

Advantage of Using Water-Emulsified Fuel on Combustion and Emission Characteristics

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Abstract

In the present study, the effect of water addition to fuel by emulsification on combustion and emission characteristics was investigated using air-assisted fuel atomizing burner. Water addition elongates the combustible range to higher fuel equivalence ratio side by reduction of PM emission. The water addition also reduces NO_x emission drastically. Although the reduction of NO_x is caused by the reduction of locally high temperature region, the reduction of global flame temperature is not significant, thus thermal penalty by adding water is negligible. Water addition is also effective to reduce PM emission especially in higher fuel equivalence ratio.

Introduction

It is inevitable to use extremely low quality fuel that has been heretofore discarded from the viewpoint of energy conservation and global warming. In the case of using such fuel in combustion, the toxic emission would be the biggest problem to be solved. NO_x and smoke are major toxic emissions that should be concerned. The strategies to reduce these emissions are generally direct contrary, thus these are in a trade-off relationship. One of the easy, cheap and effective methods for cleaner combustion is water addition to the fuel^{[1],[2]}. The water addition will reduce the NO_x emission by reducing the locally high temperature region in a flame that could be the factor of NO_x. Furthermore, the addition of water will induce the hydro-gaseous reaction thus reduce the solid carbon or smoke. Hence, water addition to the fuel is able to reduce both NO_x and smoke simultaneously.

In the present study, the combustion and emission characteristics were compared by using gas oil and water-emulsified gas oil with a burner. Firstly, the combustible limit was investigated in wide range of equivalence ratio and atomizing air ratio, then, the emissions in interesting region were intensively investigated. In the last part of this paper, the reduction mechanism of toxic gases will be discussed using the measured distributions of temperature and gaseous components in the flame.

Production and physical properties of water-emulsified fuel

In this experimental study, water, fuel and small amount of additive were mixed to form water-emulsified fuel by using ultra-sonic mixer. The base fuel used in this study was JIS#2 diesel fuel (Gas Oil: GO). The major properties of the fuel and water-emulsified fuel are compared in Table 1. The obvious difference is found in viscosity of water-emulsified fuel as compared with the base material. The viscosity increases drastically as water

added up to 30%, and it shows the water in oil (O/W) phase at this condition. Meanwhile, further addition of water changes the phase to the oil in water (W/O) and decreases the viscosity. Because GOW30 (30vol% of water and 70vol% of GO) has less physical stability for reliable experiment, the combustion characteristics of GOW50 were mainly investigated by comparing with those of pure GO fuel.

Experimental setup

Figure 1 shows the schematics of the experimental setup. The fuel was injected into the combustion area by the fuel injector shown in Fig.2, which atomizes the fuel assisted by atomizing air. Secondary air was supplied into the combustion area to cover the shortage of the air introduced firstly as atomizing air. Thermocouple was installed at $h=700\text{mm}$ from the fuel injector to measure the exhaust gas temperature. A sample gas suction probe was set at 600mm from the injector to measure the concentration of NO_x, CO, CO₂ and Particulate Matter (PM) in exhaust gas. Teflon filter was used to collect the PM inside exhaust gas and the PM density was determined by measuring filter weight before and after sampling. PM can be divided into two major components, namely solid carbon (SOLID) and soluble organic fraction (SOF). SOLID is the main component in smoke, and SOF is the unburned fuel component. SOLID and SOF were measured individually by soxhlet extraction method.

The controllable parameter of the experiment was the fuel type (pure or water-emulsified fuel), and the flow rates of fuel Q_f , atomizing air Q_a , and secondary air Q_2 . In the series of experiment, experimental results were analyzed by using two non-dimensional parameters, those are fuel equivalence ratio ϕ and atomizing air ratio Q_a/Q_t , where Q_t is the sum of Q_a and Q_2 .

Results and discussion

Combustible limit

Combustible limits of the pure diesel fuel (GO) and water-emulsified diesel fuel (GOW50) were firstly investigated. Figure 3 shows the combustible limits rearranged by ϕ and Q_a/Q_t . There are two types of

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combustible limits represented as misfire limit and smoke limit. The misfire limit was defined as the point, where the combustion cannot be sustained. On the other hand, the smoke limit was defined as the point where the smoke level increases greater than 250mg/m^3 . At lower fuel equivalence ratio ϕ , combustible limit due to misfire was observed in both fuel type cases.

Referring to the misfire limit side (lower fuel equivalence side) in both fuel type cases, increment of atomizing air ratio Q_a/Q_t shifts the misfire limit to higher fuel equivalence ratio. Meanwhile, the aspects of combustible limit in the higher equivalence ratio side shown in two fuel types are completely different. In the case of GO, the combustible limit in higher

Table 1 Physical properties of base fuel and water-emulsified fuel

Fuel type	GO	GOW30	GOW50
Water content vol%	0	30	50
Base fuel	JIS#2 diesel fuel		
Density (288K) kg/m ³	824	874	917
Kinematic viscosity mm ² /s	4.08	112	8.53
Specific heat release (LHV) MJ/kg	46.0	30.3	20.8
Type of phase	-	Oil in Water (O/W)	Water in Oil (W/O)
Additive	Detergent (Dai-ichi Kogyo Seiyaku Co., Ltd.)		
Additive content vol%	-	0.5	0.5

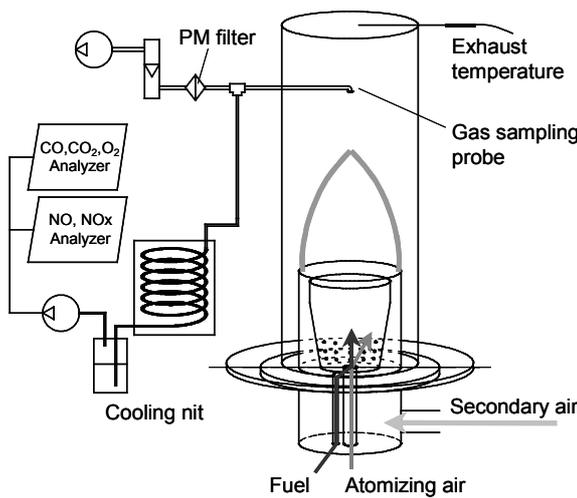


Fig. 1 Experimental apparatus

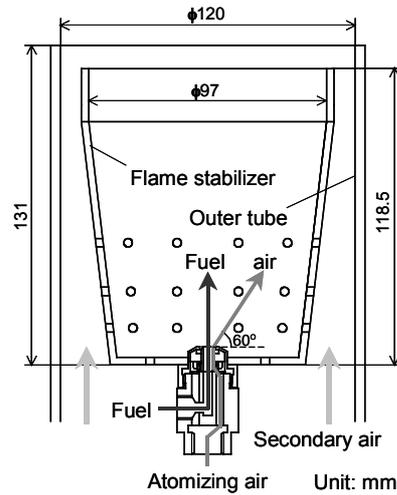


Fig. 2 Geometry of fuel injector and flame stabilizer

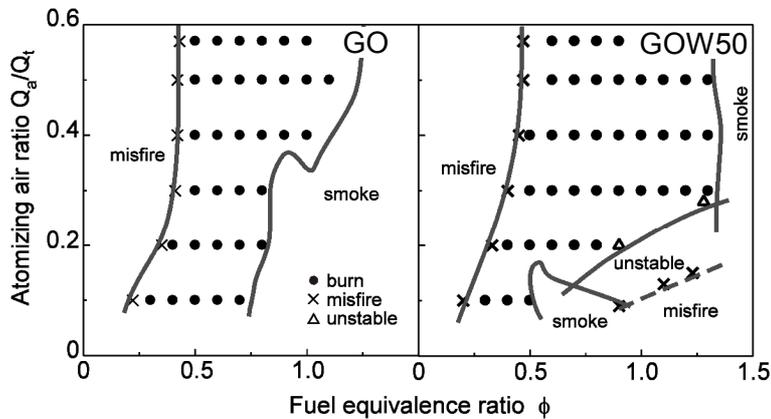


Fig. 3 Combustible limits

equivalence ratio side is smoke limit. This limit moves slightly to high equivalence side as Q_a/Q_t increases. It is assumed that higher atomizing air ratio makes better fuel atomizing and reduces the emission of smoke, thus it widens the smoke limit. On the other hand, GOW50 shows quite different aspect of combustible limit in higher equivalence ratio side. There is a smoke limit island around $\phi=0.6$, $Q_a/Q_t=0.1$. In lower Q_a/Q_t region, unstable combustion was observed with increment of

the fuel equivalence ratio. Moreover, instead of smoke limit, the misfire limit was observed when the equivalence ratio was further increased. As Q_a/Q_t increased, both limits of unstable combustion and misfire move to the higher equivalence ratio. Further increase in Q_a/Q_t produces smoke limit instead of unstable combustion and misfire limits observed in lower Q_a/Q_t . It seems that increase in Q_a/Q_t promotes atomization. Obviously the combustible area in

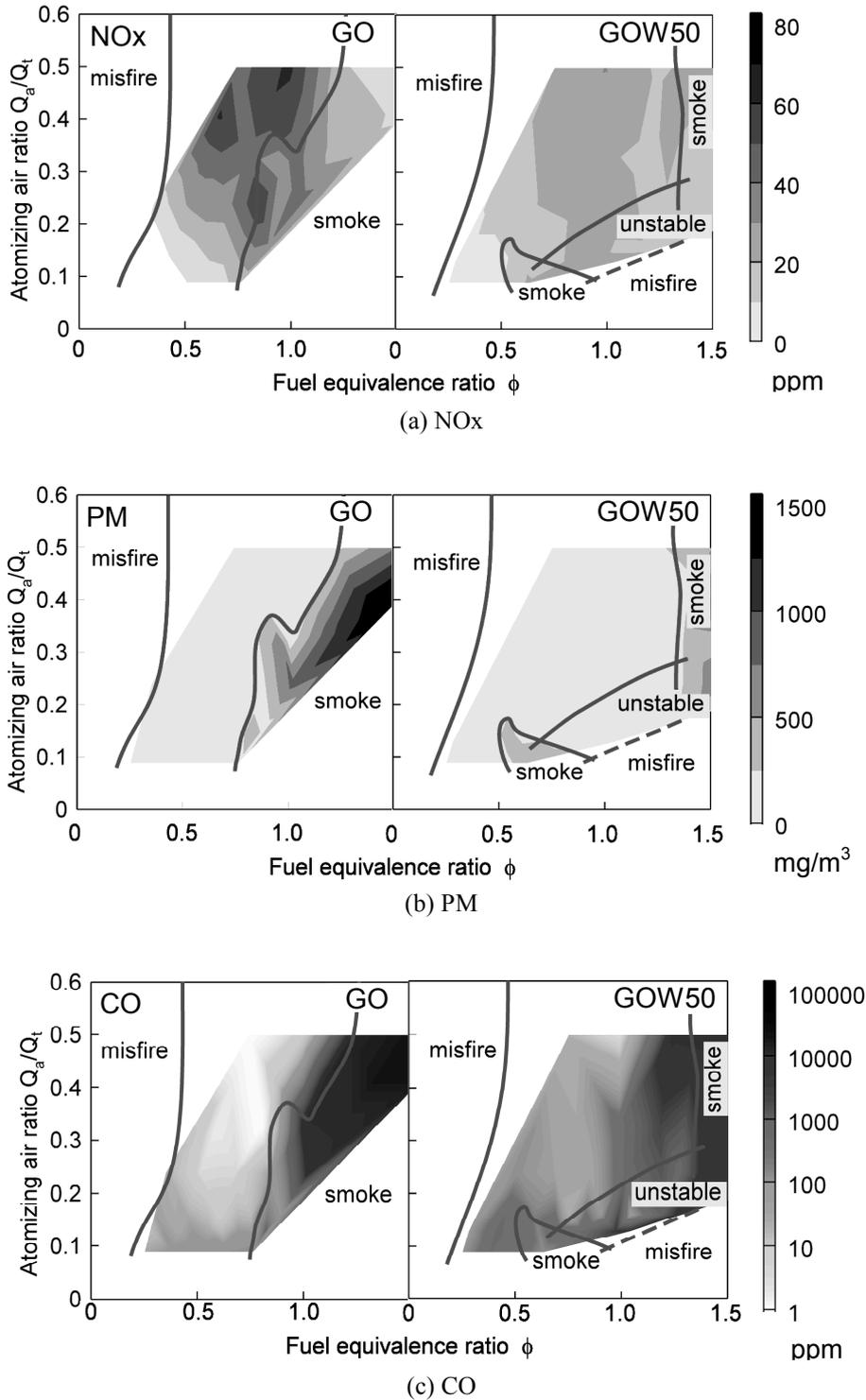


Fig. 4 Emission maps as a function of equivalence ratio and atomizing air ratio

GOW50 case is wider than GO case especially in high fuel equivalence ratio from the middle to high Q_a/Q_t range.

Emission characteristics

Figure 4 shows NOx, PM, and CO emission maps as a function of equivalence ratio ϕ and atomization air ratio Q_a/Q_t . Figure 5 shows the emission characteristics as a function of fuel equivalence ratio ϕ with fixed Q_a/Q_t .

As shown in Fig.4(a), NOx concentration in GO case becomes higher with the increment of Q_a/Q_t . This high NOx emission is resulted from promoted combustion by finer atomization of fuel from increase of Q_a/Q_t . On the contrary, NOx emission in GOW50 case does not have significant emission peak as observed in GO case. By comparing the exhaust

temperatures in all Q_a/Q_t cases in Fig.5, lower fuel equivalence ratio results lower temperature in GOW50 than GO, and higher ϕ yields higher temperature in GOW50. On the other hand, NOx emission in GOW50 is consistently lower than GO. This implies that global temperature in combustion region, which is related with exhaust temperature, is not a key factor of the NOx reduction mechanism in GOW50.

In Fig.5, the main component of PM in GOW50 is SOF in all cases of Q_a/Q_t . Furthermore SOLID component in PM is perfectly suppressed in GOW50. This indicates that water addition to the fuel suppresses the total amount of PM, but increases the SOF component. In the case of GOW50, there is a smoke limit island around $\phi=0.6$, $Q_a/Q_t=0.1$ as shown in Fig.4(b). The island is also shown in Fig.5(a) as peaked PM emission characteristics. This is assumed to be

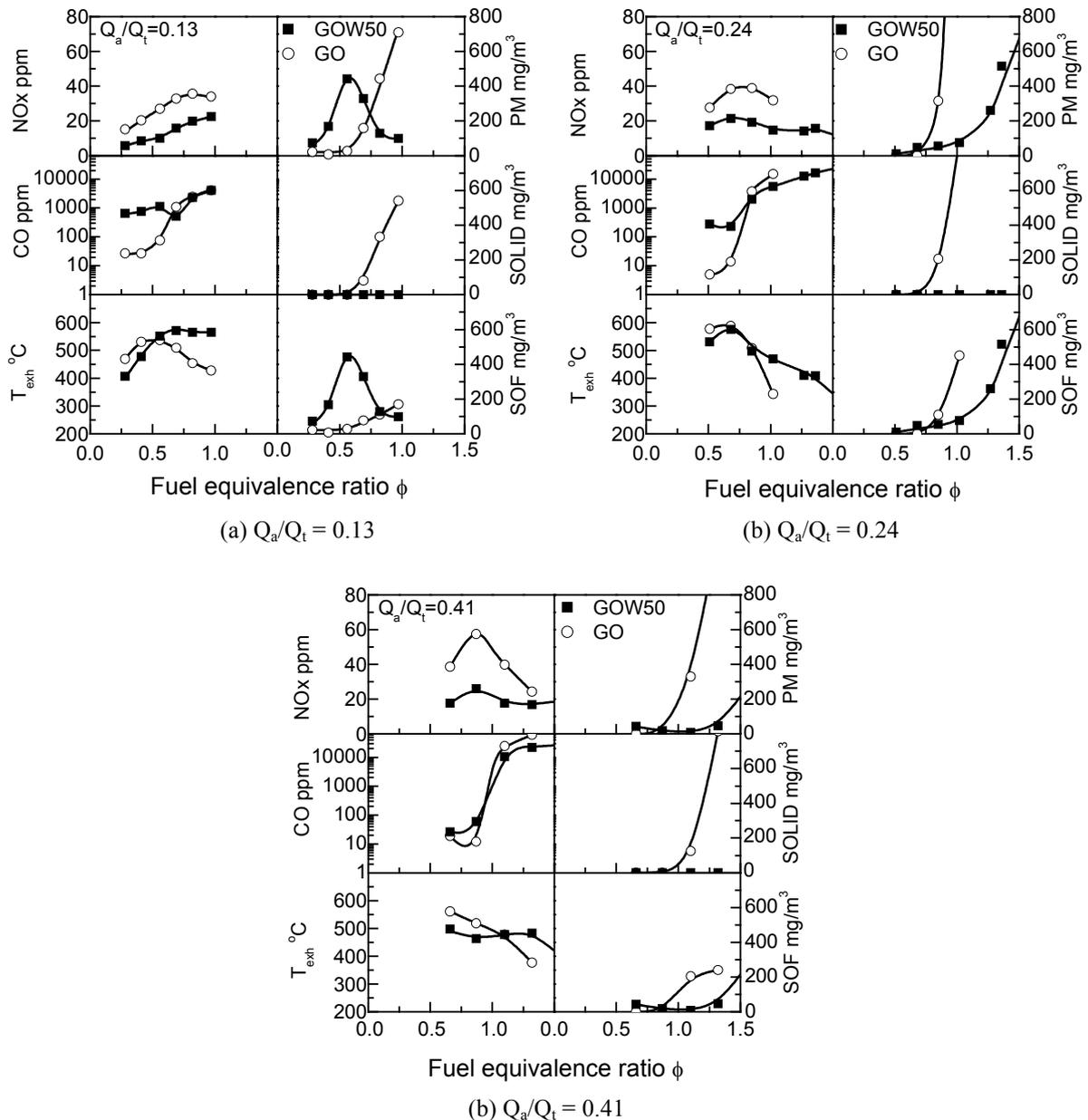


Fig. 5 Effects of fuel equivalence ratio and atomizing air ratio on emission characteristics

caused by incomplete combustion as follows. Lower atomizing air flow rate deteriorates the fuel atomization, thus combustion itself also becomes inactive. Although combustion manages to be maintained at higher equivalence ratio (around $\phi=1$), reduction of ϕ causes further degradation of combustion and SOF once increased. Further reduction of ϕ results in incomplete combustion, which means the great part of fuel does not burn, resulting all of the emission decreased. Although there must be the same problem even in GO case, GOW50 shows much severer degradation of atomization than GO case in lower Q_a/Q_t because the total volumetric injection rate of GOW50 is twice as much of the GO and GOW50 has higher viscosity.

CO emission characteristics in both fuel types are similar to the characteristics of PM emissions. In Fig.4(c), the outer region of smoke limit corresponds with PM high emission region in Fig.4(b). However, only in GOW50 case, the high CO emission region exists even in inner region of combustible limit.

Flame structure

The detailed flame structures of GO and GOW50 were measured as shown in Fig.6. Distribution of the temperature and the concentrations of each emission

component were measured by traversing the thermocouple and gas sampling probe in the flame. The experiment was conducted under the condition of $\phi=1.1$, $Q_a/Q_t=0.41$. The symbols h and r in the figure stand for vertical and horizontal distance from the center of the nozzle exit respectively.

High temperature region ($T > 1000\text{K}$) can be found around $h=75\text{mm}$, $r=0-20\text{mm}$ in GO flame. This causes the enhancement of NOx source as shown in NOx distribution map of GO flame. Highly concentrated NOx region is elongated upward because of the gas flow. In contrast, NOx distribution in GOW50 flame does not have high NOx concentration region. In addition, temperature distribution (Fig.6(a)) does not have high-temperature region ($T > 1000\text{K}$) such as found in GO flame. In spite of the temperature difference in flames, no significant temperature difference is found between the exhaust temperature shown in Fig.5(b) which was measured at relatively further point from the flame.

CO concentration at flame core region in GOW50 flame is lower than that of GO. In regard to the O_2 concentrations, GOW50 flame has relatively higher O_2 concentration in flame region than that in GO. In Fig.5, the difference of CO concentration in exhaust gas at

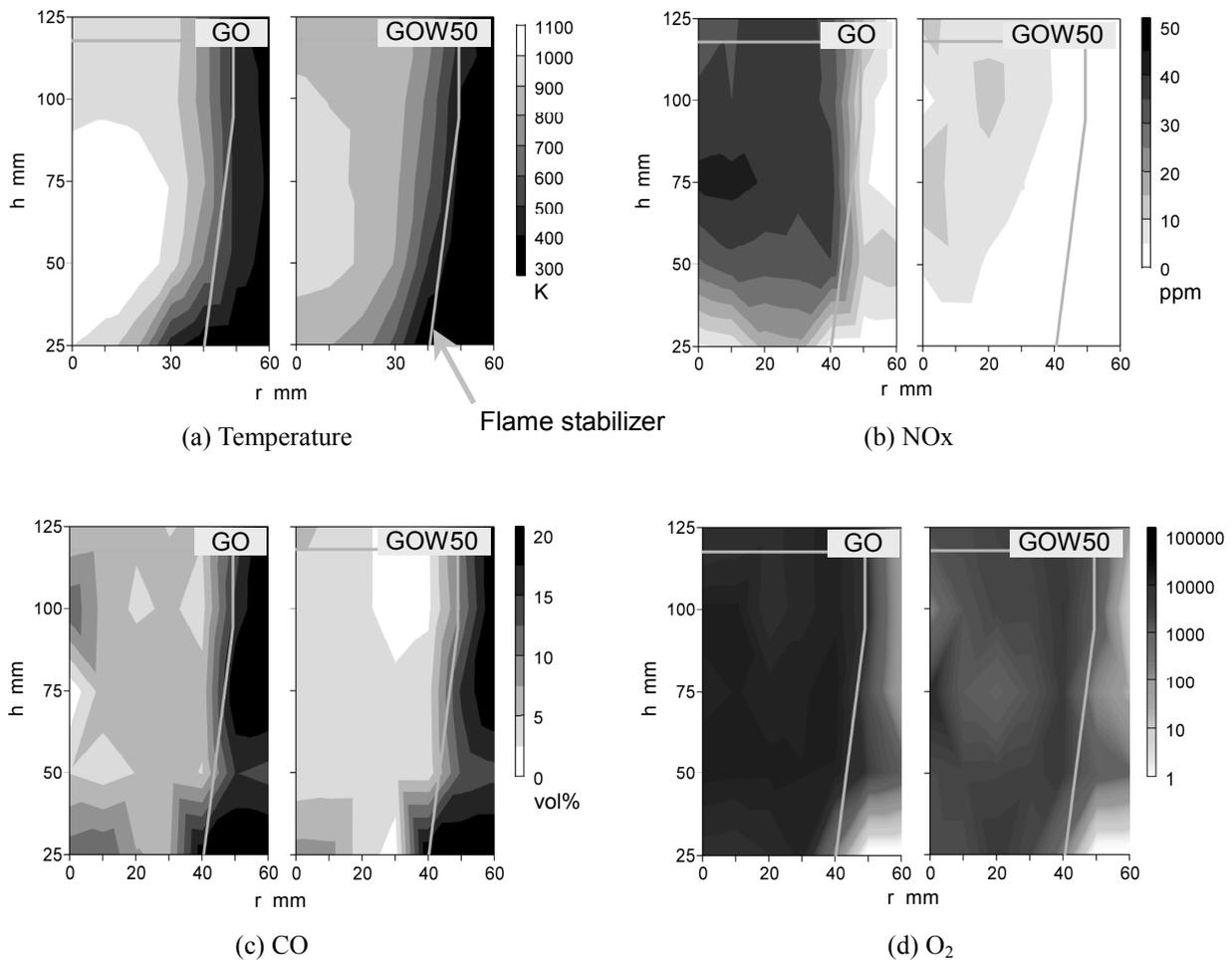


Fig. 6 Distribution of temperature and gaseous components in flame region.

$\phi=1.1$, $Q_a/Q_t = 0.41$ between GOW50 and GO is negligibly little. It is assumed that CO produced in GO flame is also oxidized actively later on. On the other hand, the CO production rate in GOW50 flame is low, but the following oxidation process is not as active as GO case. As a result, CO concentrations in exhausted gas in both cases eventually become the same level.

From these facts, the mechanism of the water-emulsified fuel combustion can be assumed as follows. The addition of water suppresses extreme temperature increase at the core region of the flame that could be the NO_x source. The reduction of high temperature area reduces the NO_x formation drastically, but it only becomes obvious in locally high temperature region. Hence, the decrease of the globally averaged temperature is less. In addition, this temperature decrease in locally high temperature region also mitigates the combustion reaction itself. Thus, CO production rate is suppressed as shown in Fig.6(c), and the O₂ is consumed slowly as shown in Fig.6(d). The reduction of reaction rate has a possibility of affording a mixing time for reducing locally high fuel-equivalence-ratio region, and thus reducing PM. Hydro-gaseous reaction is also one of the candidates to reduce PM. Solid carbon produced in the combustion process is converted into CO and H₂ by high temperature water vapor by this reaction. Quite low level of solid carbon exhaust in GOW50 as shown in Fig.5 and slightly higher emission of CO as shown in Fig.4(c) may suggest the existence of this reaction.

Conclusion

Combustion and emission characteristics of gas oil and water-emulsified gas oil were compared. The following results were obtained by this study.

1. Water addition to the fuel extends the combustible

limit especially in high fuel equivalence ratio and high atomizing air ratio side. Combustible limits in pure gas oil and water-emulsified gas oil are determined by smoke in high atomizing air ratio. In lower atomizing air ratio case, the combustible limits are determined by unstable combustion or smoke, because of the deterioration of atomization.

2. NO_x emission is drastically reduced by adding water. The reduction of NO_x is originated from the reduction of local high temperature, which is active source of NO_x production. However, reduction of global temperature is not significant, thus thermal penalty is negligible.
3. Water addition to the fuel is effective to reduce PM emission. The reduction of local high temperature may cause the reduction of reaction rate, which has a possibility of affording a mixing time for better combustion for reducing PM.

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