therefore, ignites the charge in various states.

In this paper, the engine was operated with various combinations of the prechamber and injection nozzle positions at various injection timings, and the variations of mixture state – especially nonhomogeneity and stratification – were related to NO emission and engine performances.

Models to calculate NO formation in engine cycles are also proposed to support experimental data. The models can be applied not only to a homogeneous charge of an ordinary spark ignition engine but also to a nonhomogeneous or stratified charge associated with such an engine with in-cylinder fuel-injection systems.

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2. Experimental Apparatus and Experimental Method

The engine base on which a prechamber type system was mounted is an air-cooled two-cycle gasoline engine as denoted in Table 1. The cylinder head was designed for adaptation of a fuel-injection nozzle and a small prechamber which also has an injection

Table 1. Specifications of the engine used

Type	air-cooled two-cycle
Number of cylinder	1
Stroke × bore	72 × 75 mm
Stroke volume	305 cm^3
Prechamber volume	4.9 cm^3
Main chamber volume	30.3 cm^3
Orifice diameter	8 mm
Type of scavenging	crankcase compression Schnürle type
Port timing	
Scavenging ports	TDC ± 120°
Exhaust port	TDC ± 110°

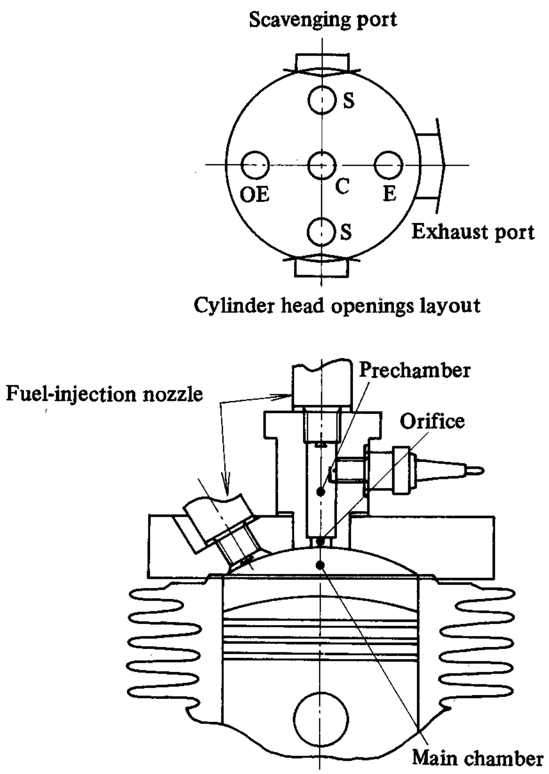

Fig. 1 Cylinder head layout

nozzle and a spark plug, as shown in Fig. 1. Also incorporated into the cylinder head were five openings, one of them being for a pressure transducer and the others for the main injection nozzle and the prechamber. These openings allow various combinations of set-up positions of the nozzle and prechamber.

The fuel-air mixture in each chamber is formed by its own fuel-injection system which consists of an outwardly opening poppet injection nozzle and an injection pump, so that the injection timing and the fuel quantity to be injected in each chamber can be separately controlled. Injection timing was kept at 60° BTDC for the prechamber and varied from 60° BTDC to 120° BTDC for the main chamber. A capacitor discharge ignition system supplies sparks at 5° BTDC in the prechamber.

The engine is ordinarily driven at full-throttle with a constant quantity of fuel injected into the prechamber where ignitions are ensured. The fuel quantity of the main chamber is controlled according to the loads. Exhaust gases are sampled in the exhaust pipe 120 cm down-stream of the exhaust port, and led to nondispersive infrared (NDIR) detectors to measure emissions of CO, HC and NO.

3. Experimental Results and Considerations

Experiments on nonhomogeneous charge include the effects of the injection timing, main nozzle position and prechamber position on exhaust emissions and engine performances.

3.1 Effect of injection timing

Injection timing is supposed to affect the charge state, which possibly includes the uniformity of the concentrations of charge and the charge stratification. The effect of the charge nonhomogeneity can be estimated by use of the combustion chamber in which the prechamber is at the center of the main chamber and the nozzle at E (C-E combination, see Fig. 1). This combination seems to be essentially inert to the charge stratification because of a central ignition of the charge and a minimal flame path, and the variation of injection timing will only affect the nonhomogeneity of the charge.

The experimental results are plotted in Fig. 2, which shows only a little effect of the timing on NO emission. Processes of heat release deduced from indicator diagrams also are almost the same for various injection timings. These results suggest that the effect of the charge nonhomogeneity on NO formation is little. As for the fuel consumption and HC emission, however, a more homogeneous charge would be favourable.

3.2 Injection nozzle position

The injection nozzle position coupled with the injection timing is the important factor affecting the mixture characteristics in the main chamber, especially the charge stratification. Figure 3 shows the performance curves obtained by various positions of the nozzle in each of the prechamber positions of four kinds. The results show that, in one particular position of the prechamber S, the nozzle position obviously affects NO emission

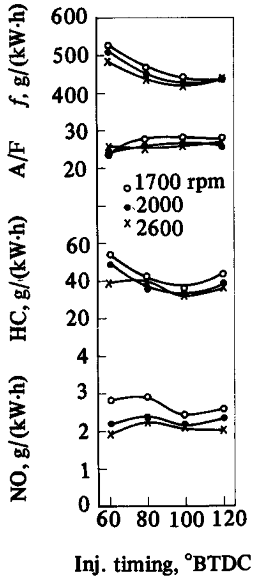

Fig. 2 Effect of injection timing with prechamber at C and nozzle at E, p_e = 0.2 MPa.

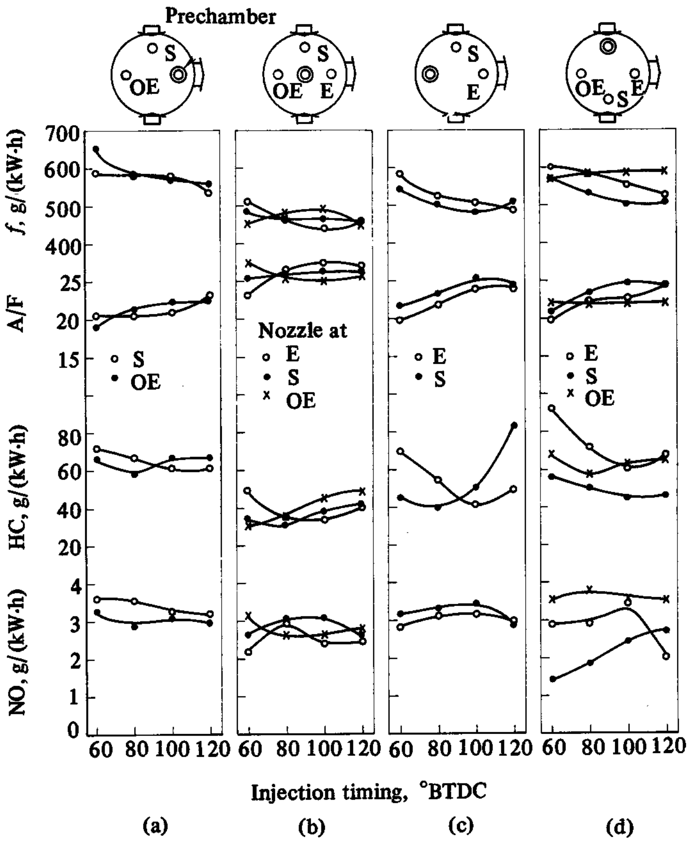

Fig. 3 Effect of nozzle position, n = 2000 rpm and p_e = 0.2 MPa.

but in other prechamber positions the effect is little. S-prechamber is characterized by its position eccentrically located on the scavenging port side, whereas the other positions of the prechamber are located along a line of the exhaust gas flow.

These results would be correlated with the consideration of the air flow inside the cylinder as follows. The fuel-air mixture formed by injection may be more or less spatially uneven in its concentration, and this aspect will be varied by the nozzle position and fuel-injection timing. During the compression process, the mixture is gradually homogenized. But, if the time available is not enough to be fully homogenized, the nonuniformity of the charge – charge stratification – would remain until the initiation of combustion. Taking account of the air motion during the compression process (see Fig. 4 (b)), the charge would be stratified as in Fig. 4 (a), because the mixing within rotating "mixture-disks" in the charge would be stronger than the mixing across the disks.

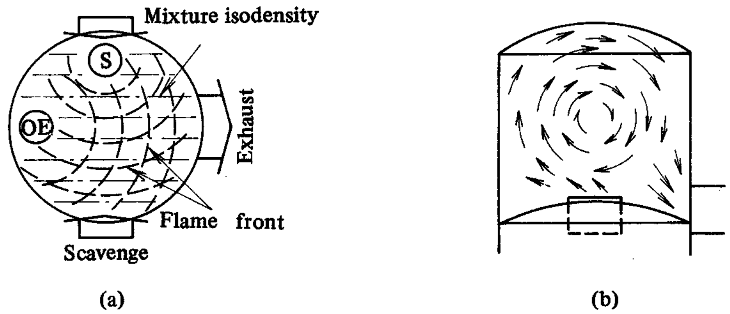

Fig. 4 Schema of mixture formation and flame fronts, and air motion[3] in cylinder.

Suppose, as shown in Fig. 4 (a), a flame propagating from OE towards the stratified charge. In this case, the flame would be nearly normal to the mixture isodensity lines, and the fraction of the charge enveloped in the flame at any instant is indeed nonhomogeneous, nevertheless its average mixture density would be nearly the same through the charge. This situation would occur also in the prechamber positions of C and E. In these cases, the non-homogeneity rather than the stratification of the charge would be essential, and the effect on NO formation is little, as described in Paragraph 3.1.

On the contrary, if the flame travels from the prechamber position of S, the flame fronts would be nearly in parallel with the isodensity lines in the charge. In this case, the density of the mixture portion enveloped in the flame at any instant depends on the charge stratification which is varied by the nozzle position. In this situation, NO emission is different according to the nozzle positions as shown in Fig. 3 (d).

The above considerations suggest that the charge stratification is caused by the air motion in the cylinder and the emission of NO is sensitive to the charge stratification and can be reduced by its appropriate control.

3.3 Prechamber position

It has be seen in the previous paragraph that the variation of the prechamber position affects NO emission because of the charge stratification. In this paragraph the effect of the geometrical change of the flame path caused by the variation of the prechamber position will be dealt with.

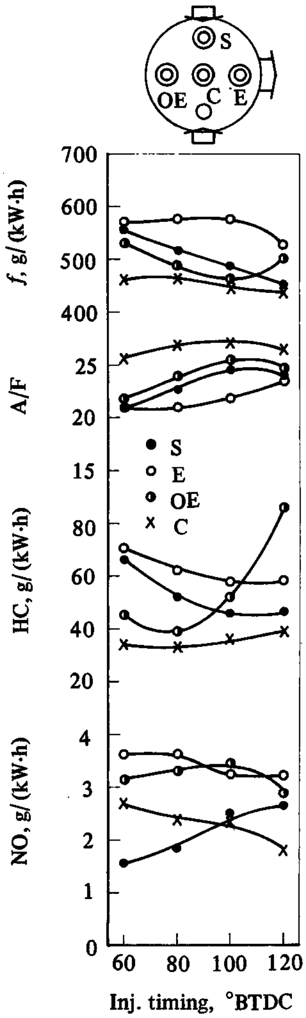

Fig. 5 Effect of prechamber position, n = 2000 rpm and p_e = 0.2 MPa.

Four prechamber positions tested can be classified into two groups, the one, OE, S and E, in which the flames propagate from the side of the quasidiscoid main chamber space, and the other, C, in which the flames from the prechamber first impinge on the piston top at the center and then propagate evenly to the circumference. In Fig. 5 are plotted the performance curves for respective prechamber positions with the injection nozzle at S. As it has already be seen that the effect of the mixture formation is almost negligible with the prechamber at E, OE or C, the comparison of the performances among these prechamber positions would be useful to estimate the effect due to the difference of the combustion process. Figure 5 shows that NO emission found with the prechamber at E or OE is higher than that at C. The indicator diagram obtained with C-prechamber shows that the pressure rise or the combustion rate is lower and the process is more gentle than with other prechamber positions. These facts suggest that, in the case of C-prechamber, in which the flame jet first impinge normal to the piston surface, the jet energy spreading to the surrounding is more or less diminished, and a comparatively long duration of the combustion is resulted in spite of the shortest flame path. But, the mixture turbulence created at the impingement would be effective to the smooth flame propagation through the charge.

On the contrary, in the case of E or OE, a part of the spurting flames is supposed to propagate the bulk of the charge without severe loss of the jet penetration, the combustion being finished comparatively speedily. This difference of the flame propagation may be the main cause of the difference of NO emission seen in Fig. 5. Note that the low emission of NO with S-prechamber is due to the effect of the charge stratification.

It can be concluded that not only low NO emission but also low HC emission and low fuel consumption are obtained by the combustion process with the prechamber C, where the smooth combustion is performed.

4. Simulation Models to Predict NO Formation

The characteristics of NO formation in spark ignition engines are estimated by the calculation. In the simulation models[4)] the adiabatic change of the gas and "unmixed model" are assumed. First, the effect of the operating conditions on NO formation is estimated by the homogeneous mixture model. Then, NO formation in a nonhomogeneous or stratified charge associated with the in-cylinder fuel-injection is estimated on the models derived from the homogeneous model.

4.1 Effect of operating conditions on NO formation

Figures 6 to 9 show the calculated results of the effect of the operating conditions on NO formation in the homogeneous charge. The parameters include air-fuel ratio (A/F), residual gas fraction (EGR), ignition timing and duration ($\Delta\theta_c$), and engine speed (n). Among these parameters, A/F and EGR remarkably affect NO formation, if the combustion process is assumed to be the same.

4.2 Models for nonhomogeneous or stratified charge

Based on the homogeneous model in which the charge is divided along the combustion process into several elements isolated thermodynamically and chemically, the present models are modified by adopting the following additional assumptions.

Each element, though it was homogeneous in the basic model, consists of small mix-

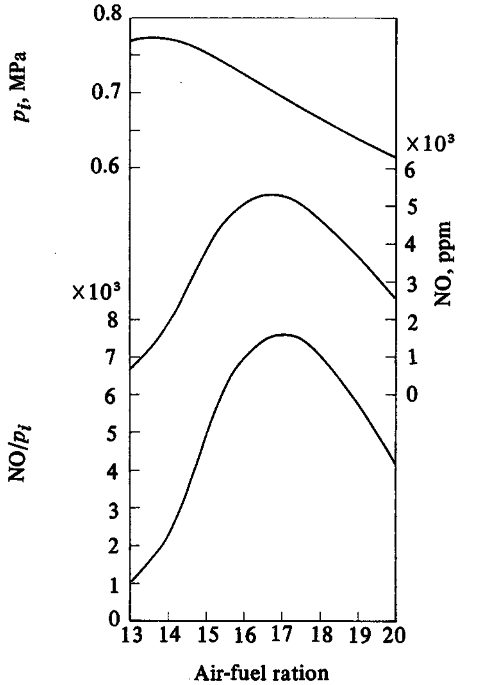

Fig. 6

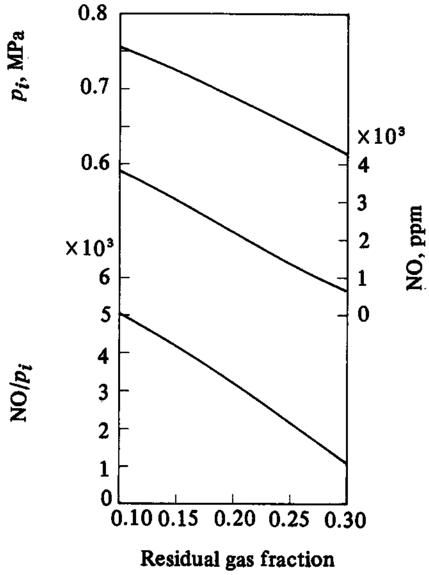

Fig. 7

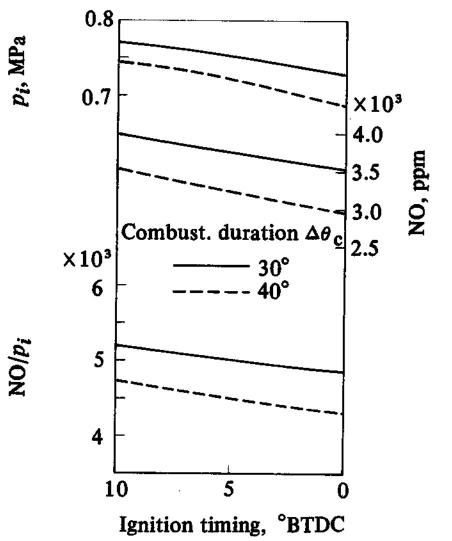

Fig. 8

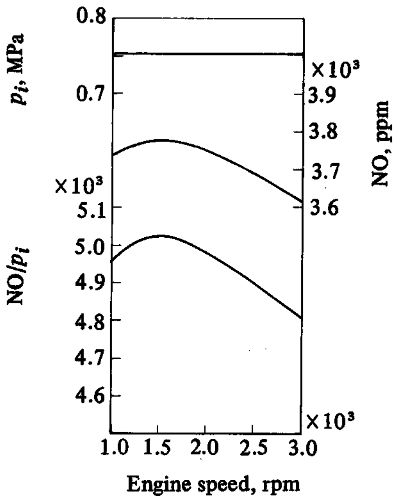

Fig. 9

Figs. 6-9. Calculated results with the homogeneous mixture model. Basic conditions, $\epsilon = 8.5$, A/F = 15, EGR = 0.1, n = 1200 rpm, $\Delta\theta_c = -5° \sim 25°$ ATDC.

ture portions of different A/F, and is gradually homogenized as the time elapses. This situation can be mathematically modeled as follows. Each element consists of portions of five kinds of A/F, and the mass fraction of respective A/F is expressed by a function of the normal distribution. In order to take an effect of the time on the distribution into account, the parameter, distortion σ, is assumed to be a function of the time or engine crank angle. Then, the mass fraction y for A/F = x is expressed as

$$y = \exp\{-(x-m)^2/(2\sigma^2)\} / (\sqrt{2\pi\sigma}) \quad (1)$$

where m is the average A/F for an element in question, and σ is the distortion written as

$$\sigma = \exp\{K/(\theta - \theta_0)\} - 1 \quad (2)$$

where θ and θ_0 are the crank angles at an arbitrary time and at the initiation of fuel injection, respectively, and K is a constant.

The transition of the A/F distribution in an element can be schematized as shown in Fig. 10. The mixture in an element is homogenized as the time elapses, the retarded fuel-injection, therefore, results in the combustion with a less homogeneous mixture.

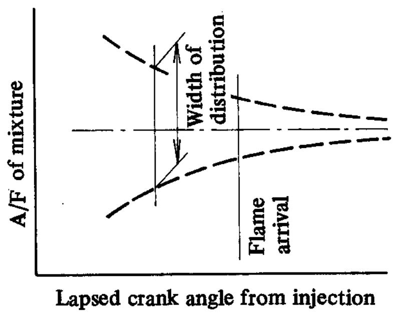

Fig. 10 Schema of the transition of mixture density distribution in an element.

Gas pressure and temperatures can be obtained under these models as follows. The unburned zone is assumed to be the mixture with overall A/F, and the burned zone consists of several elements with five mixture portions. Elements and their mixture portions in the burned zone are mutually isolated thermodynamically after the combustion process begins. Residual gas fraction is assumed to be the same through the charge.

Figure 11 shows the computed results for three kinds of the injection timing for various overall A/F. These results show only a little effect of the injection timing on NO formation, which corresponds to the experimental results given in Fig. 2.

The above mentioned nonhomogeneous model, in which the average A/F in every element was the same and corresponded to the overall A/F, was again modified so as to estimate the effect of the charge stratification. In the remodified model – stratification model –, the average A/F of each element varies according to the stratification of the

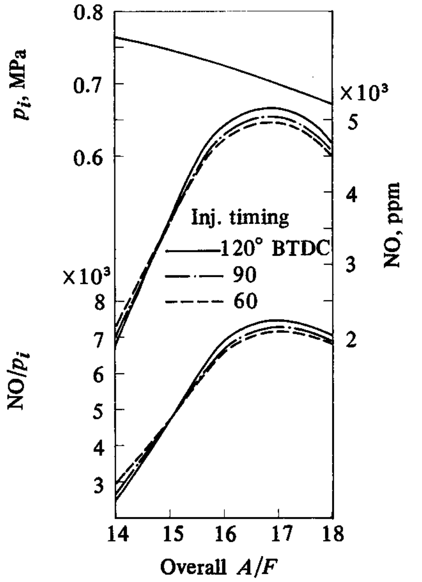

Fig. 11 Calculated results of the effect of injection timing for various overall A/F. Basic conditions are the same as Figs. 6-9.

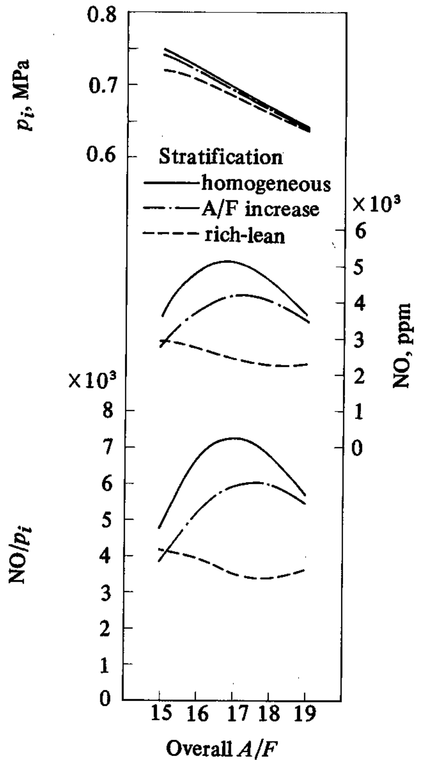

Fig. 12 Calculated results of the effect of charge stratification for various overall A/F. Basic conditions are the same as Figs. 6-9 and A/F difference between initial and end elements is 5.0.

charge. The calculated results with this model are shown in Fig. 12, in which the abcissa indicates overall A/F of the charge. From the figure it can be seen that a favourable pattern of the charge stratification is the two-phase rich-lean charge in which low NO formation can be attained in a wide range of overall A/F. In this pattern the combustion initiates from a richer mixture and progresses suddenly to a leaner mixture. It seems, however, difficult to realize a strict two-phase combustion, and a continuous change of the mixture strength among elements is not avoidable in engine combustion.

The models here offered will be useful to estimate the favourable combination of the charge stratification and combustion process.

5. Conclusions

The effect of mixture condition on NO emission and engine performances was experimentally estimated by the prechamber type engine with direct fuel injection systems. The simulation models for nonhomogeneous charge are also proposed. The conclusions obtained are as follows;

(1) The experiments of the injection timing revealed that the nonhomogeneous charge with no stratification had little effect on NO formation, though the levels of HC emission and fuel consumption were slightly lower with a more homogenized charge.

(2) From the experiments with various set-up combinations of the injection nozzle and prechamber, it was inferred that the charge stratification was caused by the air motion in the cylinder. The stratified charge coupled with the appropriately conditioned flame propagation has a potential to reduce NO emission.

(3) The prechamber position affects the aspect of the flame propagation, and a smooth combustion process yields the low emission of NO.

(4) The models for nonhomogeneous charge predict that the injection timing has little effect on NO formation, but the charge stratification affects it strongly.

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