10 Experimental Study on Pre-Shock Injection for the Reduction of NOx in Diesel Engines

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This paper investigates the effect of two-stage injection, termed pre-shock injection in the paper, as one of the attempts to enhance the mixing of spray tip region where large NOx formation occurred. NOx reduction effect was examined in three different apparatus. The results in a propane jet flame in atmospheric pressure condition and in a actual diesel engine indicated lower NOx emission levels with pre-shock injection. However the result in a constant volume combustion bomb did not show apparent difference by the pre-shock injection. The paper discusses the possibility of the concept and necessary means to achieve the concept.

Key Words: **Diesel Engines, Emissions, Combustion, NOx, Spray, Pre-Injection, Mixing, Turbulence**

1. Introduction

NOx Emission reduction is one of the most important issues in diesel engine research. Some combustion concepts available for the reduction of NOx in partial load range are proposed such as exhaust gas recirculation (EGR) and homogeneous charge compression ignition (HCCI). However there is no concept available in heavy load range. The objective of this research is to identify the possibility of the combustion concept proposed by the authors for the reduction of NOx in heavy load range: i.e. enhancing mixing of spray-tip region.

Based on a simple simulation along the jet axis, Chikahisa et al. (1995) , one of the authors, reported that extremely large amount of NOx is formed at the tip of the jet flame, where the velocity and turbulent structures are different from the steady jet flame [1]. In the steady jet flame, combustion gas passes through the flame region at high velocity, whereas in unsteady jet flame, the flame front loses its momentum with collision to the surrounding air, and the mixing intensity becomes weak at this region. This causes the combustion gas to stay around the high temperature region for sufficient period, resulting in high NOx emissions. This fact indicates that NOx may be decreased if the mixing intensity of the flame tip region is enhanced to the level of steady jet flames; this is because the reaction time for NOx formation is decreased. To confirm the fact, Kaneko et al. (2004) made experiment and numerical simulation, comparing the steady and unsteady jet flames [2]. The result indicated that flame tip region with unsteady jet-flame structure has higher NO concentration than that with steady flame. They also showed that it is effective for NOx reduction to inject inert gas prior to the fuel injection due to making the velocity profile of diesel spray similar to the steady jet. Figure 1 is the typical result of the experiment; it compares propane jet flame injected into atmosphere and the flame with pre-injection of nitrogen. The flame is apparently less luminous with the nitrogen injection.

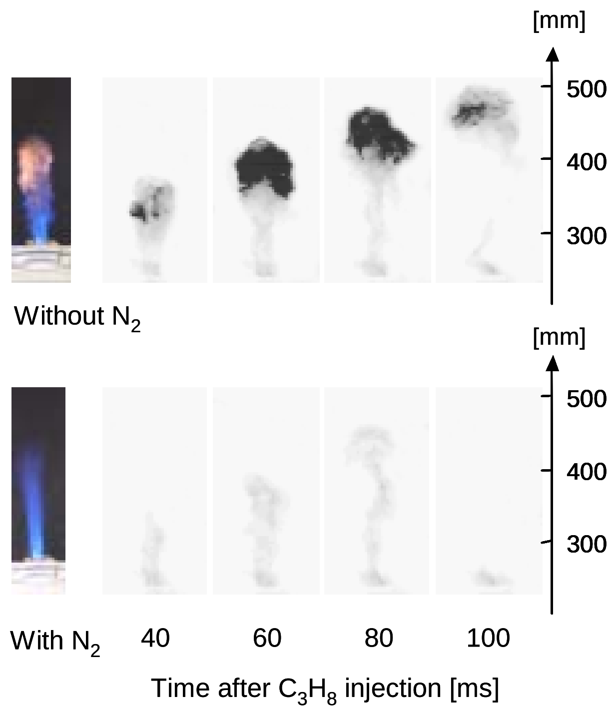


Fig. 1 Experimental result with and without pre-shock injection of N_2 prior to the propane injection: with pre-injection of N_2 the flame apparently becomes less luminous and the total NOx emission amout was less than the case without pre-shock injection.

tion and the measured NOx was 30% less than the ordinal combustion without nitrogen jet. Fujii et al. (2005) made gas sampling to measure NO concentration distribution in the propane jet flame in atmospheric pressure condition, and confirmed the NOx reduction phenomena by injecting inert gases prior to the fuel injection [3]. They also examined to inject fuel twice as a substitute of the inert gases: this was the first proposal of the concept of pre-shock injection by the authors. The result showed decreased NOx by the pre-shock injection, although the reduction amount was not as significant as inert gases.

This paper presents experimental results of pre-shock injection of diesel fuel in a real engine and in a constant volume combustion bomb. The result of the engine experiment showed slight reduction of NOx by the pre-shock injection. However the result of the constant volume combustion bomb did not show apparent difference in NOx emission between with and without pre-shock injection. Photographic analysis was made for the flames in the constant volume combustion bomb, and discussion was made on the possibility of the pre-shock injection concept. The paper first shows the gas sampling result in the propane flames with pre-shock injection in atmospheric pressure condition, which was reported previously. Then the result with a real engine is presented, followed by the results in a constant volume combustion bomb.

In this paper the pre-injection is termed as pre-shock injection, because pilot and pre-injection are commonly used to control ignition time in diesel engines, whereas the present concept is to increase mixing intensity with the injection.

2. Results in a propane jet flame in atmospheric pressure condition

A schematic outline of the experimental setup is shown in Fig. 2. A small pilot torch of hydrogen ignites the propane jet. A high voltage spark fires the small pilot torch at 10ms before the propane injection. The position of the pilot burner was 50mm from the nozzle, which was the optimum position for stable ignition. The injection period of the fuel is controlled by an electric valve. Combustion gas was collected to a sampling bag through a gas sampling valve and a vacuum pump. The opening period of the sampling valve was set 5ms, and the sampling was repeated for 550 times to collect enough volume of gas. NOx concentration was then measured by a CLD analyzer.

Figure 3 shows experimental result of gas sampling. Nozzle diameter is 1.4 mm and the injection pressure is 130kPa. The injection periods are 50ms in transient flames and 400ms in the steady jet flame. The pre-shock injection period was 10ms prior to fuel injection at 0.1MPa. The switching of the injection was done by a couple of solenoid valves connected to the each gas. Gas sampling was made at 90ms after the start of injection in transient flames. In without pre-shock injection, high NO concentration exists in the flame tip region. However, NO concentration in the

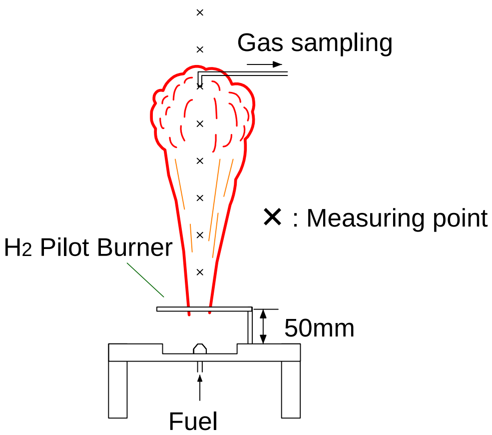


Fig. 2 Experimental setup for the gas sampling

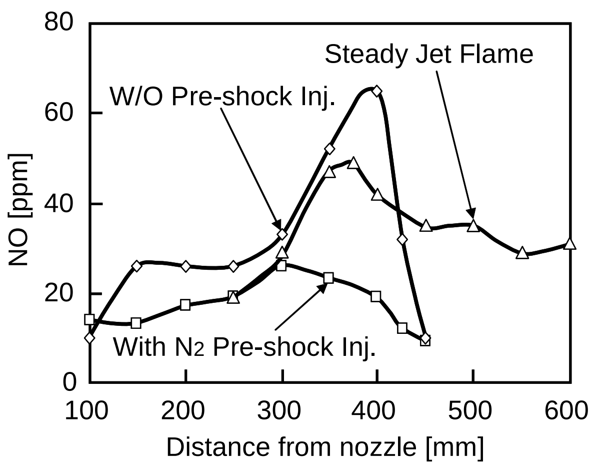
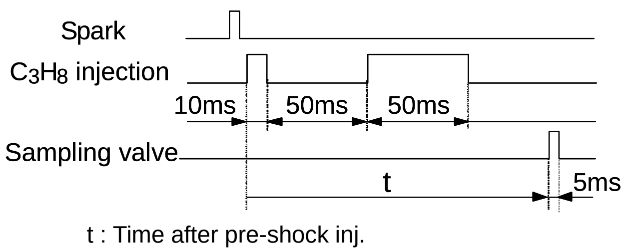


Fig. 3 Comparison of NOx concentration profiles transient flame and steady jet flame at 90ms after start of main injection



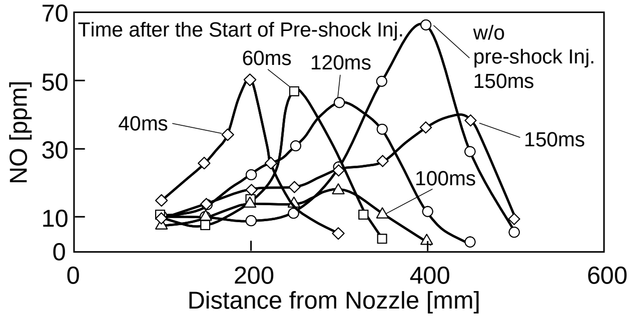


Fig. 4 Changes of NOx concentration profile on the jet axis in C3H8 pre-shock injection

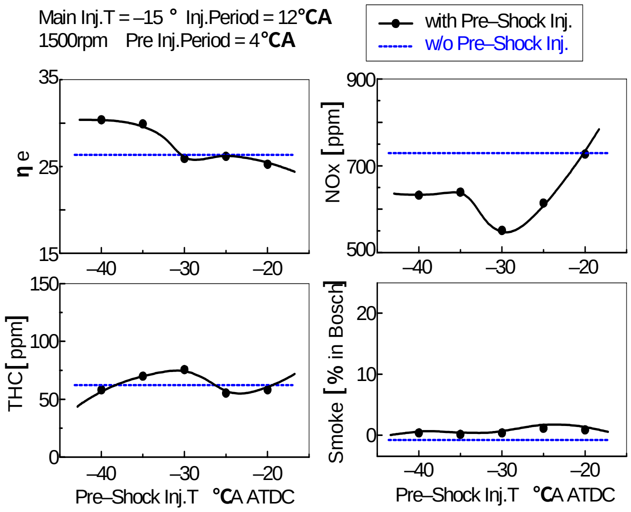


Fig. 5 Results of pre-shock injection in a diesel engine. The Main injection is set at 15 deg. BTDC and the lines show the levels of the ordinary combustion without pre-shock injection.

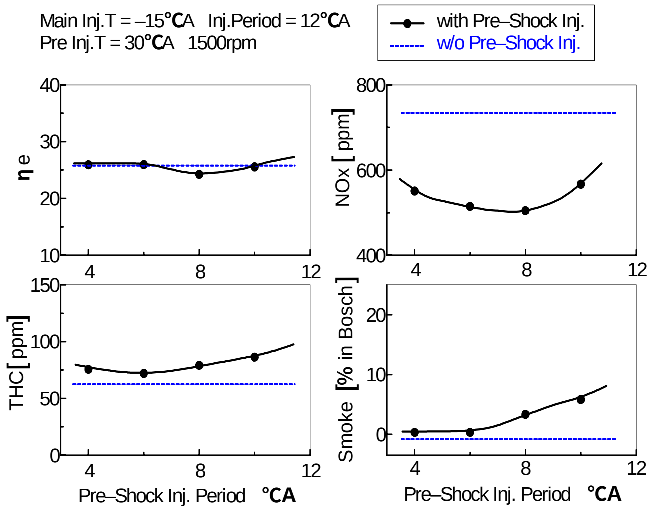


Fig. 6 Effect of pre-shock jet at varios pre-shock inj. periods

flame tip region clearly decreases in the pre-shock injection. The maximum NO decreased to 60% by N_2 pre-shock injection. This indicates that flame tip region in unsteady flame is mixed fast with the surrounding gas by N_2 pre-injection, and the residence time in high temperature condition, which produces large NOx, became short due to mixing.

Figure 4 is the experimental result of the gas sampling, when pre-shock injection of propane was applied to the propane jet flame. The pre-shock fuel is injected for 10ms, and the main injection is made for 50ms after 50ms interval from the end of the pre-shock injection. The result shows the high peak of NO in the transient jet flame without pre-shock injection and it is suppressed to 2/3 by the application of the pre-shock injection. This indicates the possibility of the pre-shock injection with common rail systems of commercially available injection apparatus for the reduction of NOx. The figure also indicates the high NO concentration at the time of 40-60 ms. This appears to be produced from the combustion of the pre-shock flame. This suggests that large amount of NO is formed even from small flame as pre-shock jet. Actually there are many experimental results reporting that pilot injection in practical engines did not reduce NOx successfully, and even homogeneous charge compression ignition produced large NOx emission when the pilot injection was applied as a ignition controller. To maximize the NOx reduction effect by the pre-shock injection, it may be necessary to control ignition of the pre-shock fuel: i.e. it may be possible to have mixing effect without producing large NOx in the pre-shock fuel if the pre-shock fuel is diluted enough to avoid NOx production before the fuel is covered by flames of the main injected fuel.

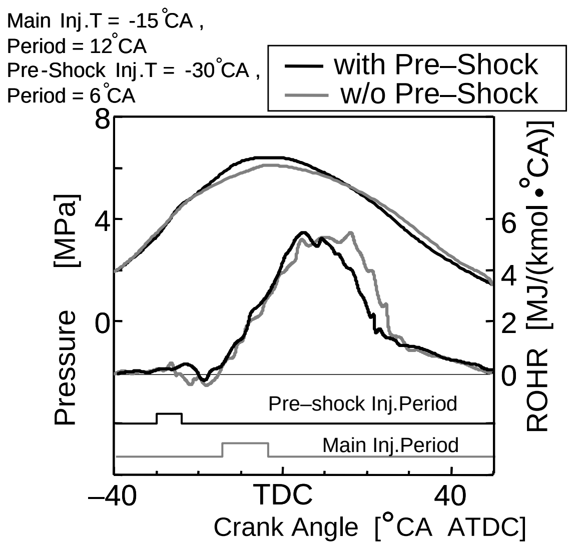


Fig. 7 Comparison for the effects of pre-shock injection

3. Results in a real diesel engine

Using a common-rail injection system, double injection was attempted in a four-stroke single cylinder diesel engine of 693cc displacement. The first injection was used as the pre-shock injection.

Figure 5 is a result of the experiment showing thermal efficiency and emissions for the different timings of the pre-shock injection. The lines in the figure indicates the level of the ordinary combustion without pre-shock injection. Compared to the ordinary combustion, NOx decreases apparently at the timing of 30 deg. BTDC of the pre-shock injection, and the other emissions and thermal efficiency are maintained at the same level of the ordinary combustion. The amount of the main fuel is set equal between the two cases with and without pre-shock injection, so that the total fuel amount is larger in the case with pre-shock injection than the other case.

Figure 6 is the result for different pre-shock amounts expressed with injection periods. The injection timing of the pre-shock injection is 30 deg. BTDC and the amount of the main injection is set constant. Apparent NOx reduction is observed with the pre-shock injection and the maximum reduction is obtained at the pre-shock injection period of 6-8 deg. CA, when other emission and the thermal efficiency are maintained.

Figure 7 is the indicator diagram and the rate of heat release comparing the effect of the pre-shock injection. Pre-shock fuel burns prior to the main fuel combustion: this suggests that the main fuel is injected in the flame of the pre-shock fuel. As mentioned previously large amount of NOx can be formed even in the small flame of pre-shock fuel, so that the further NOx reduction may be expected if the combustion of the pre-shock fuel could be controlled.

4. Results in a constant volume combustion bomb

Similar experiment was conducted in a constant volume combustion bomb, and flame behavior was observed. The volume of the combustion bomb is 236cc (ϕ100×30mm). A schematic outline of the experimental setup is shown in Fig. 8. To make a high temperature and high pressure atmosphere before fuel injection, pre-mixed charge of hydrogen, nitrogen and oxygen was ignited to leave 21% of oxygen after combustion. The mixture ratio of the gases filled in the bomb is shown in Table 1. To make a well mixed charge, the gases are mixed in a different vessel and left for enough

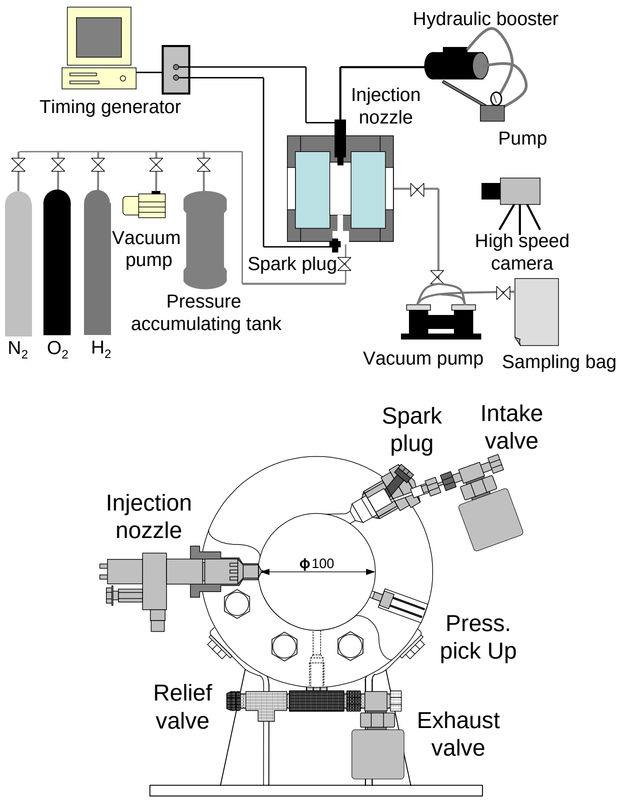


Fig. 8 Setup of a constant volume combustion bomb

Table 1 Mixture ratio of the pre-mixed gas for the constant volume combustion bomb.

N_2	0.58MPa
O_2	0.27MPa
H_2	0.15MPa
Total	1.00MPa

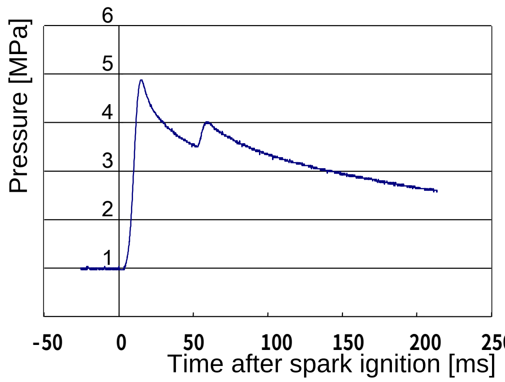


Fig. 9 Example of pressure diagram

period to complete mixing. The gas charged in the bomb is ignited by the spark plug, and then fuel is injected in the chamber through the nozzle at the time when the pressure in the bomb becomes 3.5MPa (the temperature 900K). The injection nozzle is electrically controlled and the fuel is pressurized by a hydraulic booster. An example of the pressure diagram in the bomb is shown in Fig. 9. The NOx amount produced by the combustion of the pre-mixed charge was about 30~50ppm. After completion of the combustion of the injected fuel, combustion gas was collected to a sampling bag through a vacuum pump. The gas was then measured for NOx with a CLD analyzer. The picture of the flame was taken through a glass window by a high-speed video camera.

Figure 10 is the results comparing NOx concentration for different intervals between the pre-shock and the main fuel injection, together with the result without pre-shock injection. Here, the ratio of the injection periods of the pre-shock and the main injection is 50:50, and the time sequence for the case is shown in Fig. 11. The total amount of the injected fuel is the same between with and without pre-shock injection. Injection pressure was set 90MPa, and the hole diameter of the injection nozzle was 0.28mm. Fuel is injected at 50ms after spark ignition, when the flow inside the bomb is weak. The result of the experiment shows increased NOx with the pre-shock injection compared to the case without pre-shock injection. Each experiment was made five times for the same condition. It was found that 380 ppm of NOx is formed by the combustion of the pre-shock fuel. This corresponds to about 65% of the total NOx of 1.0ms injection.

Similar experiment was conducted for the smaller pre-shock fuel amount: pre-shock and the main fuels are 30:70. The results are shown in Fig. 12. Because of different series of the experiments, the NOx level without pre-shock injection

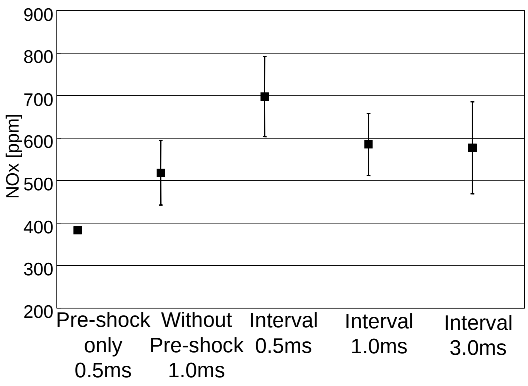


Fig. 10 Result of NOx concentration mesurement for the case of pre:main=50:50

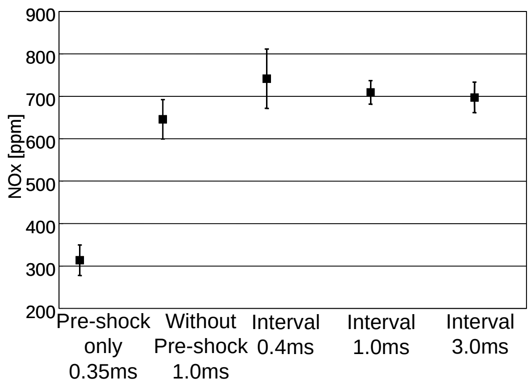


Fig. 12 Result of NOx concentration mesurement for the case of pre:main=30:70

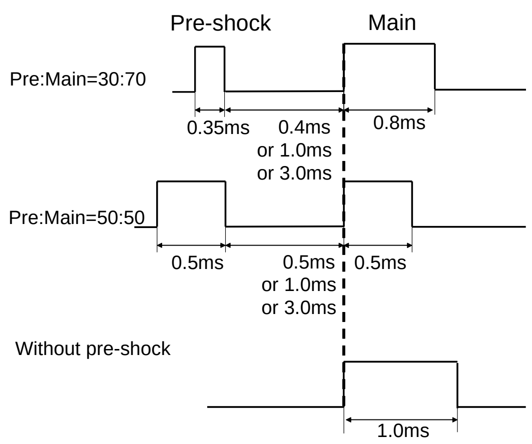


Fig. 11 Time sequence of injection

are not same between Figs. 10 and 12, which should be identical, though. This point must be investigated further, but the result shows that the pre-shock injection increases NOx similarly to Fig. 10. The amount of the increased NOx is smaller than the previous case in Fig. 10. The NOx amount produced by the combustion of the pre-shock fuel is 310 ppm this time, 45% of the total NOx of 1.0ms injection.

The above result indicates that large amount of NOx is formed in the combustion of the pre-shock fuel, and this must be decreased by the control of the combustion of pre-shock fuel.

Figure 13 compare the pictures of flames between with and without pre-shock injection. The flame of the main injection fuel penetrates more in the case of pre-shock injection than the case without pre-shock injection. This indicates that the secondary spray penetrates in the flow created by the pre-shock spray, and the flame structure

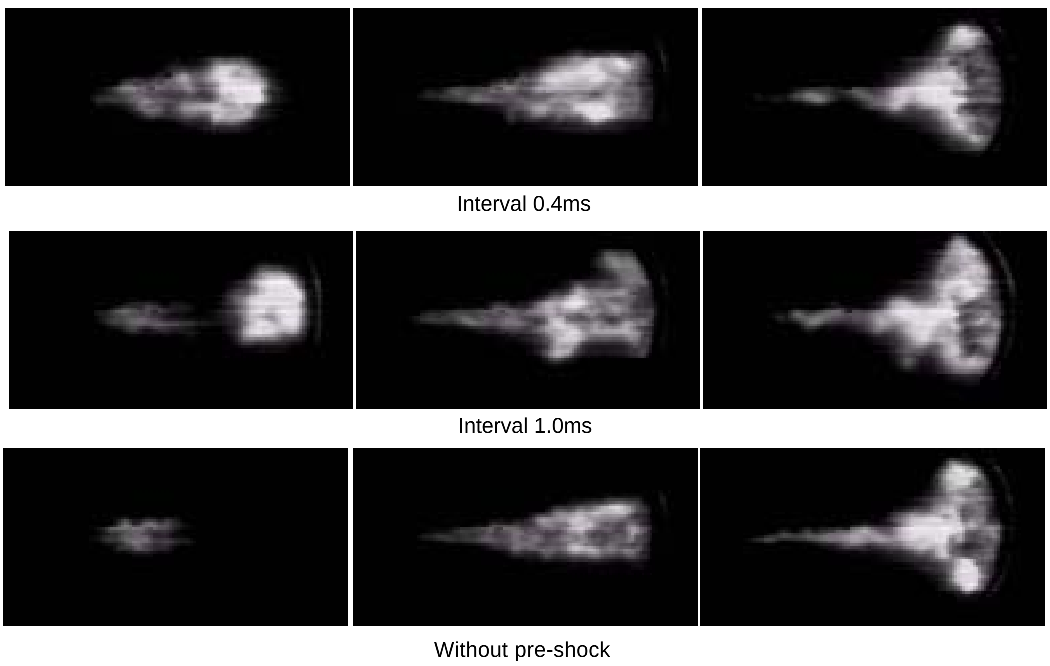


Fig. 13 Pictures of flames for the case with pre-shock injection (above and middle): the injection periods of pre:main is 30:70 and the case without pre-shock injection (below)

becomes closer to the steady jet at this moment. But the flame front of the secondary spray soon takes over the pre-shock flame and the development of the flame becomes similar to the case without pre-shock injection.

Thus the difference between the two flames appears to be small, and much larger jet should be created to have enough effect of the pre-shock injection for mixing. At the same time, however, the amount of the pre-shock injection is limited by the large NOx formation characteristics in the flame as mentioned above. These two limitations suggest difficulty of the NOx reduction by the simple double-injection method unless the ignition of the pre-shock fuel is controlled.

The reason is not clear yet why the pre-shock injection reduced NOx in a real engine but it increased NOx in a constant volume combustion bomb. The differences in the two conditions are (1) the amount of the pre-shock fuel relative to the main fuel, (2) turbulence in the field, and (3) pressure variation due to the piston motion. The difference may cause the different results in NOx reduction, but in ether case the NOx reduction extent appears to be small with the double-injection as mentioned above. To obtain substantial reduction in NOx emission, much stronger turbulent mixing is necessary.

5. Conclusions

Pre-shock injection concept is proposed based on the fact that most of the NOx is formed in the flame tip region where the mixing intensity is weak and the residence time in the high temperature region is quite long. The result of the variety of experiment indicated the possibility of the pre-shock injection. The results obtained by the research are the followings:

(1) The experiment of double injection in atmospheric pressure condition and in a real engine showed NOx reduction effect. Large amount of NOx can be formed even in the small flame of pre-shock fuel, so that the further NOx reduction may be expected if the combustion of the pre-shock fuel could be controlled.

(2) The experiment in a constant volume combustion bomb did not show NOx reduction effect. To obtain significantly NOx reduction effect, the pre-shock injection should be much stronger mixing intensity like turbulent jets without producing NOx from itself.

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