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TESTING THE LIQUID FUEL INJECTOR IN COLD FLOW USING A SUPERSONIC WIND TUNNEL

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Abstract: *This paper aims to deal the new idea of liquid fuel (kerosene) aeroramp injector/plasma igniter who was tested in cold flow using a supersonic wind tunnel at Mach 2.4. The liquid fuel injector is flush wall mounted and consists of a 2 holes aeroramp array of impinging jets that are oriented in a manner to improve mixing and atomization of the liquid jets. Scramjet combustion is a difficult and daunting task to tackle. Among other problems, there is the difficulty in mixing and ignition of fuel, especially hydrocarbons in a supersonic flow. A substantial amount of research has been performed in the field of gas injection in supersonic flows and included these techniques: transverse injection, slots, ramps and jet swirl.*
Key words: *kerosene, fuel injector, supersonic tunnel*

1. INTRODUCTION

The application of gaseous or liquid hydrocarbon fuels to scramjets has been studied on and off for about 50 years. Researchers at Fairchild, United Technologies, Applied Physics Laboratory of Johns Hopkins University, Air Force Research Labs and others in the US and overseas have contributed to this effort.

At present, the flight test vehicles for cold-start combustion uses silane as an ignition aid. Silane is a dangerous gas that ignites upon contact with oxygen. Because of the dangers of this setup, it was decided that another solution needed to be explored for cold-start combustion. The next idea was to use JP7 for both cold-start combustion and normal combustion. The concept is to cold-start the engines with liquid JP7 and to circulate the liquid JP7 through the airframe for cooling purposes.

It was decided that the liquid injection system should be an impinging jet/aeroramp design based on the work previously done by Hewitt (1983) and Jacobsen (2001), respectively. The impinging jets would help create more atomization of the liquid jets, while the aeroramp induces additional vorticity and mixing. This system would in essence create a liquid fuel aeroramp. The liquid fuel aeroramp consists of an array of liquid jets that are angled downstream and then toed in towards each other based on past research.

2. EXPERIMENT

2.1 Experimental set-up

The experiments were done in a blow-down supersonic wind tunnel. The tunnel was configured with a convergent-divergent nozzle that resulted in a free-stream Mach number of 2.4.

Figure 1 shows a sketch of the wind tunnel test arrangement. The typical run time for the tunnel in this experiment was seven seconds.

The two jets are angled downstream at 40 degrees and have a toe-in angle of 60 degrees. The plasma torch used nitrogen and air as feedstocks and was placed downstream of the injector as an ignition aid.

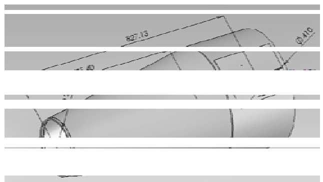

Fig. 1. Tunnel setup with injector and plasma torch

First, schlieren and shadowgraph photographs were taken of the injector flow to study the behavior of the jets, shape of the plume, and penetration of the liquid jet. The liquid fuel aeroramp was found to have better penetration than a single, round jet at 40 degrees. Next, the Sauter mean droplet diameter distribution was measured downstream of the injector. The droplet diameter was found to vary from 21 to 37 microns and the atomization of the injector does not appear to improve beyond 90 effective jet diameters from the liquid fuel aeroramp.

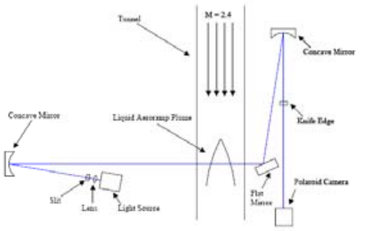

Fig. 2. Schlieren photography setup

This intensity profile can be characterized by a theoretical illumination profile, which should be valid for all forward scattering techniques as long as the droplets are roughly spherical in shape. By using two shape parameters, one can calculate the theoretical intensity of the light and the corresponding droplet diameter. The droplet diameter is calculated by using these shape parameters along with the upper limit distribution function, ULDF, to determine the volume-to-area mean diameter also known as the Sauter mean diameter or D_{32}.

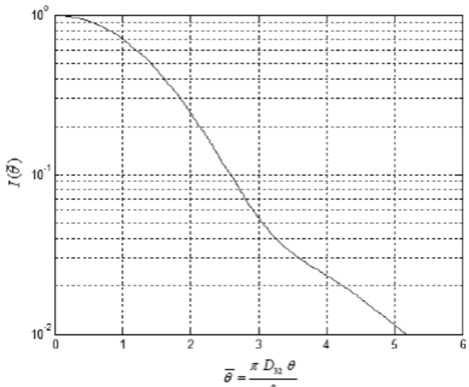

Fig. 3. Mean theoretical illumination profile

The theoretical illumination profile is shown in Figure 7. In this figure, I(θ) is the illumination normalized with the centerline value. Hence the reduced angle is:

$$\overline{\theta} = \frac{\pi D_{32}\theta}{\lambda} \quad (1)$$

where θ is the scattering angle, D_{32} is the mean droplet diameter relating volume and area of spherical droplets, and λ is the wavelength of the light.

This technique usually involves measuring the background intensity profile of the laser, windows, etc. and subtracting that from the forward scatter intensity profile due to the droplets in order to get the Sauter mean diameter, D_{32}, but it was only used as a quick way to determine if any combustion could be present in the cold, supersonic flow before deciding what the next step should be in exploring this liquid injector/plasma torch setup in preparation for hot-flow tests.

2.2 Experimental Results and Interpretation

In Figure 4 a comparison is made between the two-jet liquid aeroramp, which is angled 40 degrees downstream with 60 degrees toe in. One can notice that the liquid aeroramp has much better penetration downstream of the injector than a single, 40 degree jet. The fact that the jet penetrates considerably more than a 40 degree jet suggests that the liquid fuel aeroramp functions as it was originally intended. By impinging the two jets, a vertical liquid sheet is formed and the fluid tends to penetrate farther into the flow and perhaps the aeroramp portion of the liquid fuel aeroramp is inducing additional vorticity and lifting the liquid plume off the floor of the tunnel. The latter was found for gaseous aeroramp injectors.

		Distance, mm (x/deq)		
h/deq	**Height,mm**	17.6/23.3	35.2/46.7	52.8/70
13.5	10.2	21	23	32
10.1	7.6	28	33	-
6.7	5.1	29	-	33
3.4	2.5	27	31	29

	D_{32} in microns as a function of height	
h/deq	**Height,mm**	**D_{32} in microns**
20.2	15.2	22
18.5	14	24
16.8	12.7	23
15.2	11.4	-
13.5	10.2	32
11.8	8.9	34
10.1	7.6	34
8.4	6.4	-
6.7	5.1	37
5.1	3.8	33

Tab. 1 Vertical distribution of D32 in microns as a function of distance from the injector and Vertical distribution of D32 in microns as a function of distance from the injector

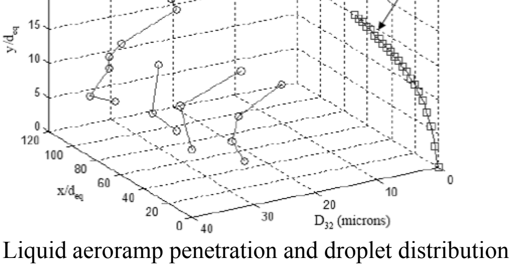

Fig. 4. Liquid aeroramp penetration and droplet distribution

The droplet diameter, D_{32}, vertical profiles were studied as a function of distance from the liquid aeroramp injector. The initial locations for droplet measurements were 30, 60, and 90 effective jet diameters downstream from the injector or 17.6, 35.2 and 52.8 mm, respectively. The results of this study can be found in Table 1. The values indicated with a dash were illumination profiles that yielded no useful results. These data points were taken on several occasions, but it is believed that there was so much absorption and scattering, due to multiple droplets in a small area, that almost all light was absorbed and no useful data could be obtained. All the droplet size data presented includes the correction for multiple scattering.

3. CONCLUSION

Conclusions from the experiment can be summarized. First, the aeroramp liquid injector functions as originally intended. Good penetration and atomization with a weak interaction shock was documented. Second, the liquid fuel flow rate has an effect on the height and width of the bright plume according to the OH wavelength filtered photographs. As the liquid fuel flow rate increases, the bright plume increases in height by 30% and increases in width slightly (2%). While, a decrease in liquid fuel flow rate resulted in an increase in height by 9% and an increase in width by 10%. Thus, as the liquid fuel flow rate varies around the baseline the width and height of the bright plume appear to always increase. Third, from the OH wavelength filtered photographs it was also shown that the bright plume appears to decrease in width by 9% and increase in height by 22% when the plasma torch is set at a lower power setting (1909 W). Fourth, when air is used as the torch feedstock, instead of nitrogen, the bright plume can increase by as much as 19% in width and 17% in height for a liquid fuel volumetric flow rate of 1.1 lpm and plasma torch power of 2516 watts for the nitrogen feedstock and 3336 watts for the air feedstock. Fifth, it was found that the plasma torch was much more consistent at around 3300 watts using air as the feedstock. It was also found that the height and width of the bright plume decreased slightly (2%) as the fuel flow rate increased when using air as the torch feedstock. Last, it is difficult to determine if any combustion is present in this cold-flow, low-pressure conditions based on direct photographs or OH filtered photography alone. One concern here is that we are not seeing combustion, but rather a large amount of scattering of the bright light from the plasma torch by the mist created from the liquid fuel injector. Testing at hot-flow conditions is needed.

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