Spray Characteristics of a Liquid-fueled Ramjet Engine under High Pressure Air-stream Conditions

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Abstract

In a liquid-fueled ramjet engine, the insufficient mixing and evaporation result in the low combustion efficiency and combustion instability. Improving its spray characteristics and devising a means of mixing fuel droplets with air may compensate these disadvantages of liquid fuel ramjet engine. The jet penetrations of various fuel injectors were measured to investigate the spray characteristics of a liquid-fueled ramjet engine under high pressure air-stream conditions. The penetrations in high pressure conditions are smaller than the values calculated from Inamura's or Lee's equations, and, in the high pressure conditions, the jet penetrations are similar each other. In the dual hole injectors, the jet penetrations of rear orifice is rapidly increased due to the reduction of the drag, which is created by the jet column of front orifice. The jet penetration of rear orifice is increased because of the drag reduction created by the jet column of the front orifice. And, because of the drag reduction formed by the column of jet, the jet penetration in the rear orifice of dual hole injector is much larger than the jet penetration of single hole injector. As the distances of the orifice are increased, the jet penetrations of the rear orifice decrease.

Introduction

A ramjet engine, one of the simplest rocket systems, directly induced air (oxygen of propulsion system) from the atmosphere without a compression system. The induced air goes through a compression process through a supersonic diffuser. Therefore, the ramjet engine has many advantages such as the maximum energy transfer rate, reduction of the weight and volume, and an increase of the flight envelopment. Especially, storable liquid fuel was attractive for use in the limited space of the ramjet engine due to its high density and heating value.[1)] However, insufficient mixing of fuel and air causes unstable combustion. Thus, spray mechanisms were carefully investigated to yield stable flame and high combustion efficiency. And, the empirical equation for the penetration and mean droplet diameter in a subsonic airstream was deduced by Kashwagi.[2)] Droplet mass flux and velocity distributions were studied by Inamura and Nagai.[3)] However, their report was conducted for a single hole injector, which is the simplest fuel injector, one of the pressure atomizer. Therefore, the purpose of this study is to clarify the spray mechanism of various fuel injector. Especially, the jet penetrations of the dual hole fuel injector is closely investigated.

Experimental Apparatus and Conditions

In this study, two rocket stand were established to conduct a rocket ground-test of combustion and spray. These facilities are made of high pressure air compressor, gas depository(N_2, O_2, H_2), protection wall, and control room.

A schematic diagram of an experimental apparatus is shown in Fig. 1. The experimental facilities consist of the air supply section(compressor, dryer), the measurement section, the visualization apparatus, and fuel injection system.

The air supply section provides the high pressure air into the visualization apparatus. The air generated in a compressor goes through a dryer to extract a moisture, and controls its pressure in pressure regulating valve.

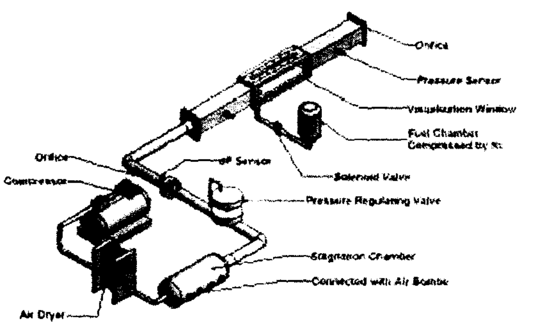

Fig. 1 Schematic diagram of experimental apparatus

The air controlled by the pressure regulated valve is induced into the visualization facility. Fig.2 shows the visualization facility which has the three windows of sides and upper. Its rectangular cross section area is 100mm×100mm, and the pressure sensors are located in the upward and downward direction of windows to measure the pressure.

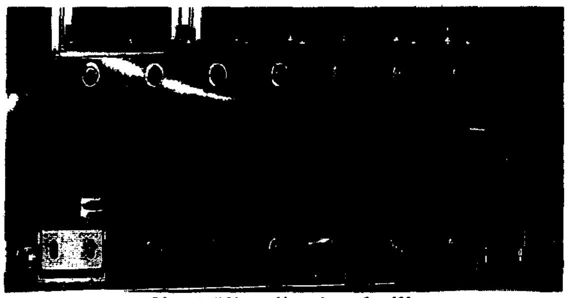

Fig. 2 Visualization facility

The fuel is injected on the lower side of visualization facility. The fuel injectors used in this study are single hole injector, dual hole injector. Their configuration is shown in Fig. 3, 4.

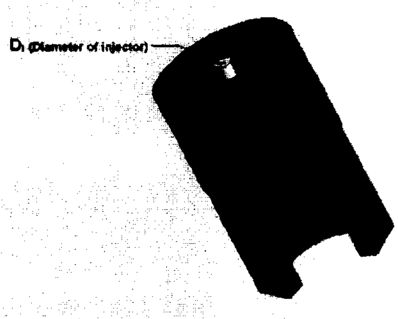

Fig. 3 Single hole injector

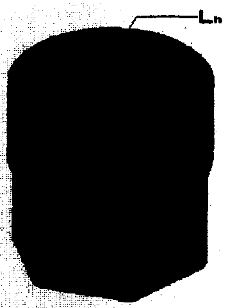

Fig. 4 Dual hole injector

The single hole injectors have an orifice in the center, and their inner diameters of orifice are 1.65mm, 1.83mm, 2.10mm. The dual hole injectors have two orifice in the direction of air-stream. The inner diameters of orifice are same as 1.65mm, and the distances of the orifices(L_h) are 5mm, 10mm, 15mm. The specifications of fuel injector are arranged in Table 1. It is realized from Table 1 that parameters are the diameter of orifice and the distances of the orifices.

Table 1 Fuel injector specifications

Fuel injector	single hole injector (SH)	D_i = 1.65, 1.83, 2.10mm
	dual hole injector (DH)	L_h = 5, 10, 15 mm D_i = 1.65mm 2ea

The hydraulic injector characteristics can be evaluated accurately and can be designed for orifices with the desired injection pressures, injection velocities. Therefore, the discharge coefficients are measured in 6 other injectors. The typical variation of injection orifice flow and pressure drop is shown in Fig. 5, and. the discharge coefficient is arranged in Table 2.

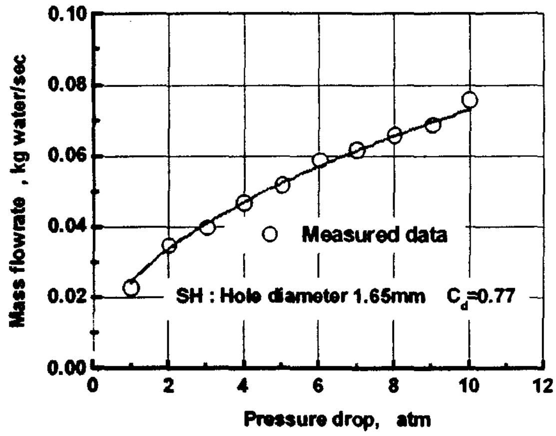

Fig. 5 Discharge coefficient

Table 2 Discharge coefficient

Nozzle Type		C_d
SH (Single Hole)	D_i=1.65mm	0.77
	D_i=1.65mm	0.78
	D_i=1.65mm	0.77
DH (Dual Hole) D_i=1.65mm	L_h=1.65mm	0.79
	L_h=1.65mm	0.78
	L_h=1.65mm	0.79

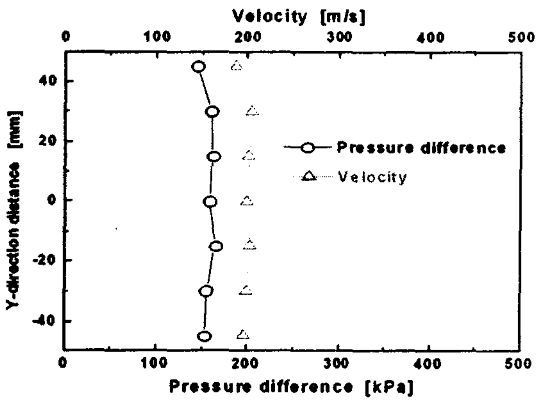

Fig. 6 Velocity distributions (P_s=6.76 atm)

The velocity distribution of the air induced into ram-combustor influences on the performance of atomization, vaporization, and ignition. The velocity distribution at the visualization facility is represented in Fig. 6. They are uniform except for the wall. Thus, it is postulated that there is no abnormal results due to the ununiformity of velocity and temperature.

Results and Discussions

Fig. 7 shows characteristics of a liquid jet. The jet penetration is defined as the maximum vertical distance from the bottom of the jet to the tip of the liquid jet with respect to the arbitrary point. The jet penetration rapidly increases in the vicinity of the nozzle exit, and then the gradient of penetration become more gently due to the increase of the air-stream drag. The penetration is determined by the relative difference between the jet kinetic energy and the aerodynamic drag of the air-stream. In the case of the ramjet engine, the adequate penetrations must be created since the low penetrations exert bad influences on performance of combustion.

Fig. 7 Schematic instantaneous photography of a liquid jet

The single hole injector is the typical pressure atomizers which rely on the conversion of into kinetic energy to achieve a high relative velocity between the liquid and the surrounding air. In the single hole injector, there are many reports in relation to jet penetrations. Especially, Inamura's empirical equation,[4] which is including a high temperature flow-field, and Lee's empirical equation(Eq.(1)),[5] which is revised from Inamura's equation, are representative results for jet penetrations.

$$\frac{Y}{D_O}=(1.2+0.4D_O)q^{0.36}\ln[1+(1.56+0.48D_O)]\frac{X}{D_O} \qquad \left(q=\frac{\rho_j U_j^2}{\rho_a U_a^2}\right) \quad (1)$$

However, these reports don't cover the effects of air-stream pressure. Therefore, the jet penetrations considering the air-stream pressure is investigated. Fig. 8 shows comparison of experimental data with the empirical Eq. (1), when the pressure of air-stream is 2.39 atm. The penetrations in high pressure conditions are smaller than the values calculated from Eq. (1), and, in the high pressure conditions, the jet penetrations are similar each other. Such result imply the fact that the exponent(0.36) of Eq.(1) must be modify smaller than present value.

In the dual hole injectors, the jet penetrations of rear orifice is rapidly increased due to the reduction of the drag, which is created by the jet column of front orifice. Namely, the jet penetrations are determined by the relative difference between the jet kinetic energy and the aerodynamic drag of the air-stream, and, in the case dual hole injectors, the rear orifice has a smaller effect on drag of air-stream than front orifice. When the air-stream pressure and dynamic pressure ratio(q) are respectively 2.39atm and 7.82, the jet penetrations are shown in Fig. 9. In Fig. 9, the distance of the orifices is 5mm. The jet penetration of rear orifice is increased because of the drag reduction created by the jet column of the front orifice. In Fig. 10, the comparison of jet penetrations between single hole fuel injector and rear orifice of dual hole fuel injector is shown. Because of the drag reduction formed by the column of jet, the jet penetration in the rear orifice of dual hole injector is much larger than the jet penetration of single hole injector.

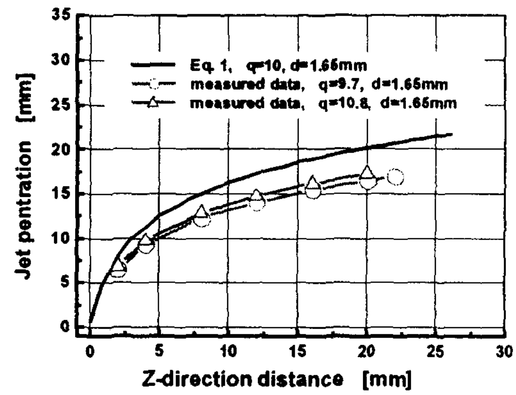

Fig. 8 Jet penetration (P_a=2.39atm)

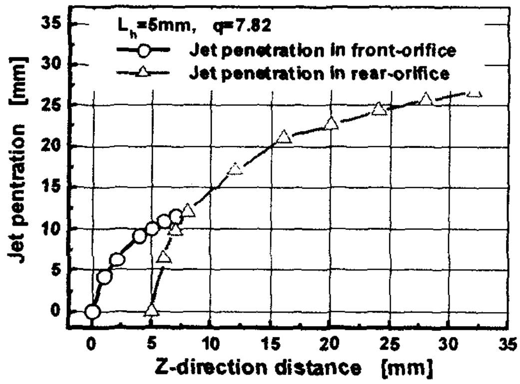

Fig. 9 Jet penetration (dual-hole injector) (P_a=2.39atm, L_h=5mm, q=7.82)

In the Fig. 11, the jet penetrations of rear orifice in dual-hole fuel injector are represented as the change of the distances of the orifice(L_h). As the distances of the orifice are increased, the jet penetrations of the rear orifice decrease. This result is caused the increase of drag as the distance of the orifices is increased.

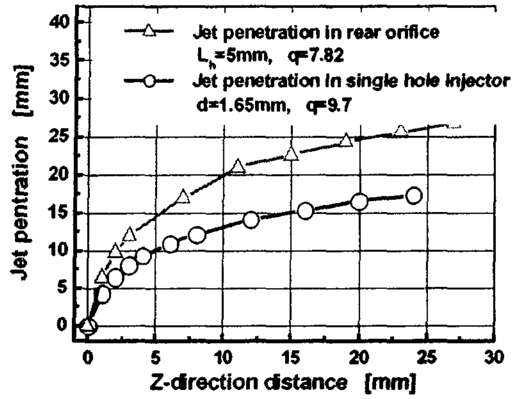

Fig. 10 Comparison of jet penetration between single hole and rear orifice

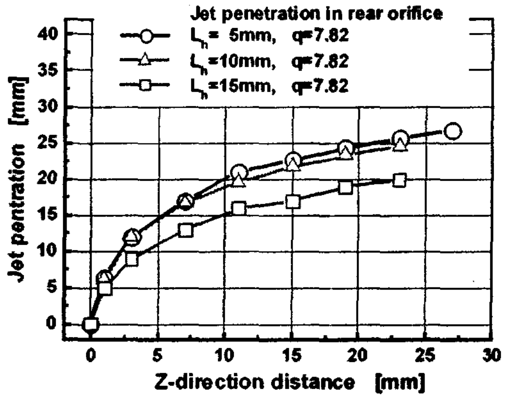

Fig. 11 Jet penetration in variation of distance of orifice

Conclusions

The jet penetrations of various fuel injectors were measured to investigate the spray characteristics of a liquid-fueled ramjet engine under high pressure air-stream conditions. Through these experiments, our conclusions can be summarized as follows :

(1) The penetrations in high pressure conditions are smaller than the values calculated from Inamura's or Lee's equations, and, in the high pressure conditions, the jet penetrations are similar each other.

(2) In the dual hole injectors, the jet penetrations of rear orifice is rapidly increased due to the reduction of the drag, which is created by the jet column of front orifice. The jet penetration of rear orifice is increased because of the drag reduction created by the jet column of the front orifice. And, because of the drag reduction formed by the column of jet, the jet penetration in the rear orifice of dual hole injector is much larger than the jet penetration of single hole injector.

(3) As the distances of the orifice are increased, the jet penetrations of the rear orifice decrease. This result is caused the increase of drag.

Nomenclature

C_d : Discharge coefficient
D_i : Inner diameter of orifice (mm)
L_h : Distances of the orifice (mm)
q : Dynamic pressure ratio
X : Horizontal distance from the center of an injector exit (mm)
Y : Vertical distance from the center of an injector exit (mm)
Z : Distance in the direction perpendicular to X and Y axis (mm)

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