JOURNAL OF CRITICAL REVIEWS

ISSN- 2394-5125 VOL 8, ISSUE 04, 2021

NOX REDUCTION IN DIESEL COMBUSTION BY ENHANCED MIXING OF SPRAY TIP REGION

KIRANMAYI VEMIJ,RAMAKRISHNA GOLLA,MOUNlKA VELPULA
Dept of Mech, Sree Dattha Group of Institutions, Hyderabad, Telangana, India

In diesel combustion it is commonly known that NOx emissions increase when the fuel injection velocity increases. On the other hand, increased fuel velocity reduces NOx in steady jet flames due to a decreased residence time in the flame region. To answer this contradiction, the authors have made variety of experiment and numerical simulation. The results indicated that the large NOx formation in diesel engine is due to the weak mixing intensity in the spray tip region, where the flow and turbulence structure is quite different from the continuous jet flames. The fact indicates that there is a possibility of reducing NOx from diesel engines by enhancing mixing intensity at the spray tip region to the level of continuous jet flame. As one of the attempts to make the velocity profile of diesel spray similar to the steady jet, an inert gas was injected prior to the fuel injection in a model apparatus in atmospheric pressure condition. The result showed that the flame apparently became less luminous by the pre-injection of nitrogen, and the NOx emission index was two-thirds of the non pre- injection case. Numerical simulation also showed the effect of pre-injection for the reduction of NOx. The paper presents the experimental and numerical simulation results together with photographic analysis of enhanced mixing of spray tip region when water was injected as the pre-injection for increasing mixing.

Key Words: NOx, Spray, Jet, Mixing, Pre-Injection, Diesel Combustion

1.Introduction

In diesel combustion, NOx is one of the most difficult elements to control in heavy load range, because the equivalence ratio is outside of the available range of NOx catalysts and also because lean combustion, e.g. homogeneous charge compression ignition, can not be applied in the load conditions. To reduce smoke emissions, high-pressure fuel injection with small nozzle holes is commonly used, however this causes increased NOx emissions. This is generally explained as the fuel mixes well with air and high temperature region is established widely. When considering residence time in the continuous jet flame, however, the available time for NOx formation would decrease in high-pressure fuel injection due to faster diffusion of the combustion gas with the air. This would reduce NOx emission in the high-pressure injection, in contrast to the fact. There is no explanation for the differences in NO emission characteristics between diesel combustion and steady jet flames.Based on a simple simulation along the jet axis, Chikahisa, one of the authors, and his colleagues reported that a large part of the NOx is formed at the tip of the jet flame, where the velocity and turbulent structures are different from the steady jet flame. They showed that the increased NOx by higher fuel injection speeds is due to the development of this region(1).

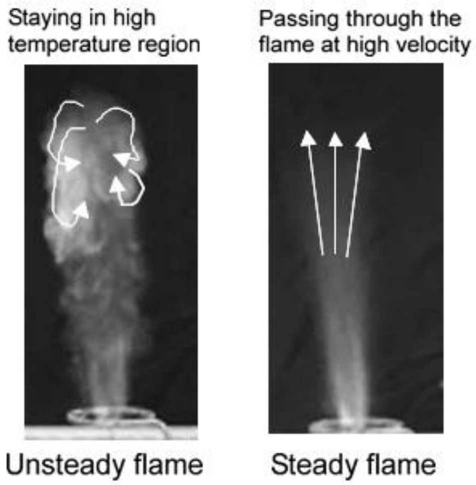

Fig. 1 Images of different flow patterns in flame tip region between unsteady (transient) and steady flames

steady 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.

The authors reported the concept of the large NOx formation in the flame tip region in the Transaction of the Japan Society of Mechanical Engineers in 2003 in Japanese(2). They measured NOx amount in a vessel for different injection periods and showed that the large part of NOx is formed in this flame tip region by comparing with numerical simulation. The major part of the paper was then presented in English in The 6th ASME/JSME Thermal Engineering Joint Conference in 2003(3). The authors considered that one way to reduce NOx would be making the velocity profile at the tip region similar to the steady jet. They injected inert gases prior to the fuel injection for this purpose and succeeded to reduce NOx emissions from unsteady jet flame. The result was presented in JSAE/SAE International Spring Fuel and Lubricant Conference in 2003(4). The present paper reports newly measured results of NOx distribution in unsteady jet flames by gas sampling, and shows increased mixing intensity of the flame tip region by pre-injection of water. The relating work is referenced in Refs. (3) and (4).

2. Experiments and Simulation Methods

To show the significance of NO formation in the tip region of the jet flame, NO concentration in the jet flame was measured. 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 torch at 10 ms before the propane injection. The NO emissions due to the high voltage spark and the hydrogen torch were measured and corrections were made for the NO from the propane flame. The position of the pilot burner was 50 mm from the nozzle, which was the optimum position for stable ignition. The injection period is controlled by an electric valve. To maintain constant injection speed during the injection, a large accumulating tank (ca. 3 200 cc) containing the fuel is placed close to the injection nozzle. Combustion gas is collected in a sampling bag by a vacuum pump. The electric valve controls the sampling period to 5 ms, and the sampling is repeated for 550 times to collect enough volume of gas at a position. NOx concentration in the collected gas was measured by a CLD analyzer. It was confirmed that the injection speed during the injection was almost constant and it has good repeatability.

Axisymmetric two-dimensional numerical simulation was performed with the commercial code of FLUENT ver.6.1 (Fluent Inc). The k-ε model was applied for the tur- bulence model. The ignition option was set to start com- bustion when the air-fuel mixing ratio is in the flammable range. The NO formation is calculated for thermal NO, based on the Extended Zel'dovich Reaction Mechanism, and prompt NO proposed by De Soete(5).

The NO amount is expressed in ppm or in NO emis- sion index. The NO emission index at time t from the start of injection is calculated by the total NO mass relative to the total mass of the injected fuel as follows

$$[NOei] = \int_0^t \frac{d(NO)}{dt} dt \cdot \int_0^t \frac{d(m_f)}{dt} dt \qquad (1)$$

3.Results and Discussion

3. 1 Analysis of lager NO formation at the tip of spray flames

Figure 3 shows the numerical simulation results of the changes in temperature and NO concentration in a devel- oping propane gas jet after start of injection. Compared to the steady jet flames shown at the bottom of the fig- ure, there is a wide area of high temperatures with a large NO concentration at the tip of the jet. This clearly indi- cates that the mixing in this region is slower than in the other regions and that a large amount of NO is formed due to the longer residence time at the high temperature. The NO formation at the tip of the jet continues beyond the steady flame length shown at the bottom of the figure. When the jet is well developed as a steady flame, the high temperature region is limited to a thin flame zone, and the gas jet passes the region at high velocity. The maximum temperatures were the same between the transient and the steady jet flames. Thus the difference in the NO formation was caused by the different mixing phenomena between the two flames rather than temperature difference.

Figure 4 shows experimental result of gas sampling.

Nozzle diameter was 1.4 mm and the injection period was 400 ms at 130 kPa injection pressure.

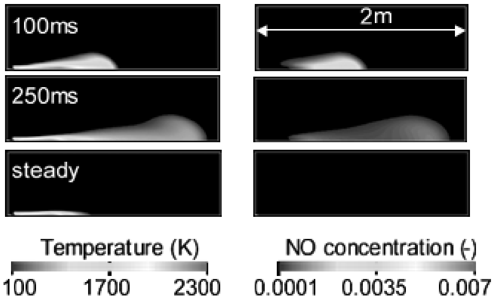

Fig. 3 Changes in temperature and NO concentration (molar fraction) after the start of injection, compared with a steady flame: numerical simulation

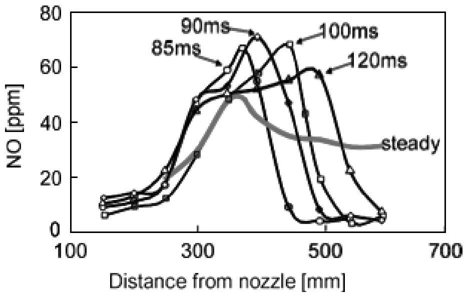

Fig. 4 Changes in NOx concentration profile on the jet axis for the time after the start of injection

made at the four difference timings (85 ms, 90 ms, 100 ms and 120 ms after the start of injection). The result of a steady jet flame is also shown in the figure. The NOx dis- tribution is similar to the numerical simulation in Fig. 3:

i.e. high NOx is seen in the flame tip region and it is maintained beyond the peak position in the steady jet flame. This indicates the validity of the above discussion in Fig. 3.

Figure 5 shows the NO concentration in the radial direction at 90 ms after the fuel injection. The height of the measured section is set at 400 mm from the nozzle, where the maximum NO was obtained at the measuring time. The figure apparently shows high NO concentration area extends widely to the radial direction in the unsteady flame. This indicates that the flame front loses its momentum and it is pushed sideway by the following fuel as illustrated in Fig. 1. The mixing intensity here is weak due to the decreased momentum and high temperature is maintained with keep producing NO in this area.

3. 2 NOx reduction trial by pre-injection of air and inert gases

The above discussion indicates that a large part of the NO emission is formed in the early stage of injection due to an under developing velocity profile at the tip of the jet flame and smaller amounts of NO is formed from fuel injected later. This suggests that one way to reduce NOx would be: (1) enhancing mixing of the combustion zone in the tip region, and (2) making the velocity profile at the flame tip region similar to the steady jet flame. An inert gas injection prior to the fuel injection may be effective to achieve (2) above, because the fuel moves ahead in the jet flow made by the forgoing gas jet.

Figure 6 is the experimental result with and without pre-injection of N2 prior to the propane injection. The N2 is injected for 10 ms followed by propane injection of 50 ms. The switching of the injection was done by a couple of solenoid valves connected to the each gas as shown in Fig. 2.

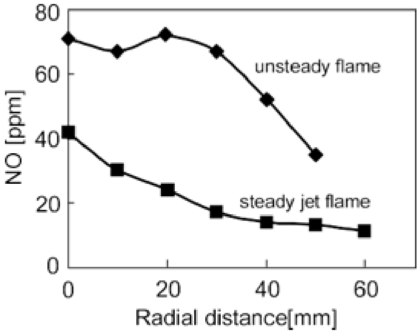

Fig. 5 Comparison of NOx concentration profiles in radial direction in unsteady and steady jet flames

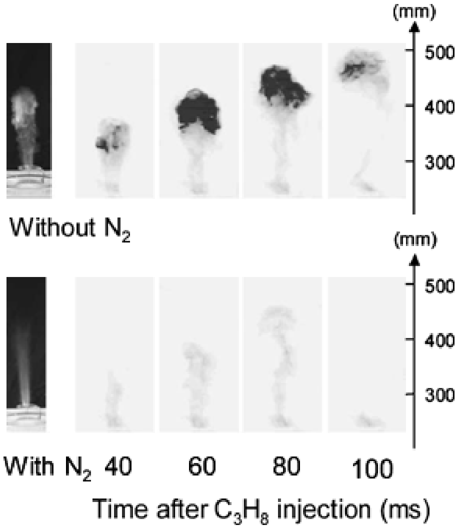

Fig. 6 Experimental result with and without pre-injection of N_2 prior to the propane injection: N_2 injection is 10 ms followed by 50 ms propane injection

3. 3 Analysis of microscopic diffusion structure in flames with water pre-injection

An experimental result of water pre-injection, which is one of the applications of the above pre-injection method, was analyzed. K. Takasaki and H. Tajima investigate flame structure and NOx emissions when water is injected prior to the fuel injection(7) – (9). Figure 8 shows shadowgraph pictures of flames with and without water pre-injection provided by

Prof. Koji Takasaki of Kyu- shu University. The timings of the pictures were 7 ms and 7.5 ms after the start of fuel injection. The pictures were taken in a high-pressure vessel, and the heavy oil was used for the fuel. Detailed conditions are listed in the figure caption and also in Refs. (7) and (8).

The diffusion state and the mixing intensity were an- alyzed with the entropy method detailed in Refs. (10) and (11). This method evaluates the homogeneity degree in pictures and calculates diffusion intensity from the change in the homogeneity degrees in the period. In statistical dy- namics, entropy is a state quantity and increases with the progress of uniformity.

Figure 9 is the results of the entropy analysis, show- ing scales, entropy, and number of clouds in three dimen- sional figures. The cloud here means the fluid area re- garded as a cluster in the picture. The size of the cloud is normalized by the analysis window, x0, which is 65 mm

in this analy. sis. T.he Σnumber of the clouds in the figure is found in the field, and xw and x0 are sizes of the cloud and the total field respectively. The normalized numbers indi- cate the total area of the clouds relative to the whole space analyzed.

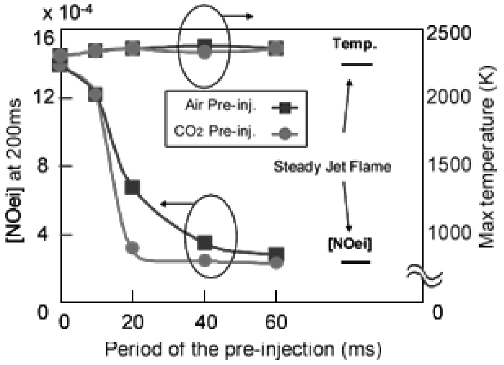

Fig. 7 Changes in [NOei] and the maximum temperature for the period of pre-injection of inert gas

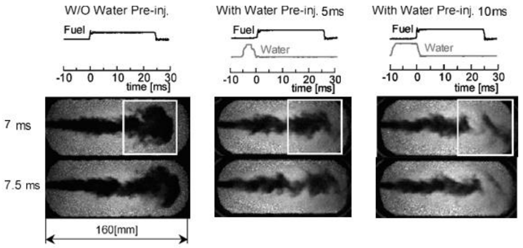

Fig. 8 Shadowgraph pictures of spray flames with and without pre-injection of water. The pictures are provided by Prof. Takasaki at Kyushu University. The squares are the analyzed windows for the entropy analysis. The experimental conditions are the followings: *fuel injection*; 50 MPa, φ0.16 mm^{-1}, C-heavy fuel: *water injection*; 25 MPa, φ0.23 mm^{-1}: *air condition in the vessel*; 2.5 MPa, 670°C.

4.Conclusions

The assumption was made that the large amount of NOx is formed in the tip region of spray flames shortly af- ter the start of injection due to weaker mixing and larger residence time at high temperatures in this region. Exper- iments and numerical simulation were made to confirm this assumption, and a method to enhance mixing in this region was examined. The results obtained by the research are the followings:

(1) Gas sampling experiment in the gas jet flame showed that the main region of NO formation is the tip of the jet flame and this region is the source of most NO emissions. This is because the jet velocity at the tip region is slow and there is little mixing of the surrounding air, maintaining the region in high temperatures with sufficient residence time for NO formation to occur. The amount of NO formed in a well-developed jet flame is smaller than the transient flame shortly after the start of injection.

(2) Pre-injection of air or an inert gas is effective to change the velocity profile of the fuel to that of a well de- veloped jet flame, and so reduce the residence time at high temperatures at the tip of the flame, resulting in decreased NOx formation.

(3) It was confirmed that pre-injecting water prior to the fuel injection promotes diffusion of burned gas in the flame tip region, and this appears to be effective for the reduction of NOx.

References

(1) Chikahisa, T., Konno, M. and Murayama, T., Analysis of NO Formation Characteristics and Control Concepts in Diesel Engine from NO Reaction-Kinetic Consider- ations, SAE Paper 950215, (1995), pp.1–8.

(2) Kaneko, T., Chikahisa, T. and Hishinuma, Y., Charac- teristic of Significant NOx Formation in the Tip Region of Unsteady Jet Diffusion Flames and Its Reduction Concepts, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol.69, No.677, B (2003), pp.213–220.

(3) Kaneko, T., Chikahisa, T., Kikuta, K. and Hishinuma, Y., Significance of the Spray Tip Region in NOx Emissions of Diesel Combustion, Proc. of the 6th ASME/JSME Thermal Engineering Joint Conference, TED-AJ03-289, (2003), pp.1–7 (CD–ROM).

(4) Chikahisa, T., Kaneko, T., Kikuta, K. and Hishinuma, Y., Significant NOx Formation at the Tip of Diesel Spray Flames and Its Reduction by Enhanced Mixing in the Tip Region, JSAE/SAE International Spring Fuel and Lubricant Conference, SAE2003-01-1786, (2003), pp.1–8.

(5) De Soete, G.G., Overall Reaction Rate of NO and N2 Formation from Fuel Nitrogen, Proc. Comb. Inst., Vol.15 (1974), pp.1093–1102.

(6) Dec, J.E. and Espey, C., Soot and Fuel Distribution in a D.I. Diesel Engine via 2-D Imaging, Trans. of SAE, Vol.101, No.4 (922307) (1992), pp.1642–1651.

(7) Takasaki, K., Takaishi, T., Ishida, H. and Tayama, K., Direct Water Injection to Improve Diesel Spray Com- bustion, Proc. ICES03, Spring Technical Conference of the ASME Internal Combustion Engine Division, (2003), pp.554 1–8 (CD–ROM).

(8) Tajima, H., Takasaki, K., Stroem, A. and Masuda, R., Diagnosis of Combustion with Water Injection Using High-Speed Visualization and CFDs, Proc. Thermo- and Fluid Dynamic Processes in Diesel Engines, THIESEL 2004, (2004), pp.341–352.

(9) Takasaki, K., Tajima, H. and Nakajima, M., Study on Combustion Physics for Ignition and Flame Propaga- tion, Detailed Analysis on Combustion of Low-Grade Heavy Fuel Oil, RC-207 Final Report, JSME (2005), pp.108–113.

(10) Chikahisa, T., Yuyama, R. and Hishinuma, Y., A Method for Analyzing Heterogeneity Degree in Dif- fusion Process, Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol.67, No.658, B (2001), pp.1563–1570.

(11) Chikahisa, T., Yuyama, R., Kikuta, K. and Hishinuma, Y., Entropy Analysis of Microscopic Diffusion Phe- nomena in Diesel Sprays, JSME Int. J., Ser. B, Vol.46, No.1 (2003), pp.109–116.