Diesel spray combustion of liquified petrolium gas

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1 Introduction

The shock-tube technique has been used for fundamental studies of diesel spray combustion. The authors' group has also been studying diesel-spray ignition and combustion using a reflected shock wave and obtained the heat loss due to thermal radiation[1]. We observed the influences of the air pressure and temperature on the thermal radiation. We also studied them in the air containing burnt gas and in the oxygen-enriched air. Besides, liquified petroleum gases are also alternative fuels for internal combustion engines.

Adding to the above-described background we also reported the possibility of injecting the liquid fuel such as liquified hydrogen(LH_2) like the fuel used for SCRAM-jet engine. However, since the LH_2 is a dangerous fuel for the experiments to be conducted in the university laboratories instead, we used LPG for our experiments. In our previous study we observed the n-pentane ignition and oxidation in the hot gas in the supersonic flow of Mach-number 4-5[2]. Taking this study into consideration we used propane and n-butane as LPG, as well as n-pentane as the liquid fuel. The evaporation of propane and n-pentane was observed, and the ignition and the combustion were followed in the cases with propane, n-butane and n-pentane.

2 Experimental apparatus

The experiments of combustion were performed in a steel shock tube having an internal diameter 97 mm with a 7 m long low pressure section filled with dry air and a 6 m long high pressure section filled with air. We used an "overtailored" condition. The pre-compressed fuel (liquified propane and n-butane gases and n-pentane) was injected through a throttle nozzle (pintle diameter: 1mm) into the high temperature gas. The injection pressure P_{inj} was 9.8 $\pm$ 0.2 MPa (100 kgf/cm^2), while the amount of fuel M_{fuel} was 5.0 $\pm$ 0.4 mg for the combustion study, and 5.0 $\pm$ 0.5 and 37.0 $\pm$ 0.4 mg for the spray study in an atmospheric condition. The duration t_{d} was 5.5 $\pm$ 0.6 ms. The radius of the flame, $r(z,t)$, where soot particles radiated at distance z from the end of the shock tube at time t, was determined by the presence of light passing through the 2-mm-diameter light guides (tubes). PIN-Si photodiodes with a 10^o angle of view were set radially in relation to the shock tube. Color filters ($\lambda \geq 0.67$ μm) were set between the PIN-Si photodiodes and the acrylic guides. With the PIN-Si photodiode the emission was measurable till 0.90

μm. Therefore the center of the spectral intensity was at the wavelength 0.8 μm. The locations of the observation windows were at radii r=6,18,30, and 42 mm from the center axis of the shock tube and z= 18,46,78,110,138,166,198,230,258,286, and 318 mm from the injection nozzle. More details about the shock tube can be seen in the reference[1].

3 Results and discussion

3.1 Evaporation of fuel

Before the experiment of spray combustion, we observed the evaporation of spray droplets of the liquified propane (the purity 99.6 %) and n-pentane (special grade) in an room temperature(20 °C). The injection pressure $P_{\rm inj}$ was 9.8 ± 0.2 MPa (100 kgf/cm^2), while the amount of fuel $M_{\rm fuel}$ was 37 ± 1 mg (n-pentane) and the duration $t_{\rm d}$ was 4.0 ± 0.2 ms (n-pentane) and 4.8 ± 0.2 ms (propane). The He-Ne laser at 632.8 nm was used to know the existence of sprayed droplets at the location between 40 mm and 280 mm. The infrared He-Ne laser at 3.39 μm was used for measuring the light extinctions due to the evaporated propane-gas as well as the liquid spray.

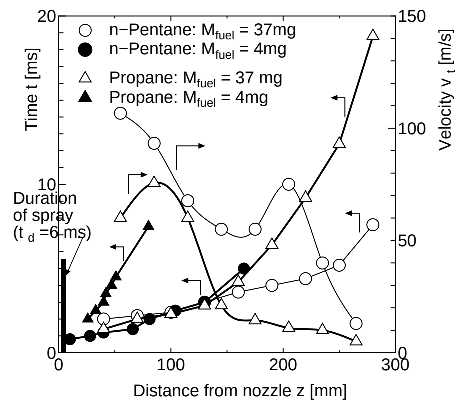

Figure 1: z-t diagram of spray tip and the velocity

The location z=40-100 mm is near the injection nozzle, the location z=130-190 mm is in the middle of the spray, and the location z=220-280 mm is the farthest places of the spray-tip. The light extinction of propane could not be observed at z ≥280 mm, except a small perturbation of light, while the light extinction of pentane spray could be observed at z=280 mm. This shows that the penetration-force of propane was weaker than that of n-pentane.

The light extinction -ln(I/I_0) due to spray is proportional to the extinction coefficient of spray particles. The coefficient depends on the complex index (m=n(1-κi)) of the particle and the wavelength. Therefore, the light extinction -ln(I/I_0) at 632.8 nm did not agree with that of 3.39 μm. However, the complex indexes of the liquified propane and liquid n-pentane are not known. The value -ln(I/I_0) at 3.39 μm was made agree with the value -ln(I/I_0) at 632.8 nm at z=40 mm at the moment of spray arrival, by multiplying the value -ln(I/I_0) at 3.39 μm by 0.4. Here, we assumed that the evaporation did not occur at this moment. This was done for both propane and pentane, respectively. After that, the value -ln(I/I_0) at 3.39 μm became larger than that of 632.8 nm. The difference increased with time and increasing distance z. This was observed more clearly in the case of liquified propane. This difference is due to the evaporation of propane, because the hydrocarbon absorbs the light at 3.39 μm. Fig.1 shows the relation between the time t and the place z of the spray tip. It also shows the relation between the tip-velocity v_t and z. The tip-velocity of propane decreased very quickly from 70 m/s to the value ≤20 m/s at places z ≥100 mm. Here again one can see that the penetration of

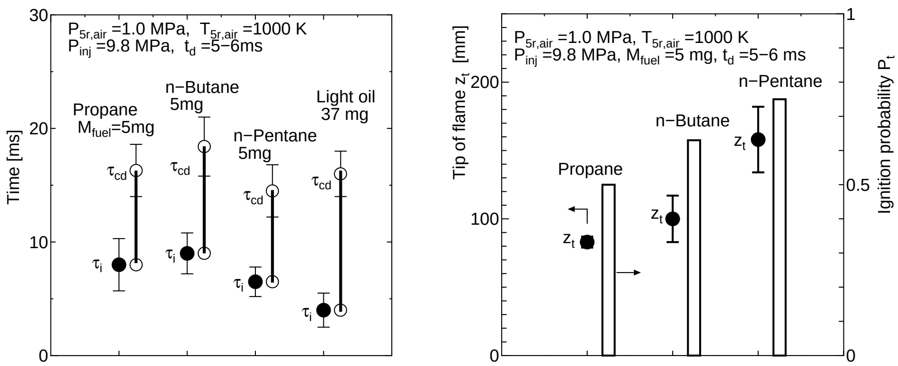

Figure 2: The left: Ignition delay, τ_i and the combustion duration, t_{cd}: the bars show the combustion duration starting from the ignition τ_i. Fuels are propane, n-butane, and n-pentane (M_{fuel}=5mg). For comparison the results of light oil (M_{fuel}=37mg) are shown on the right side of the figure(1st data from the right). The experiemntal condition is described in the body of the manuscript. The right: The farthest places from injection nozzle (z_t, solid circles) and the ignition probabilities (P_t, bar graph): The experiemntal condition is the same as that of the left-figure. The x-axis is the number of C-atoms of the LPG. The vapor pressure decreases with increasing C-number.

n-pentane is stronger than that of propane.

3.2 Ignition and Combustion

Liquified propane and n-butane, and liquid n-pentane were injected into the shock-heated air under the conditions $P_{\mathrm{5r,air}}$=1.0 MPa, $T_{\mathrm{5r,air}}$=1000 K with P_{inj}=9.8 MPa, M_{fuel}=5.0 mg and t_{d}=5.5 ms. The ignition and the combustion were followed with the PIN-Si photodiodes. The flame form was defined as the region, where the radiation intensity was larger than 30 kW/m$^2\mu$m, . The radiation due to propane appeared later than the radiation due to n-pentane, and the intensity was weaker. The ignition probability of propane was lower than those of other fuels, and the flame length of propane was shorter than that of n-pentane. The result of butane was between those of n-butane and n-pentane, as expected.

The left figure in Fig.2 shows the ignition delay, τ_i (the solid circles) and the combustion duration, t_{cd}. The combustion duration is shown from the time τ_i to the end of combustion (i.e. the time between the opencircles). The ignition delay of propane was larger than that of light oil. The right figure in Fig.2 shows the place of the flame tip which was the farthest from the nozzle, z_t and the probability of ignition, P_t, which is the ratio of ignitions to the whole experiments performed under the same condution.

From these results we can discuss as follows:

As described in our paper[1], the duration time is more than 20 ms in the conventional shock tube. Using this gas phase, the ignition and the combustion of the fuel spray of liquified petroleum gas (LPG) were followed under the similar temperature and pressure condition to that of light oil. The same fuel injection system as used in the diesel spray combustion of light oil[1] was used in this study, i.e. the fuel was compressed beforehand with a hand pump and was reserved in an accumulator. The liquified fuel gas was sprayed into the hot gas phase. The only difference was that a new small accumulator of the volume 100 cc made of stainless steel was used, instead of using a gas as a pressure-reserving material in the accumulator for the sake of safety.

The compressibilities of LPG are larger than that of light oil. Therefore, the maximum pressure in our system was smaller than that of light oil. Although there were some difficulties in compressing the fuel, we could compress the fuel to 10 MPa. The maximum pressures, which we obtained with our hand-pump system, were 14-15 MPa for liquified propane, 22-23 MPa for liquified n-butane. The surface tensions σ were relatively smaller, and the vapor pressures P_{vapor} were much larger than those of light oil. Therefore the airtightness of injection system was insufficient. Some amount of the LPG flowed out of the compression system, yet fortunately not into the shock tube. We performed the experiment within one minute after compression.

The ignitability (the self ignition) of propane spray was lower than that of n-pentane. The penetration due to liquified droplet became weaker and the mixing with compressed air behind the shock wave was not enough. Consequently, the region with fuel-rich mixture remained in the gas phase. In this region the ignitability of the mixture became weak. The flame of propane was small, and existed only in a small region. Though n-butane is also liquified gas, the evaporation-rate was not so large as that of the propane. The penetration of spray was weak especially in the case of propane, when the amount of injected fuel was small.

When the monochromatic emissive powers $I(x)$ at r=6,18,30,42 mm were inverted with the Abel-transformation, the distribution of the local monochromatic emissive powers $I(r)$ could be calculated along the radial direction. The tip of the spray reached the place z=138 mm at maximum. Here, the fuel mixed enough with the air along the center line of the tube and the strongest emission was observed. On the contrary, near the injection nozzle ($z \leq 78$ mm), the complex mixing of fuel with air occurred between spray-tip and injection nozzle.

4 Conclusion

The liquified propane, n-butane and n-pentane were injected into the gas phase with the constant pressure and temperature under an "over-tailored" condition of the shock tube. The gasification-rate of propane was very high and the penetration of propane was smaller than that of n-pentane. Consequently, the mixing of propane with air was not sufficient, and the region of the ignitable gas mixture was small. Therefore, the ignition probabilty of propane was smaller and also thermal radiation was weaker than those of butane, pentane, and the light oil.

References

[1] Tsuboi T et al. (2005) Combust. Sci. and Tech. 177 pp.5-13.

[2] Tsuboi T et al. (1997). Liquid spray combustion in supersonic flow. Proceedings of 21st International Symposium on Shock Tubes, pp 391-395.