Effects of Velocity, Turbulence and Wall Impingement on the Ignition of Fuel Sprays Perpendicularly Injected into a Heated Air Stream

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Introduction

The modeling and numerical analyses of the spontaneous ignition of sprays or turbulent jets have recently made startling progress. For example, Takagi et al.[1], Kong and Reitz [2] and Chang et al.[3] have analyzed the ignition process of diesel sprays using KIVA code or similar ones with k-ε model and a special chemical kinetic scheme or time variable included. The atomization, impingement and coalescence of droplets are also considered. The research of Mastorakos et al.[4] into the spontaneous ignition of nonpremixed turbulent jets is also interesting.

The database to be compared with those analytical results, on the other hand, is far behind them. The reasons are as follows. (1) There is wide variety in ignition detecting method; e.g., those using pressure rise, visible emissions, and OH-chemiluminescence. (2) Fuel injection perpendicular to the (swirling) stream like in diesel engines is seldom adopted with the exception of Onuma et al.[5]. (3) The effects of flow velocity, turbulence and spray impingement are seldom studied with the exception of Mizutani et al.[6]. (4) The difference in induction process between stagnant and flowing atmospheres and between low and high temperature ones is not adequately considered.

Under this situation, it may be useful to elucidate the effects of flow velocity and turbulence on the autoignition of sprays perpendicularly injected into a heated air stream, and those of spray tip impingement against a wall. Once, one of the authors studied the effects of turbulence on the autoignition of premixed spray columns using a shock tube [6]. In the present paper, the effects of flow velocity and turbulence on the autoignition of the sprays perpendicularly injected into a heated air stream were examined as well as the effects of spray tip impingement against a wall.

Experimental

For the purpose of conducting spray ignition experiments by supplying hot air to a preheated test section, a novel method was employed. A test section was buried within a radiant tube-type heater having on each end a natural gas burner coupled with a heat regenerator, and the hot-air stream immediately after cutting off the fuel-gas supply was utilized. The test section is shown in Fig.1 along with variations in installation of a spray collision plate.

The heater tube and test section was made of square carbon steel tube of 188mm x 188mm, being internally lined with 20 mm thick soft refractory. The regenerative burners on both ends alternately repeated combustion and heat accumulation runs every 30 seconds. If natural gas was cut off in the third cycle, the air preheated up to 1500 K by one of the heat regenerator was sent to the test section. The temperature of the air stream was monitored by a thermocouple, and ignition experiments were carried out at the instant when the air temperature descended down to the preset value. The intensity of turbulence was varied in steps of 13%, 30%, 50% and 60% by exchanging a set of multi-hole deflector and rectifier plates made of 50mm thick perforated refractory board.

The test section was a portion, 140 mm long, of the radiant tube equipped with a Vycor window of 140mm x 244mm as shown in Fig.1. A water-cooled fuel-injection nozzle (Pintle type automatic nozzle, DN10PD76) was installed downwards in the ceiling with a cavity of 95mm x 95mm and 260mm deep embedded in the floor to avoid spray impingement as shown Fig.1(a). For investigating the effects of spray impingement, an impingement plate was placed on the cavity, or at 70mm above the floor as shown in Figs.1(b) and (c).

The liquid fuel used was diesel light oil, which was fed to the injection nozzle from a four-cylinder distribution-type injection pump (DENSO, VE4) using one of the four ports. The number of revolutions was 500 rev/min, the injection pressure 12 MPa, the volume of single injection 126 mm^3, and injection period was 6-7 msec. Unfortunately, neither droplet size distribution data nor spray-tip velocity ones were obtained during ignition runs due to the difficulty.

The ignition delay was determined as the period from the instant when the He-Ne laser beam was intercepted by the liquid jet to that when the photomultiplier detected the OH-radical chemiluminescence through a pinhole and a metallic-membrane interference filter. The ignition processes were recorded using a high-speed video camera.

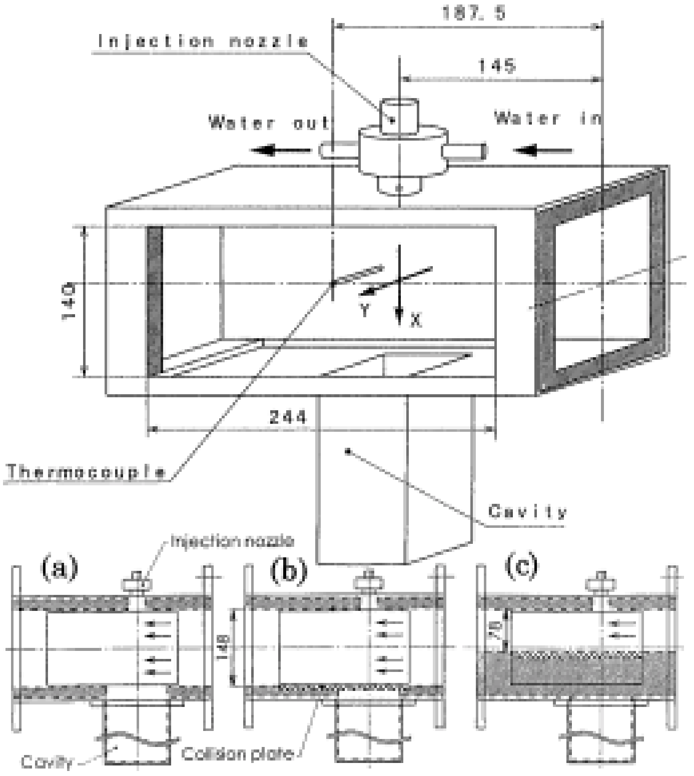

Fig. 1: Test section and installation of spray collision plate. Hatched area denotes heat insulator lining. (a) No spray collision plate is installed, (b) A collision plate is installed even with the floor, and (c) A collision plate is installed at an elevated position.

Results

The ignition delay, observed with no collision plate installed on the cavity is shown in Figs.2(a) through (d). These figures correspond to turbulence intensities of ca. 13, 30, 50 and 60%, respectively, while the mean velocity, *V* in the injector cross section is varied in steps of 0, 1, 2, 3, 4, 5 and 6 m/sec. In low flow-velocity conditions, no ignition is observed, and even for higher flow velocities, no ignition occurs outside the region surrounded by broken lines.

No ignition occurs above the horizontal broken line, probably because the spray tip enters the cool cavity and the flamelets, if any, are quenched. If, however, the turbulence intensity is higher, the temperature gradient through the cavity entrance is decreased and the gas exchange through the entrance is activated. Therefore, the ignition of the spray tip can take place even in the cavity and the resultant flame can propagate upwards. As a result, the horizontal broken line shifts upwards. In the low-temperature region on the right of the vertical broken line, on the other hand, no flamelet is formed in a limited period due to the too slow chemical reaction.

As turbulence is strengthened, the ignition delay is increased in the region above 1300 K, and subsequently, the gradient of the Arrhenius line (corresponding to the apparent activation energy, *E*, with the temperature dependence of physical processes like mixing as well as that of chemical kinetic processes included) decreases. This may be ascribed to the fact that the weak flamelets, which have appeared in an early stage, are stretched and quenched by the intense turbulence, so that they hardly grow into a stable flame ball until some strong flamelets appear. In fact, a weak OH-emission signal, which is obviously different from noise, is frequently detected prior to ignition. In a low-temperature region below 1300 K, turbulence promotes ignition through accelerated mixing, while too intense turbulence exceeding 50% retards it even at a low temperature.

Next, the ignition delay is shown in Figs.3(a) and (b) for the case that the turbulence intensity is 13% and a spray collision plate is installed on the cavity as shown in Figs.1(b) and (c). For comparison, the data obtained with no plate installed on the cavity are shown as broken lines. Although the ignition delay is increased by the installation of the collision plate, ignition takes place even in a low velocity region below V = 2 m/sec and the ignitable region is expanded down to 1000 K and up to 30 msec delay period. The reason why the ignitable region has expanded above the τ = 5 msec line is that ignition occurs after the impingement of spray tip against the collision plate. The reason why the region has expanded below T = 1200 K line, on the other hand, may be that the temperature and flow patterns near the collision plate are changed by its installation, and that the slip of droplets is increased due to the deceleration of spray tip. Since the characteristic time for chemical reaction is increased as the temperature is lowered, the data points transfer to the higher gradient line dominated by chemical reaction between 1000 and 1100 K. Consequently, the apparent activation energy increases from ca. 60 kJ/mol to 158 kJ/mol in case of Fig.3(a).

It seems, in case of Fig.3(b), that the ignition process after the impingement of spray tip is initiated around 3 msec, because the decreased channel height has advanced the spray impingement timing. No transition to reaction-dominant state is seen in this case, probably because the characteristic time for mixing is increased as the impinging point approaches the nozzle tip so that the mixing dominancy is maintained even below 1100 K.

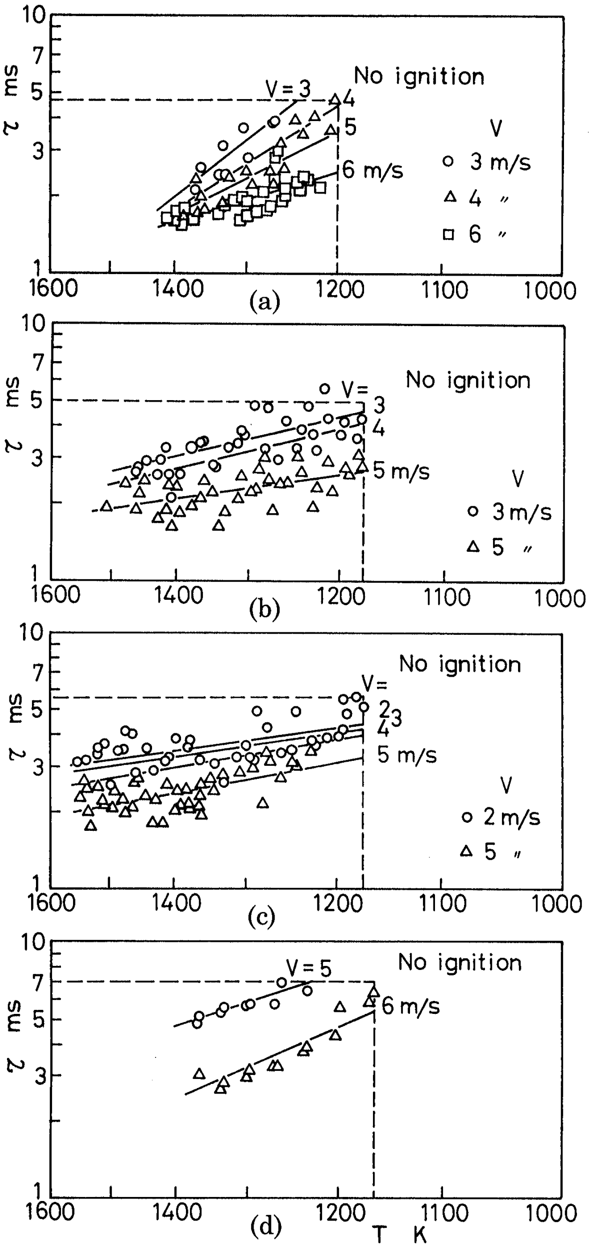

Fig. 2: Ignition delay with no collision plate installed. (a) V'/V_{avg}= 13%, (b) 30%, (c) 50% and (d) 60%

Concluding Remarks

Aiming at improving the experimental database which is to be compared with the rapidly developing modeling and numerical analyses of spray autoignition, the effects of various factors such as the flow velocity, turbulence and temperature of the air stream on the ignition behavior and delay of sprays were elucidated. Liquid fuel was perpendicularly injected into a heated air stream. As a result, in spite of the velocity extremely lower than the fuel injection velocity, notable effects of the stream velocity and turbulence were observed. In addition, the effects of the spray impingement against a wall were also observed.

References

[1] Takagi, T. et al., Combust. Sci. and Tech., 75 (1991), pp.1-12.

[2] Kong, S-C. and Reitz, R.D., J. Eng. for Gas Turbines and Power (Trans. ASME), 115 (1993), pp.781-789.

[3] Chang, C-S., Zhang, Y., Bray, K.N.C. and Rogg, B., Combust. Sci. and Tech., 113-114 (1996), pp.205-219.

[4] Mastorakos, E. et al., Combust. Sci. and Tech., 125 (1997), pp.243-282.

[5] Onuma, Y. et al., Trans. JSME, 51B (1985), pp.4327-4333; 52B (1986), pp.3380-3387 and pp.3577-3580.

[6] Mizutani, Y., Nakabe, K.. and Chung, J.D., The Twenty-Third Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, 1990, pp.1455-1460.

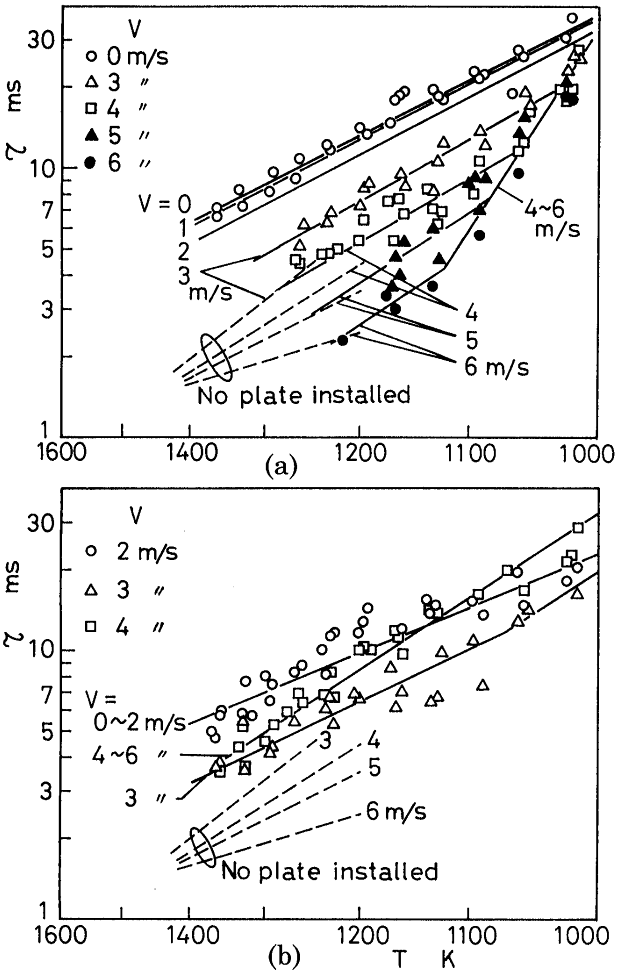

Fig. 3: Ignition delay with a collision plate installed. V'/V_{avg} = 13%. (a) Plate lift = 0 mm and (b) Plate lift = 70 mm.