Effects of the Structure of Turbulent Diffusion Flame on Its Combustion Characteristics

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ABSTRACT

In order to investigate into the effects of turbulent motion in fuel jet on the diffusion burning rate and Nitric Oxides formation rate in the combustion region, the non-combustion tests using the steady gas jet and the steady fuel spray combustion tests under diesel like high gas pressure and high gas temperature condition were carried out.

By measuring turbulent characteristics in the jet, flame structure, fuel and air mixing rate, fuel burning rate, and Nitric Oxides formation in the combustion region it was concluded that higher turbulence in the combustion region keeps higher burning rate under lower temperature with lower Nitric Oxides formation.

INTRODUCTION

To improve the thermal efficiency of the diesel engine and reduce its Nitric Oxides emission enhancement of air utilization and increasing of burning rate in diesel combustion are necessary. These are greatly affected by both the fuel distribution in combustion chamber and turbulent mixing of fuel and air in combustion region.

Although the thermal efficiency nearly depends on the mean gas temperature in cylinder, burning rate and the formation of combustion products especially Nitric Oxides and soot depend on the local mixture condition such as local fuel concentration, local temperature. Accordingly, the local turbulent mixing is the extremely important factor to reduce the formation of Nitric Oxides, unburned hydrocarbons, and soot without a deterioration in the thermal efficiency.

Mixing of fuel and air in the local combustion region is strongly affected by the local turbulence which is produced by kinetic energy of fuel spray and gas motion in the mixing region. However the burning rate becomes higher as the speed of injected fuel spray at the injection nozzle exit increases, the relation between the local turbulent characteristics in the combustion region and combustion characteristics is not clear.

MIXTURE FORMATION IN TURBULENT DIFFUSION FLAME

Since the rate of chemical reaction is so high, the burning rate is governed by the fuel and air mixing rate in the diffusion combustion such as diesel combustion. Therefore local fuel and air mixing has significant effects on the burning rate and the formation of combustion products. Figure 1 shows the fuel and air mixing process in the diffusion combustion. Entrainment of surrounding air into the fuel spray by its movement and the local fuel and air mixing by the local turbulence are progressed at the same time in the fuel sray. (1) (2) (3) Accordingly it is needed to generate strong turbulence in the local combustion region to incease the fuel and mixing rate, which leads to raise the burning rate in the diffision combustion. To generate strong turbulence in the local mixing region is obtained by increase of the kinetic energy of fuel spray and air motion. That is the objective of this study to clarify how much kinetic energy of fuel spray and air motion is being converged to the turbulence and influence of kinetic energy on fuel and air mixing and burning rate. Therefore basic experiments to find the relation among the kinetic energy of fuel spray and air motion in the local mixing region, turbulent structure, and combustion characteristics were performed.

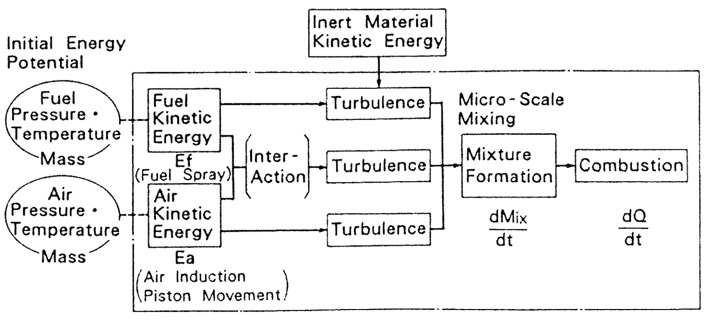

Fig.1 Mixture Formation in Diffusion Jet

TEST EQUIPMENT

Experimental apparatus

It is so much difficult to measure the turbulence and mixture formation in the actual diesel combustion. In this study, the steady non-combustion tests using gas jet and measuring turbulent characteristics, fuel and air mixing rate and the steady spray combustion tests measuring flame temperature, burning rate, and Nitric Oxides formation were carried out, here, the kinetic energy of gas jet and fuel spray is equivalent to that of the fuel spray in the small size diesel engine.[4] [5]

High pressure combustion bomb and experimental apparatus used in this study are shown in Figure 2 and Figure 3. High pressure air controlled its pressure and temperature and led from high pressure air bomb was injected in the case of non-combustion test and supplied in the case of fuel spray combustion test into the combustion bomb. The electronic controlled fuel injection equipment with variable fuel injection pressure was used. The electronic controlled water injection equipment to inject water for increasing the kinetic energy into the mixing region was also used. The high pressure combustion bomb of which pressure limit was 9.8MPa had the combustion chamber of φ124mm diameter and 1100mm length. It also had heaters for heating its inner wall up to 800k. Gas and fuel for the formation of the diffusion non-combustion jet and diffusion spray combustion flame respectively were injected from the injector located at the one end of the combustion chamber and from around the injector high pressure air was supplied. In addition, it had two windows for measuring the turbulence and mixture formation in the non-combustion jet, and flame temperature and burning rate in the combustion flame. With these equipments it was achieved that the formation of the steady diffusion jet and the steady combustion flame under the constant pressure and the constant amount of air flow in the bomb.

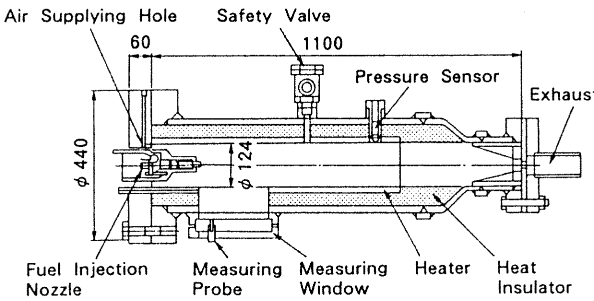

Fig.2 High Pressure Combustion Bomb

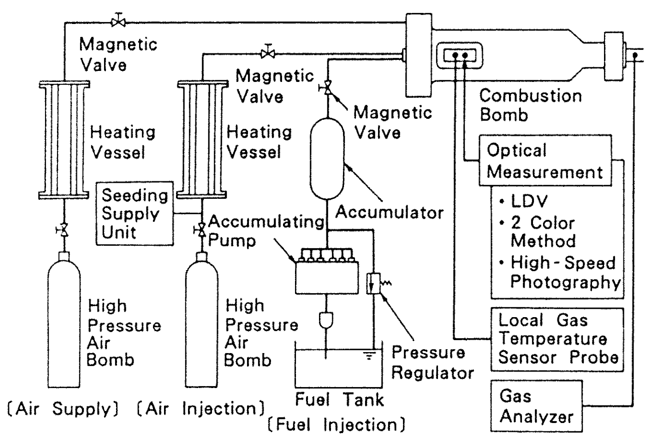

Fig.3 Experimental Apparatus

Main specifications of experimental apparatus is shown in Table 1.

Measurement and instrumentation

Local flow velocity and turbulence in the jet were measured by the LDV method with the Argon laser (wave length is 514.5nm), which was set as the foward scattering arrangement. Hollow glass particles of which mean diameter was 40 μ and density was 0.35 was used for seeding.

Local concentration ofinjected gas in the jet was obtained by measuring the local temperature in the jet. The temperature of the mixed gases which had different temperatures before mixing is determined by the volume ratio of each gas to mixed gas if there is no heat loss. That is, assuming that the each gas temperature before mixing is Ta and Tg, and that after mixing is Tm, concentration of gas with suffix g is

$$Cg = \frac{TgTa(\kappa a-1)-TmTg(\kappa g-1)}{TmTa(\kappa a-1)-TmTg(\kappa g-1)-TgTa(\kappa a-\kappa g)}$$

Here, κ is the specific heat ratio. In order to measure the local and instantaneous gas temperature, thermocouple which was consisted of platinum wire and rhodium wire whose diameters were φ0.25mm each other was used with delay compensating circuit. In this experiment, both gases of jet and inside the combustion chamber were air and the temperature of the wall of combustion chamber was held to be equal to that of the inside air, so the heat loss of the gas jet and radiant heat could be neglected.

Local flame temperature was measured by 2 color method, one wavelength was 800nm and the other was 950nm. The instantaneous flame image was taken by high speed photography and mean flame length which indicates mean combustion velocity of the flame was taken by still camera. Combustion products were measured by gas analyzer. Main specifications of these instrumentation for measuring is shown in Table 2.

Table 1 Specification of Experimental Apparatus

Combustion Bomb		φ 124 × 1,100 Vc=13,280cm³ Pa max=9.8MPa 1kW Cartridge Heater × 12
Gas Injection System	Gas Source	High Pressure Air Bomb (Pair=14.8MPa)
	Injection	φ 3.0 × 1N
Fuel Injection System	Injection Nozzle	φ 0.14 × 1N φ 0.10 × 1N
	Injection Pump	Accumulator Type (Variable Injection Pressure)
Air Supplying System	Air Source	High Pressure Air Bomb (Pair=14.7MPa)
	Heating Vessel	φ 50 × 1,500 Vc=2,945cm³ 1.2kW Cartridge heater × 12

Table 2 Instrumentation

Object	Method	Instrument
Local Velocity & Turbulence	LDV Method	Laser : Argon (λ=514.5nm, 2W) Focal Length of Front Lens : 739mm Beam Intersection Angle : 10.05° Measuring Volume : 0.035mm^3 Bandwidth of Photomultiplier : DC-150MHz Arrangement : Forward Scattering Seeding : Hollow Glass Particles (d=40 μ, ρ=0.35) Signal Processor : Counter
Local Gas Concentration	Temperature Measurement	Thermocouple : ϕ 0.25-PR Type With Delay-Compensating Circuit
Local Flame Temperature	2 Color Method	Wave Length : λ_1 =800nm, λ_2=950nm Measuring Area : ϕ 6 at Flame
Combustion & Flame Configuration	High Speed Photography	Camera : NAC-E10 Film Speed : 6000fps Shutter Speed : 30 μsec
Exhaust Gas Composition	Gas Sampling & Analyzing	Gas Analyzer : YANAKO-7552D

Table 3 Experimental Condition

Gas Injection (Non-Combustion)		Air Pressure	Pa=1.9MPa
		Supply Air	Ta=288K
		Injection Air Pressure	Pg=4.9, 3.9, 2.9 MPa (Pg/Pa=2.5, 2.0, 1.5)
		Injection Air Temperature	Tg=620K
Fuel Injection (Combustion)		Air Pressure in Test Rig	Pa=6.9MPa
		Supply Air Temperature	Ta=620K
		Effective Fuel InjectionPressure	ΔPf=6.9, 13.7, 39.2 MPa
	Water Injection	Ratio of Water Mass in Emulsion Fuel	Gw/Gf=10, 20, 30 % (Ew/Ef=10, 20, 30 %)
		Ratio of Water Mass in Stratified Fuel-Water Injection	Gw/Gf=25 % (Ew/Ef=25 %)
		Ratio of Kinetic Energy of Individually Injected Water Spray	Ew/Ef=10, 25, 45 % (dw = ϕ 0.1, ΔPw = 7.4, 9.8, 14.7 MPa)

Experimental condition

In the exiperiment with the non-combustion gas jet, the kinetic energy of jet was set to nearly correspond to that of actual diesel fuel spray injected at the pressure range of 50 ~200MPa, so that the hole diameter of gas injector was determined to ϕ 3mm when the range of gas injection pressure ratio that was the gas injection pressure to that inside the chamber was varied between 1.5~3.0. The air density in the combustion chamber was arranged to be equal to that of actual diesel engine under the room temperature. In the experiment with the spray combustion flame, the kinetic energy of the fuel spray was changed by means of varing the hole diameter of fuel injector and fuel injection pressure. Air pressure and air temperature inside the chaber were held to be constant during experiment of 6.9MPa and of 620K respectively. In the case of injecting the kinetic energy of water, the ratio of water mass to fuel mass was varied to change its kinetic energy. These experimental condition is shown in Table 3.

EXPERIMENTAL RESULT

Basic characteristics of turbulence and mixing in the diffusion jet

Figure 4 shows the instantaneous velocity, turbulent intensity and concentration of injected air on the radial points at a distance of 0mm, 10mm, 20mm, 30mm from the jet axis those were on the cross section 90mm away from gas injector. In this case, gas injection pressure ratio, that is mensioned above, was kept to Pg/Pa= 2.5. Fluctuation of injected gas concentration corresponds so well to that of turbulent intensity. This result indicates that the mixing in the diffusion jet strongly depends on the turbulent condition. Figure 5 is the distribution of the mean value of velocity, turbulent intensity and concentration of injected air, those were normalized by the values on the axis versus normalized radial position in the cross sections at 30, 90, 150mm away from injector. The normalized distribution profiles of these mean values on each cross section are almost the same. From this result, it was found that the distribution profile of mixing rate on any radial cross section in the jet is almost fixed, the turbulent characteristic and the mixing characteristics in the jet can be represented by the values on the jet axis.

Effect of kinetic energy on turbulence and mixing

The effects of the injection pressure on the turbulence formation and mixing rate in the jet are shown in Figure 6. Here, injection pressure ratios were kept to Pg/Pa= 2.5, 2.0, 1.5 and kinetic energy of air jet at each injection pressure condition corresponded to that of diesel fuel spray at injection pressure Pf=73.5, 133.3, 155.9MPa respectively. At 0.5msec after injected out from nozzle, turbulent intensity at the injection pressure ratio Pg/Pa= 2.5 is nearly 35% larger than that at Pg/Pa=1.5, and mixing rate, which has the range of 5~10x10^{4}sec^{-1}, becomes nearly 35% larger. From this result, it was indicated that the turbulent intensity becomes larger and mixing rate becomes higher according to the increase of the kinetic energy of the jet. Figure 7 presents the relation among the kinetic energy of the jet and the characteristic value of turbulence, which is represented as the ratio of turbulent intensity u' to turbulent length scale ℓ, and mixing rate Vmix at 0.5 msec after injected out from nozzle. From this result, following relations were obtained.

$$u'/\ell = 12 \cdot \varepsilon f^{0.5} = 12 \cdot (Pf/\rho f)^{0.5} \quad (1)$$

$$Vmix = 2050 \cdot \varepsilon f^{0.5} = 170.8 \cdot (u'/\ell) \quad (2)$$

here, εf is the kinetic energy converted into the unit mass of the diesel fuel oil.

The instantaneous flame images under various fuel injection pressure conditions are shown in Figure 8. From these pictures, it can be seen that under the higher fuel injection pressure condition, the flame images become more complicated, its fluctuation becomes more frequent, and its luminosity becomes lower. This result indicates that the structure of the flame is getting the stronger turbulent characteristics accoding

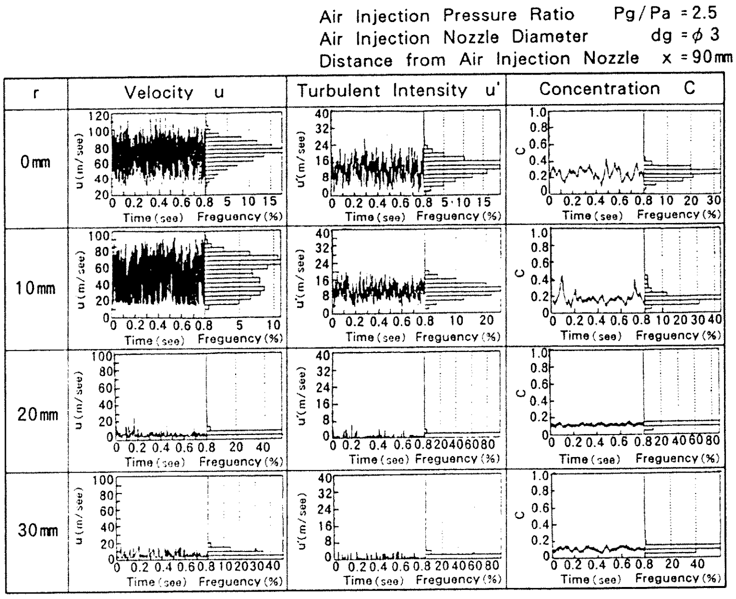

Fig.4 Local Velocity, Turbulent Intensity, Concentration in Jet

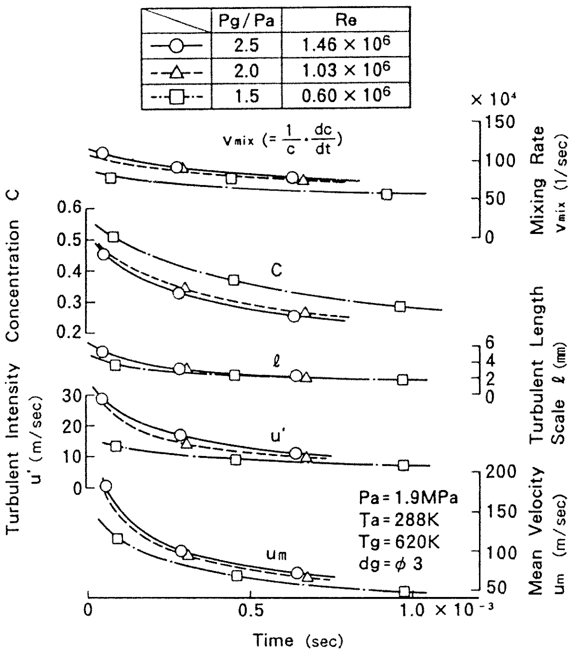

Fig.6 Effect of Kinetic Energy of Jet on Turbulence and Mixing

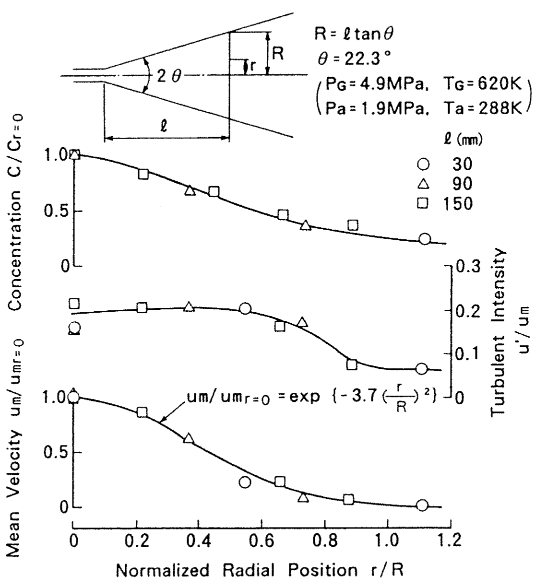

Fig.5 Radial Distribution of Mean Velocity, Turbulent Intensity and Concentration in Jet

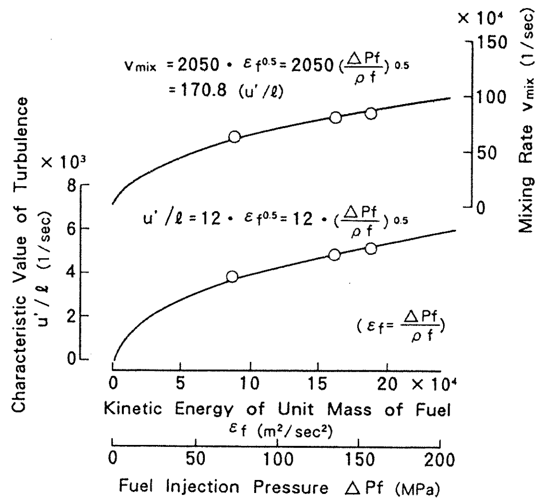

Fig.7 Relation Between Kinetic Energy of Jet and Turbulent Mixing

to the increase of the fuel injection pressure, that is the speed of the fuel spray at the fuel nozzle exit.

The burning rate can be obtained from the flame length and the speed of fuel spray under the steady combustion codition like this experiment. In the case of the fuel injection pressure Pf=39.8MPa, burning rate is 1.55 times that at Pf=13.8MPa. This result corresponds to the relation between the injection pressure and mixing rate represented by Equation (1) and (2).

The fact that the luminosity of the flame becomes lower under higher injection pressure indicates that the soot formation reduses in the flame, this implies that both the increase of burning rate and the reduction of unburned products can be obtained by means of the increase of turbulence in the diffusion flame.

The kinetic energy in the mixing region can be also increased by means of the injection of inert material like water. Figure 9 shows the comparison of the instantaneouse flame images of ordinary fuel injection, fuel-water emulsion injection of which the ratio of water to fuel Gw/Gf was 10% in weight, and fuel spray injection which is impinging with water spray of which kinetic energy was 25% of fuel spray. It is obvious that both flame images in emulsion fuel injection and fuel spray impinging with water spray injection are more complicated than those of ordinary fuel injection. The local temperature fluctuations in emulsion fuel combustion flames under the various water mass ratio at a distance of 90mm from injection nozzle

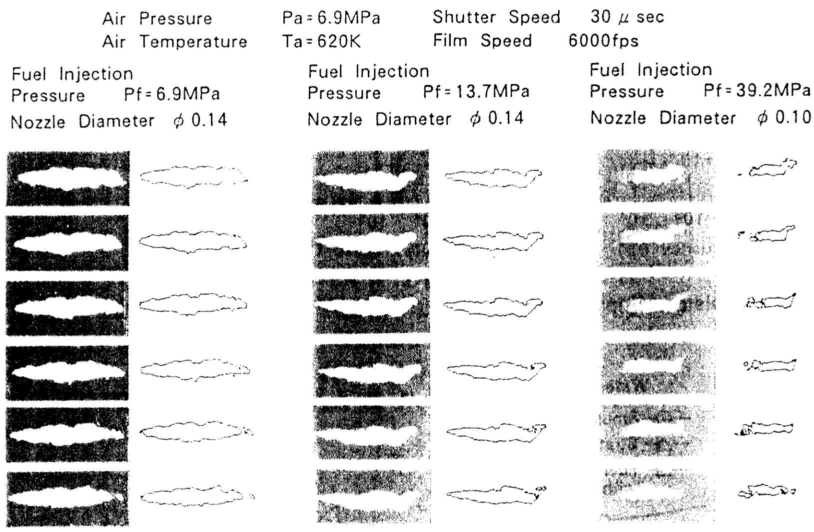

Fig.8 Effect of Fuel Injection Pressure on Combustion and Flame Formation

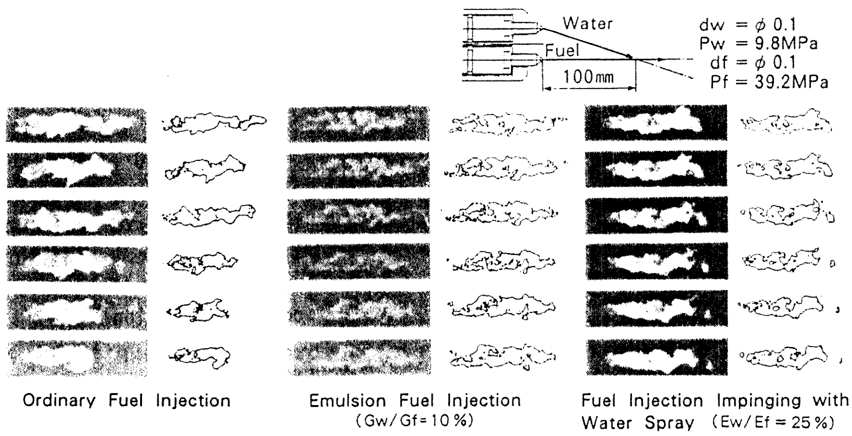

Fig.9 Effect of Water Injection on Combustion and Flame Formation

hole are shown in Figure 10. As the ratio of water mass to fuel mass increases, that is, the kinetic energy of unit mass of the fuel increases, the mean temperature goes down, the amplitude of temperature fluctuation becomes small and frequency of that becomes higher. Figure 11 is the comparison of the spectra of above temperature fructuations data. Amplitude of the temperature fluctuation of the frequency range over 5kHz is becoming larger as increasing the ratio of water, this range of frequency is nearly coincident with the mixing rate in the ordinary diesel fuel spray that was indicated at Figure 7. Local temperature fluctuation in the flame can be considered to correlate to the local turbulent structure because there are many flows of small size flamelets in the diffusion flame.

In this experiment, three types of water injection methods were examined. First was the emulsion fuel injection, second was the stratified fuel-water injection, and third was fuel spray injection impinging with water spray. Figure 12 indicates the effects of injected water mass in those three methods on the mean flame temperature, reaction rate constant, mixing rate,

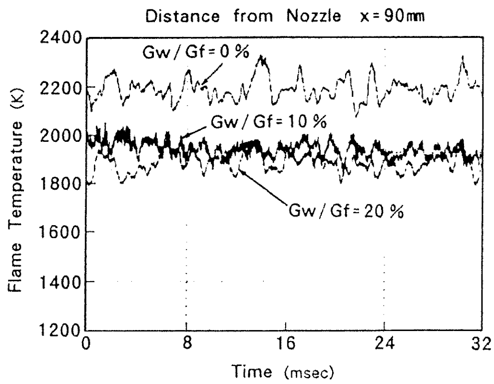

Fig.10 Temperature of Emulsion Fuel Combustion Flame

burning rate, and Nitric Oxides formation. Here the rate constant was obtained from the flame temperature using the Arrhenius equation and the burning rate was obtained from the flame length. According to the increase of the injected water mass, although the reaction rate constant becomes smaller owing to the reduction of flame temperature, burning rate does not

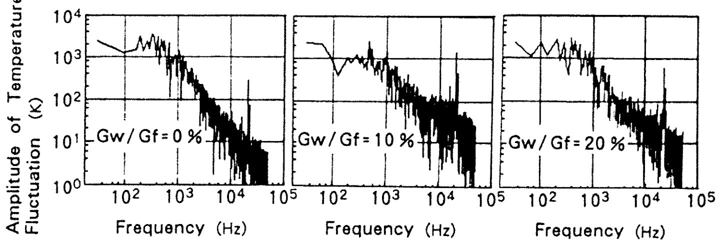

Fig.11 Spectra of Emulsion Fuel Combustion Flams

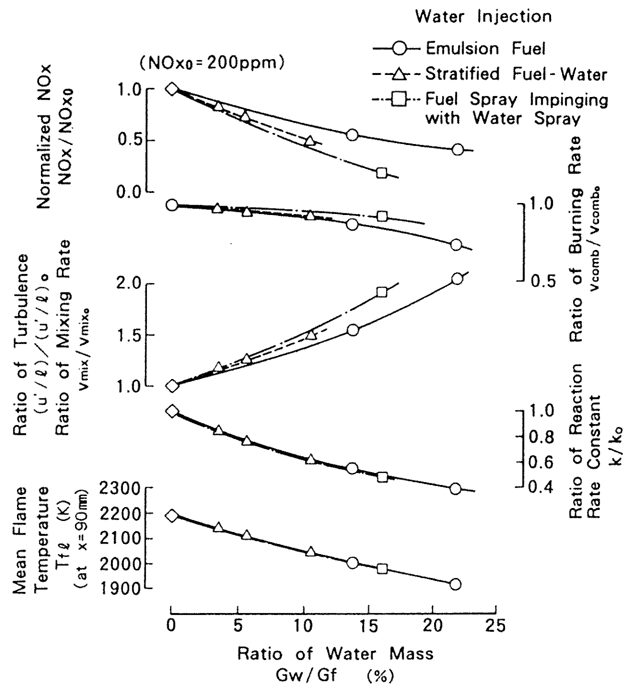

Fig.12 Effect of Water Injection on Air-Fuel Mixing Rate, Burning Rate and NOx Formation

drop so much because of the increase of turbulence, and Nitric Oxides formation becomes drastically lower because of the reduction of flame temperature.

Figure 13 shows the relation among turbulence, burning rate, and Nitric Oxides formation at the mean flame temperature of 2050K where the ratio of water mass to fuel mass is 10%. From this result, it becomes clear that the increase of turbulence makes burning rate higher and Nitric Oxides formation lower even under the same mean temperature condition. Therefore it was concluded that the reduction of Nitric Oxides formation can be obtained with higher burning rate under lower temperature by means of the increase of the turbulent mixing rate in the combustion region.

CONCLUSION

From foregoing experimental study, the following conclusions were obtained.

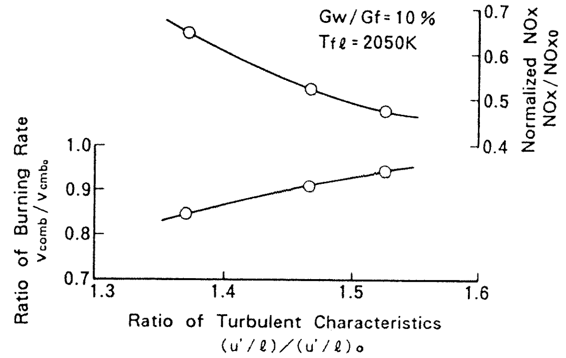

Fig.13 Effect of Turbulence on NOx Formation

(1) According to the increase of the kinetic energy of fuel spray, the turbulent intensity in the mixing region becomes stronger, and fuel and air mixing rate bocomes higher.

(2) From experimental result, following relations among the kinetic energy of the fuel spray, turbulent structure, and mixing rate were obtained.

$$u'/\ell = 12 \cdot \varepsilon f^{0.5} = 12 \cdot (Pf/\rho f)^{0.5}$$

$$Vmix = 2050 \cdot \varepsilon f^{0.5} = 170.8 \cdot (u'/\ell)$$

(3) The reduction of Nitric Oxides formation without the decrease in the burning rate can be obtained by the increase of the turbulent mixing rate especially the frequency range of over 5kHz in the combustion region.

NOMENCLATURE

κ = specific heat ratio		
u' = turbulent intensity	m/sec	
ℓ = turbulent length scale	m	
εf = kinetic energy per unit mass of fuel	m^2/sec^2	
Pf = fuel injection pressure	MPa	
ρf = fuel density	kg/m^3	
Vmix= mixing velocity	1/sec	

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