Effects of Turbulent Mixing on Spray Ignition in Spray System

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When a column of droplets freely falling from an ultrasonic atomizer was ignited behind a reflected shock, no ignition occurred at a temperature below 1100 K, even if the pressure was as high as 1MPa. Although, a higher temperature condition ensured ignition, no luminous flame was observable by high-speed photography, and even if a luminous flame lump appeared at an extremely high temperature, it disappeared without spreading over the entire column of droplets in this case. It is known however that, if a fuel is injected into a diesel cylinder or an electric furnace, ignition occurs even at a temperature as low as 650 K with a luminous flame spreading over the entire spray. These differences could be caused by the effects of turbulent mixing between fuel droplets and hot air, in fact, turbulence-generating rods were placed on the upstream side of the spray column. Experimental results indicates that the ignition limit was lowered to 840 K, and the ignition delay period was decreased by increasing the intensity of turbulence. Furthermore, the light emission of the flame was intensified, and normal spray combustion was maintained in the low-temperature atmosphere after the shock tube ceased its operation.

Key Words : Ignition Process, Ignition Delay Period, Turbulent Generating Rods, Turbulent Mixing, Shock Tube, Apparent Activation Energy.

1. Introduction

About 20 years ago, a technique was invented by Miyasaka and Mizutani (1975) to observe the ignition process of a spray in an ideal condition that involved neither atomization nor turbulent mixing process, where, using a shock tube, a column of droplets freely falling from an ultrasonic atomizer was ignited behind a reflected shock. In the early stage of the research, the droplets column was disturbed by secondary flows which originated from the incident shock having entered into the droplets feeder and receiver tubes at the top and bottom, respectively, of the horizontal shock tube, and ignition occurred at 800 K and above with a luminous flame spreading over the entire cross section at temperatures above 900 K.

Mizutani et al. (1988) pointed out that the occurence of the secondary flows were prevented by removing the droplet tube and by throttling the exit of the droplet feeder tube. As a result, no ignition occurred below 1060 K even at pressures around 0.85 MPa. (Note that the available period is only a few milliseconds in a shock tube experiment.) Although the probability of ignition rapidly increased as the temperature was raised to 1060 K, no luminous flame was observable by high-speed photography below 1300 K, and if a small lump of luminous flame appeared above 1300 K, it was quenched without spreading through the droplets.

According to the previous experimental results,

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Kwon et al. (1989), Ikura et al. (1975), Ikegami et al. (1987), Fujimoto et al. (1979), and Mizutani et al. (1990) when a fuel is injected into a diesel combustion chamber or an electric furnace ignition takes place even at a temperature as low as 650 K with a luminous flame spreading over the entire spray. It was conjectured from the above facts that the turbulent mixing process between the droplet cloud and the surrounding hot air played an important role in the ignition process of a spray. In the present study, therefore, a controlled turbulence was generated around the column of droplets by placing turbulence-generating rods in its upstream to examine the effects of turbulent mixing on its ignition process. As a result, the role of turbulent mixing in promoting the ignition process of a spray was successfully elucidated.

2. Experimental Apparatus and Instrumentation

The shock tube used was the same as the one used in Mizutani et al.(1988) which was of 66 mm i. d. and of double diaphragm type; the lengths of the high- and low-pressure sections of which were 3.5 m and 6.7 m, respectively. Its high- and low-pressure sections were filled with a helium-nitrogen mixture and high-purity air, respectively, and a cetane droplet column of 8 mm in diameter produced by an ultrasonic atomizer was ignited by the reflected shock. The Sauter mean diameter and initial fuel-to-air equivalence ratio of the column were about 50 μm and 20, respectively experimented by Chung et al. (1989, 1990, 1994). The equivalence ratio may be an order smaller behind the reflected shock than the initial value if the droplets do not follow the gas motion on rapid compression.

In order to generate turbulence around the droplet column, a pair of vertical rods of 8 mm in diameter were placed at a distance, S, from the end plate as shown in Fig. 1. The intensity of turbulence at column position increased as S was decreased in steps of 64, 44 and 24 mm, although

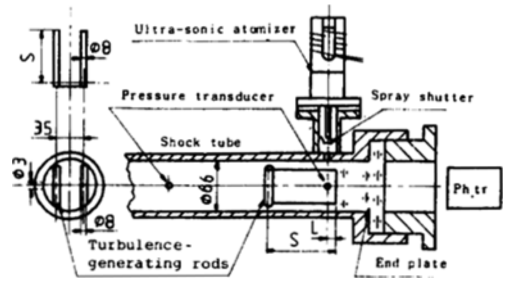

Fig. 1 Test section of shock tube and turbulence-generating rods.

the intensity could not be determined quantitatively. The distance, L, between the droplet column and the end plate was kept at 10 mm.

Since the incident shock was followed by a supersonic stream, oblique shock waves were formed from the turbulence-generating rods while the rods were exposed to the stream, i.e., during the period between the passage of the incident shock by the rods and the arrival of the reflected shock at the rods. In addition, the stream was throttled by 25 % at the rod position. Then, their effects were evaluated as follows.

Suppose that the tip of the oblique shock moves toward downstream at the same velocity with the incident shock and that it disappears or dissipates on colliding against the reflected shock. Then the period that the droplet column is under the direct influence of the oblique shocks is between the passages of the incident and reflected shocks successively by the column, which is only 40 μs from Table 1 in Mizutani et al.(1988). In addition, the period that the oblique shocks are formed is only 250 μs even for S=64 mm. Therefore, the droplet column is barely affected by the oblique shocks directly, but is only affected indirectly through the turbulence of the surrounding atmosphere.

It is also supposed that the effects of throttling by the turbulence-generating rods are almost the same as those of the boundary layer, since $S/D \leq 0.97$ and S is less than 1 % as long as the low-pressure section of the shock tube, the inner diameter, D, of which is 66 mm. In particular, the effects of throttling on the ignition region near

Table 1 Classified ignition delay data of sprays

Key	Researchers	Fuel	Temperature range K	Pressure atm	Activation energy kJ/mol
I	Ikegami et al.	Gas oil	700 - 1000		26.4
	Ikura et al.	Cetane	645 - 1000	1.0	59.5
	Ikura et al.	Cetane	645 - 1000	21	32.7
	Fujimoto et al.	Heavy oil	710 - 1806		42.7
	Mullaney		600 - 1000	17.5	21.4
II	Mullins	Cetane	1113 - 1243	1.0	129
	Koizumi-Kataoka	Gas oil	973 - 1153	1.0	148
	Spadaccini-TeVelde	Cetane	660 - 750	1.0	211
	Onuma et al.	nHeptane	1043 - 1223	1.0	160
	Onuma et al.	iOctane	1043 - 1223	1.0	147
III	Present data	Cetane	1210 - 1430	8.0 - 9.0	204.2
	present data	Cetane	1060 - 1210	8.0 - 9.0	50.4
	present data	Cetane	840 - 1110	9.5 - 11.6	29.5 - 29.8

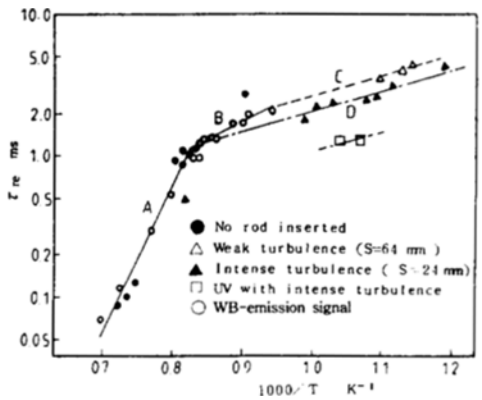

Fig. 2 Ignition delays of cetane droplet columns.

end plate may be small.

The light emission in the ignition process carried out by Mizutani et al. (1988) that it was monitored through the end plate fabricated of strengthened glass, using a wide-band detector system made of 13 high-sensitivity phototransistors (Wide-band emission, hereafter to be called "WB emission"), or through a quartz window of 10 mm in diameter at the center of the end plate using an OH-band emission detector system made of a metallic interference filter and a photomultiplier (Ultraviolet emission, hereafter to be called "UV emission"). In addition, the pressure around the droplet column was monitored using a pressure transducer (Kistler 201B2) installed on the sidewall at the column position.

The experiment was conducted for cetane. The fuel injection rate, q, and the pressure, p, behind the reflected shock were kept at 0.5 cm^3/min and 1MPa respectively, and only the temperature, T, was varied.

3. Results

3.1 Dependence of ignition delay on turbulence

The ignition delay, τre, measured from the passage of the reflected shock was determined from the WB-emission signals (keys other than ○) and the UV-emission ones (key□) for the case with no rods inserted as well as for the cases of weak turbulence(s=64mm) and intense turbulence (s=24mm). The results are shown in Fig. 2.

The WB-emission signal was amplified by 500 times to determine its rise time. The data reported in Mizutani et al. (1988) are also plotted (key●). Although each plot does not correspond to the average value of plural measurements but to a single one, the amount of scatter is small enough and the reproducibility of the data is excellent, which is characteristics of spray ignition data.

The portion, A, of the solid bold line corresponds to the high-temperature ignition, whereas the portion, B, corresponds to the medium-temperature ignition, and the line breaks between both portions. A luminous flame lump recordable by highspeed photography appeared only at the high-temperature end of curve A, and no luminous flame appeared at lower temperatures. The reasons proposed by Mizutani et al. (1988), is probably because only the vapor, formed around the droplets column or in its downstream by the evaporation of micromist or minute droplets, was ignited. The main body of the column left is unignited probably because of the quenching effect of the densely populated droplets (8.6 droplets/mm^3 if monodispersion is assumed). The probability of misfire gradually increased along curve B as the temperature was lowered, finally becoming completely unignitable around T=

1100 K. The apparent activation energy is 204 kJ/mol, for curves A and B.

When, on the other hand, the turbulent mixing between the droplets cloud and the surrounding hot air was generated by inserting turbulence-generating rods in the upstream of the droplet column, ignition took place even around 840 K accompanied by a considerably intense light emission. The broken line C, corresponds to the weak turbulence case (s=64 mm), whereas the chain line D, corresponds to the strong turbulence case (s=24 mm). There are only three datum points for curve C. Since, however, the amount of scatter of datum points is small enough as already mentioned, it may be concluded that both curves are almost parallel to each other, and that curve D is located by 30% below curve C. The apparent activation energy is 29.8 kJ/mol and 29.5 kJ/mol, respectively, for curves C and D.

The temperature T, is kept at its nominal value within 2 to 3 ms, and thereafter it gradually falls along with the pressure as mentioned later. Therefore, the temperature is not always constant during the ignition delay period for curves C and D in their low-temperature portions. Nevertheless, the ignition delay does not increase so rapidly as to be expected for those portions, which suggests the smaller contribution of chemical kinetics than that of droplet evaporation. The ignition delay data obtained in shock tube was different from those in rapid compression machine, where fuel is injected into a hot air stream.

3.2 Dependence of ignition process on turbulence

It was examined how the ignition delay and ignition process were affected by the intensity of turbulence by changing the position. S, of the turbulence-generating rods in steps of 64, 44 and 24 mm while the temperature, T, behind the reflected shock kept roughly constant. The results are shown in Fig. 3. along with the pressure signals monitored at the position of the droplet column in Fig. 4. The initial time was taken at the instant that the reflected shock passed by the droplet column.

Figure 3 shows the WB-emission signals, where the ignition delay is shortened in steps of 1.9, 1.7 and 1.5 ms as the turbulence intensity is increased. The intensity of light emission increases rapidly as the turbulence intensity is raised, and even for the weakest turbulence case, Fig.3(a), the intensity is ca. 2.5 times as intense as the one for no rod insertion case carried out by Mizutani et al. (1988). In any cases, the emission intensity continues to fall until 10 ms. This is the time when the rarefaction fan reflected by the end plate of the high-pressure section reaches the column position and the pressure and temperature fall to respective final value. However, the second peak appears at 12~14 ms probably synchronized with the flows produced by the residual waves or gas-column oscillation.

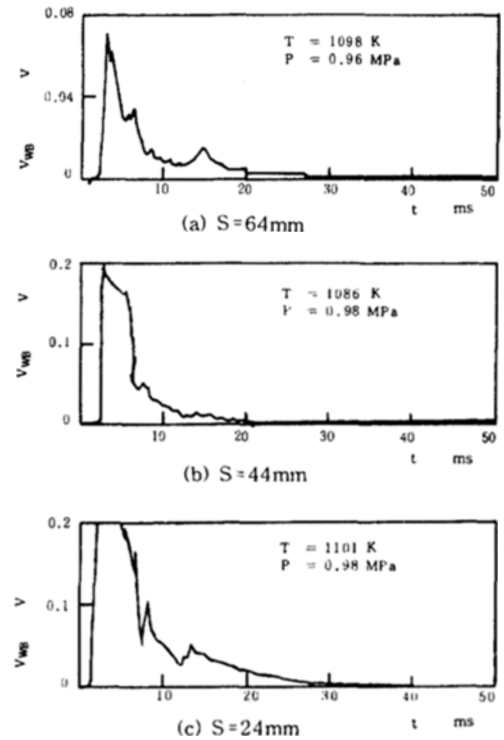

Fig. 3 Variation of WB-emission pattern with turbulence intensity.

Let us here examine the pressure signals shown in Fig. 4. Rather strong disturbance is seen until 0.1 to 0.25 ms in the period of occurrence of oblique shock waves, then residual weak distur-

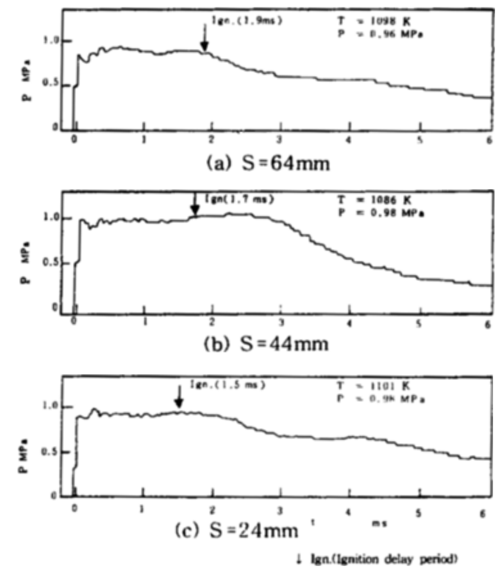

Fig. 4 Pressure signals corresponding to Fig. 3.

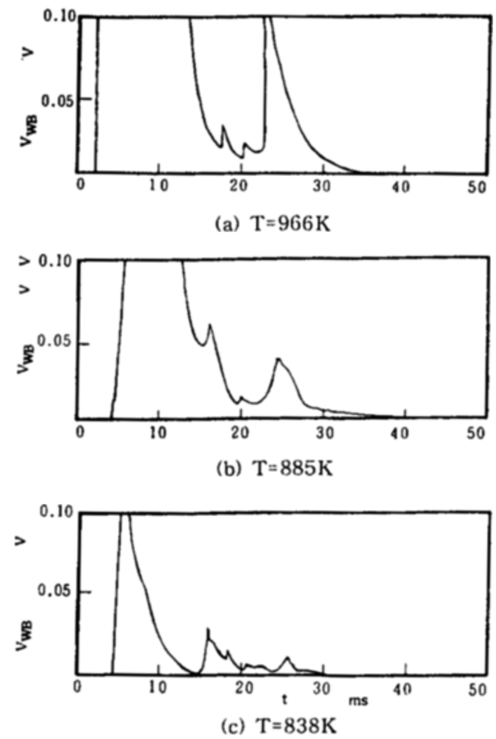

Fig. 5 WB-emission signals in turbulence condition.

bance follows that. Those disturbances, however, cause no overshoot in pressure, but on the contrary, they damp the pressure rise. This fact supports the previous assumption that no direct effect of oblique shock waves might exist on the droplet column. Since, in addition, the disturbed portion of the pressure signal is followed by an undisturbed flat portion, it is expected that the throttling of stream by the turbulence-generating rods has no significant effects on the environment of the droplet column. Ignition takes place before the rarefaction fan, which has been produced by the collision of the reflected shock against the contact surface, arrives and the pressure starts to descend. Therefore, these are taken to be convection-free ignition processes.

3.3 Ignition processes with turbulent mixing

The ignition process accompanied by turbulent mixing was examined in detail.

Figure 5 shows the WB-emission signals under the influence of a strong turbulence, while was generated by placing rods at s=24 mm, while the temperature, T, behind the reflected shock varied in steps of 966, 885 and 838 K.

The emission intensity is almost equivalent to that of high-temperature ignition (T=1280 K in Fig. 2) without rods inserted, marked with ● and the emission continues until 30~40 ms synchronizing the flows produced by the residual waves or gas column oscillation after the shock tube has ceased its operation. Especially for T> 900 K, strong emission continues until 30 ms, and the major portion of the droplets column may have completed its combustion in normal spray combustion mode. Although the emission intensity lowers as T is decreased, it does not lower so violently as in the medium-temperature ignition without rods inserted in previous results.

Although the pressure signals are omitted, ignition takes place on the pressure plateau in case (a) T=966 K, whereas ignition occurs in the middle of the slope in case (b) T=885 K, and at the foot of the slope in case (c) T=838 K. It is difficult, however, to understand how ignition occurs after both pressure and temperature have significantly or completely lowered.

Then, the UV emission from the middle of the droplet column was monitored. The results are

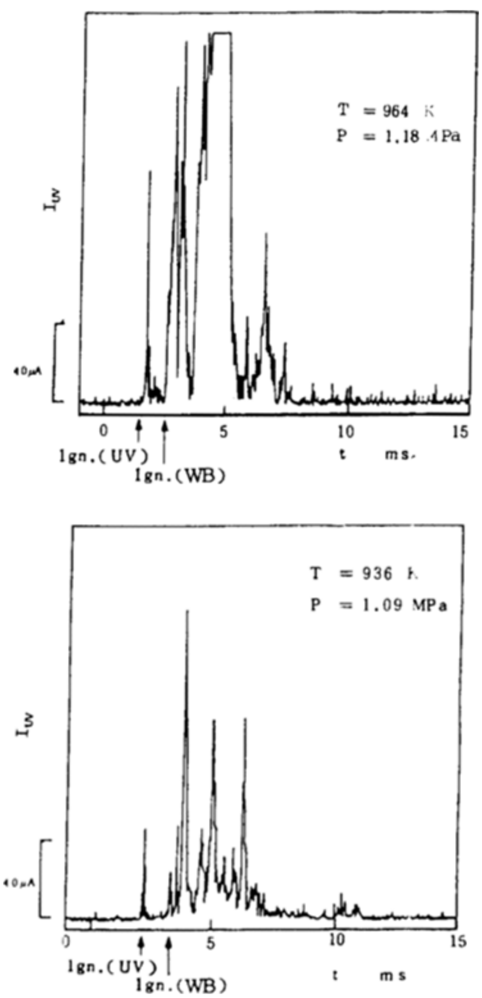

Fig. 6 UV-emission signals in turbulence condition.

shown in Fig. 6. In the figure, the arrows marked with Ign.(UV) or Ign.(WB) represent the ignition time determined from the UV-or WB-emission signal. Ign.(UV) is also plotted in Fig. 2. The ignition delay determined from the UV-emission signal is only ca. 55% of τ_{re}. This fact implies that the vapor produced around the droplet column or in its downstream by the evaporation of minute droplets or micromist, starts its gas-phase reactions well before the delay period, τ_{re}. The micromist is formed by the shuttering or peeling of droplets by the incident shock. Note that the Weber number for a droplet of 50 μm dia. located behind the incident shock is a few hundreds, which is well larger than the critical Weber number, 20, for shattering. Since, however, the shattering period is only a few tens microseconds, the amount of micromist produced is not large, and it depends on the shock intensity.

The UV-emission signals shown in Fig. 6 completely differ from those without rods inserted.

That is, in case of no rod insertion, only a single peak appeared immediately after Ign.(UV) followed only by a small peak or nothing. If, on the other hand, rods are inserted, intense UV-emission appeared after Ign.(WB) in spite of the low temperature below 1000 K, even in the pressure-descending period after the arrival of the rarefaction fan reflecting from the high-pressure end plate. This fact implies that a large amount of vapor evaporated from the droplets, which have been heated up by the hot air entrained into the droplet column, joins with the mist-origin vapor after the droplet heat-up period, and causes intense gas-phase reactions, which leads to normal spray combustion.

4. Discussions

The experimental facts may be summarized as follows. In the high-temperature region represented by curve A in Fig. 2, the ignition process is governed by the gas-phase reaction of the fuel vapor originating from minute droplets or micromist. As the temperature is lowered on weakening the incident shock, the initial vapor concentration gradually decreases because the amount of micromist reduces due to the weakened shuttering and peeling of droplets, and the ignition process gradually gets affected by the vaporization of droplets in the medium-temperature region represented by curve B in Fig. 2. Since, however, droplet evaporation is too slow without turbulent mixing to accumulate enough vapor before the arrival of the first rarefaction front, ignition ceases around T=1100 K. If, on the other hand, the droplet evaporation process is accelerated by turbulent mixing, the ignition process becomes dependent on the droplet evaporation process and the ignition region expands towards the low-temperature region represented by curves C and D in Fig. 2.

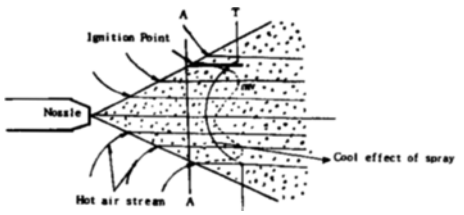

Fig. 7 Model of ignition mode by the injecting spray mode.

The present data are compared with other researchers' in Table 1. Although the pressure level differs from study to study, at least the temperature dependence (apparent activation energy) of ignition delay may be compared with each other, since it does not depend much on the pressure (see for example the data of Ikura et al., 1975).

In the table, Ikegami et al. (1987) used a rapid-compression machine, Ikura et al. (1975) experimented a pressurized electric furnace, Fujimoto et al. (1979) used a pressurized electric furnace of diesel engine type and Mullaney (1956) injected fuel behind a reflected shock.

In these studies, which belong to group I., fuel was injected into a stagnant hot atmosphere, and data were obtained at low temperature below 1000 K. The apparent activation energy was as low as 21～60 kJ/mol.

In group II, Mullins (1953), Koizumi and Kitaoka (1962) and Slpadaccini and TeVelde (1982) continuously injected fuel into a vitiated hot air stream coaxially, whereas Onuma et al. (1986) intermittently injected fuel into a hot air stream obliquely. Data were taken at high temperatures above 970 K except for Spadaccini and TeVelde, and the activation energy was as high as 129～211 kJ/mol.

The present shock tube data are summarized in group III. The high-temperature data (curve A in Fig. 2) are close to group II, whereas the medium-(curve B) and low-temperature data (curves C and D) are close to group I. This fact suggests that the data of group I are governed by the evaporation process of droplets, whereas the data of group II are governed by the gas-phase

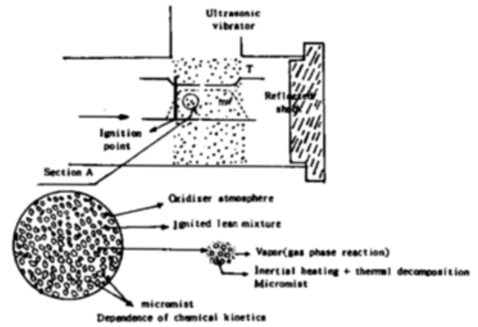

Fig. 8 Model of ignition mode by the shock tube.

reactions of fuel vapor.

In fact, Kadota et al. (1975) ignited a suspended single drop in a pressurized electric furnace and obtained activation energies of 30.7～37.4 kJ/mol, which are close to the ones of group I. Concerning fuel vapor ignition, Yoshizawa et al. (1977) obtained activation energies of 129～166 kJ/mol above 1200 K using a shock tube, Krishnan and Ravikumar (1981) obtained 188 kJ/mol for methane ignition behind a reflected shock, and Freeman and Lefebvre (1984) observed 160～171 kJ/mol by injection fuel vapors into a hot stream of 930～1050 K, which are close to the data of group II. It is conjectured that, in the condition where an abundant time is available for droplet evaporation prior to ignition and the resultant fuel vapor is accumulated in the spray, such as the case that fuel is injected into a hot stagnant atmosphere, the spray ignition process is governed by the droplet evaporation process, otherwise it is governed by the chemical kinetics in the vapor.

The ignition modes observed by this technique seem to be different from those observed by the usual injection method, in which fuel is injected into a hot atmosphere, electric furnance etc. In shock tube have been obtained ignition delay data was different from rapid compression machine, electric furnance, by injecting sprays into a hot air stream (Chung and Mizutani, 1994). Unlike the case of a jet spray type, the effects of fuel injection rate of ignition delay are little because of rapid increasing of temperature, different of flow pattern, turbulent intensity effect and cooling effect of hot air by spray as shown Figs. 7 and 8.

5. Conclusions

In order to elucidate the crucial role of turbulent mixing on the ignition processes of sprays, a controlled turbulence was generated behind a reflected shock using turbulence generation rods and a column of droplets freely falling from an ultrasonic atomizer was ignited under the influence of turbulence. The ignition limit temperature was considerably lowered by the turbulent mixing, and ignition delay was shortened. The turbulent mixing also changed the ignition process from a chemical kinetics-controlled mode into a droplet evaporation-controlled one. The present study clearly indicates that the turbulent mixing has the important role in the spray ignition process.

The ignition modes observed by this technique seem to be different from those observed by the usual injection method, in which fuel is injected into a hot atmosphere, electric furnance etc. The ignition delay data obtained in shock tube was different from those in rapid compression machine, where fuel injected into a hot air stream.

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