radiation. This observation is in conformity with the results of Naegeli and Moses.[7]

The presence of water affects the combustion characteristics of fuels in burning sprays in several ways. First, the heat abstraction by water prolongs the ignition delay and reduces the vaporization rate. Also, the reduction in the near-nozzle region temperature decreases the rates of liquid and vapor phase pyrolysis of fuel. Consequently, the soot formation rate would be lowered.

Since microexplosion effect is expected to be weak, the observed reductions in radiation emission in the microemulsion spray flame in the present study and in Refs. 7 and 8 suggest that the thermal and chemical effects of water are more dominant than the mechanical effects of microexplosion.

The emissions of CO and NO decreased when the microemulsion was substituted for pure fuel in the present study and the study by Adiga.[8] However, the opposite was observed in the study by Naegeli and Moses.[7] The fuels in the present study and the study by Naegeli and Moses are jet fuels, whereas the fuel in Adiga's study was a diesel fuel. The similarity of the present results and Adiga's results suggest that the microemulsion effects are not highly sensitive to fuel volatility. The surfactant in the present study and Adiga's study was the same, but different from the surfactant used by Naegeli and Moses. The surfactant in the study of Naegeli and Moses contained organically bound nitrogen, and hence, the increase in NO emission in emulsion flames was attributed to it. The surfactant in the present study and Adiga's study did not contain nitrogen, but it did contain sulfur, which partly accounts for the reductions in NO and CO emissions. However, the concentration of SOx, which was not measured in these studies, could have increased. Hence, the composition of surfactant seems to exert a large influence in the flames of microemulsions.

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Pulsed Jets in Supersonic Crossflow

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Introduction

SINCE the late 1960s much interest has been focused on the subject of jet penetration in a supersonic crossflow. Now, however, the push for feasible schemes of efficient and practical gaseous fuel injection is much greater because of projects such as the National Aerospace Plane, which involve hypersonic travel.[1] The high Mach numbers such a plane could attain require that certain difficulties be overcome. One of these difficulties is the poor penetration of a transversely injected fuel in a SCRAMJET combustor. Progress in this area of research has been disappointing. Injection has been limited to heights that could cause a large thermal loading on combustor walls if combustion did occur.[2] For this reason, it is important to develop injection schemes that can provide fuel penetration to the combustor core. Once this objective is reached, the injection method may be further modified to improve the mixing characteristics of the fuel jet. Fuel injection struts or very high-pressure injection could place fuel within the combustor core, but the large shock losses associated with these methods make them undesirable.[3] The momentum flux ratio ($R = \rho_j v_j^2/\rho_a v_a^2$) has been shown to correlate very well with injection height for the steady jet, however, attempting to increase the injectant penetration depth by increasing R through higher injection pressure is not practical since the effect of this overpressure produces a highly underexpanded jet. Underexpanded jets display a shock feature termed a "Mach disk" (normal shock), which was observed by Dowdy and Newton[4] and later discussed by Schetz and Billig[2] in their steady jet studies. The overall effect of the Mach disk is to reduce the dynamic pressure of the gaseous injectant to a fraction of its original value. This is detrimental since the dynamic pressure represents the energy available to produce turbulence and mixing in a supersonic flow.

A practical approach to this area of study is to investigate methods for increasing jet penetration without increasing R, thus strengthening the Mach disk. In this regard, unsteady injectants show promise. Previous studies of unsteady jets tend to focus on mixing characteristics. One of the first investigations of unsteady jet phenomena was conducted by Viets.[5] He developed a self-exciting, oscillating jet and injected helium into the injector flow to observe the mixing of the injectant with quiescent, ambient air. Viets found that the half-width spreading rate of the injectant exceeded that of a slot nozzle by a factor of 3. Similar studies of oscillating-type injection[6–10] have confirmed that mixing is greatly enhanced by the use of an unsteady jet. Studies have also been conducted using a pulsating injectant in still air[11,12] and in water,[13] but the objective of the investigation in every case was to determine the mixing characteristics of the pulsed jet. As noted earlier, supersonic airstreams have been used in con-

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junction with steady injectants. Penetration has been examined in detail by Schetz[2,3] and others,[4] whereas more recent studies have concentrated on the breakup of liquid jets in a supersonic crossflow.[14] Our conclusion is that some people have examined pulsating flow, and many have concentrated on the interaction between various types of steady injection with a supersonic airstream, but no one has put a pulsating injectant in a supersonic crossflow. The injection scheme summarized in this Note makes use of a pulsed, transverse jet injected into a supersonic crossflow to examine the penetration characteristics of the pulsed jet as compared to the steady jet with matching peak and steady exit pressures, respectively. The force of a pulsating injectant is given by the rate of change of momentum $F = \mathrm{d}(Mv)/\mathrm{d}t$. A change in the magnitude of F can be accomplished by either varying Mv or $\mathrm{d}t$. Most previous schemes to enhance jet penetration have increased the momentum flux ρv^2 through an increase in v, by converging/diverging nozzles, or M, by raising jet exit pressure (increasing ρ). These methods neglect the $\mathrm{d}t$ term. Given a constant momentum change, smaller time intervals will produce greater flow impact.

Practical implementation of pulsating fuel injection in a SCRAMJET would be difficult in some respects. More injectors would be required than with steady injection at the same injection pressure to give the required mass flow rate. These injectors would have to spray fuel into the combustor in an interdigitated manner in order to maintain the proper equivalence ratio at all times. In addition, if adjustments to injection pressure were required in-flight, some injectors would have to be turned on or off to maintain the proper fuel mass flow rate. Although some difficulties exist with such an injection system, we believe pulsed injection shows great promise. Theoretically, the impulsive force of the injection can be raised to any value required to place the fuel into the combustor core by lowering the pulse width ($\mathrm{d}t \rightarrow 0$). Also, although mixing is not the primary subject of this Note, unsteady injection methods have shown much higher mixing rates than steady injection methods, as discussed earlier. For these reasons, pulsating fuel injection should be given serious consideration as an injection method.

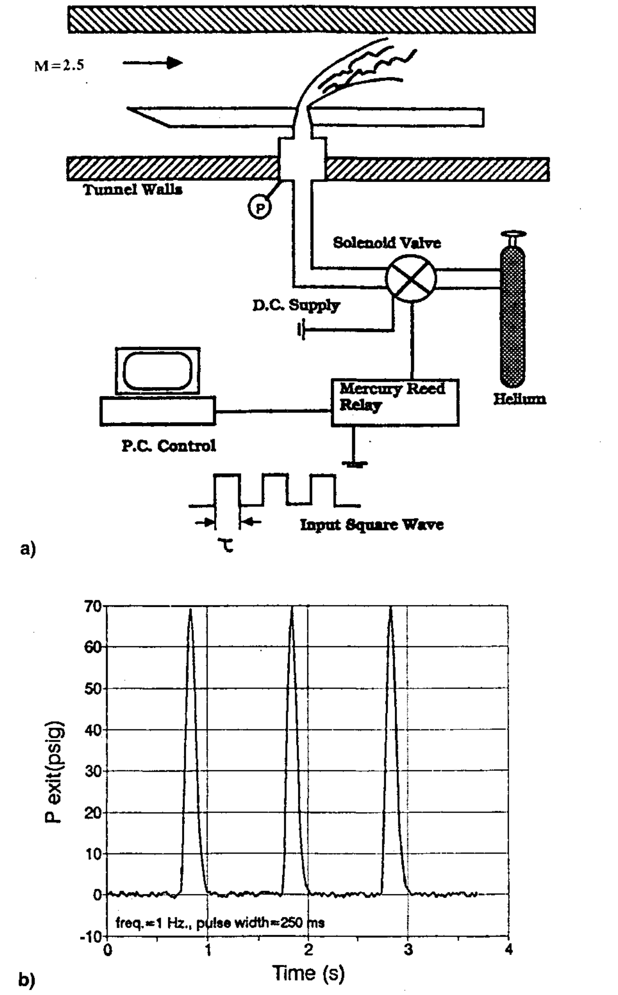

Fig. 1 Test apparatus shown schematically: a) pulsing system and b) typical pulse shape.

Apparatus and Procedure

This study was conducted in the supersonic wind tunnel at the University of Central Florida. The test section of the tunnel is square with 10.2-cm sides. The freestream Reynolds number was $Re = 2.29 \times 10^7$/m at a Mach number of 2.5. A flat plate was constructed from 1.1-cm-thick acrylic to serve as an injectant surface. The leading edge was milled to a sharp edge at an 8-deg angle and mounted in the tunnel test section so that shock effects were deflected underneath and through the test section without affecting the flow. Interchangeable nozzles were fabricated to screw directly into the flat plate. A converging, choked nozzle with an orifice diameter of 0.145 cm was used to provide an injectant Mach number $M_i = 1.0$. Helium (99.999% pure) was supplied by a 0.635-cm-diam line which was coiled in an ambient temperature water bath and connected to the bottom of the nozzle. This procedure ensured a constant injection temperature and density for each injection pressure used. It should be noted here that density, pressure, and velocity do change with time for the pulsed injectant, however, the change is the same in every pulse for a given nozzle exit pressure. The test apparatus is shown schematically in Fig. 1a. The pulsing system consists of a PC, an A-D board, a reed relay, a dc power supply, and helium supply tanks. A 12-V dc, inert-gas solenoid valve was used to pulse the injectant. The valve is rated at 150 psig with a response time of 5–10 ms. The PC supplied a 5-V, square-pulse signal to a relay which opened and closed a circuit containing the solenoid valve and power source. A square wave train turns the valve on and off with minimal lag time. With this configuration, a variety of pulse widths ($\tau = \alpha/f$) and injection to freestream pressure ratios ($PR = P_{oi}/P_{oa}$) could be tested by independently adjusting the duty cycle α, frequency f, and injector exit pressure P_{oi}. A 0.1-s square wave signal with a frequency of 1 Hz was used to produce an injectant pressure pulse width of 250 ms. All data were collected with this pulse width and frequency. The injection Reynolds numbers for the three pulse pressures reported ranged from 1.71×10^4 to 5.76×10^4 based on the orifice diameter. A typical time history for pulsed injection nozzle exit pressure is shown in Fig. 1b. The freestream Mach number was held constant at $M_a = 2.5$, and injection pressures ranging from 206.8 kPa (30 psia) to 696.4 kPa (101 psia) were used to compare steady and pulsed injection. For pulsating injection, the peak nozzle exit pressures were matched to steady injection pressures. The use of peak exit pressures for the unsteady injectant provides a more meaningful comparison of penetration results. If the average values of the nozzle exit pressures were used in the study, then it could be argued that the increase in injectant penetration resulted from the fact that the nozzle exit pressures were actually higher for the unsteady jet than the steady injection pressures for part of the pulse duty cycle.

Results and Discussion

After establishing the flow parameters, pulsed and steady injection of helium were introduced into the $M_a = 2.5$ freestream at equal jet exit pressures (peak exit pressure for the pulsating flow) to compare the penetration depths. A continuous slit-source schlieren system was used to visualize the flowfield. The injectant/freestream interaction was filmed with

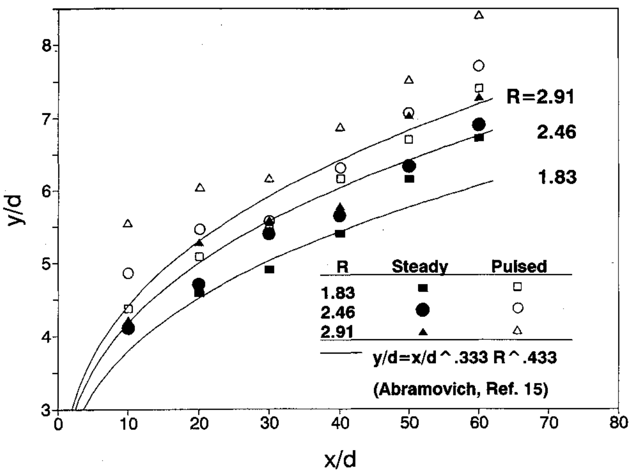

Fig. 2 Pulsed and steady injection penetration.

a video recorder at a frame speed of 0.001 s and then evaluated with a video playback unit capable of freezing individual frames. The tape was used to examine frames where the pulsed injectant was emerging from the orifice. In these frames, measurements were made between the flat plate surface and the visible edge of the helium/air boundary. These measurements were repeated five times for each downstream station to account for the deviation in measured depth caused by the fuzziness of the helium/air boundary. The average reading was used for data. With this method, penetration depths y/d at axial stations x/d were measured to an accuracy of 0.35 nozzle diameters. Steady and pulsed injection penetration data are shown in Fig. 2. The steady data (filled symbols) fit the empirical correlation (solid line)

$$(y/d) = (R)^{0.433}(x/d)^{0.333} \tag{1}$$

given by Abramovich[15] reasonably well. Here, x and y are the axial and transverse locations of the injectant, respectively, d is the nozzle orifice diameter, and R is the jet to freestream momentum flux ratio. This empirical relationship provided a validation check of the measuring technique used to obtain penetration data. Penetration depths resulting from pulsed injection (empty symbols) are also shown. Momentum flux ratios of R equal to 1.83, 2.46, and 2.91 are reported. For the same value of R, pulsing of the helium increased penetration an average of 12% over the steady injection case, with a standard deviation of ± 0.22 jet diameters. This increase in penetration may be derived from two different aspects of pulsating flow in a supersonic freestream. The first is the most obvious; the acceleration of the injectant through time interval dt from zero velocity to Mach 1 at the injector exit produces an inertial force which pushes the Mach disk further into the crossflow in much the same way as increased injection pressure for the steady jet does. This force will provide some increase in penetration; however, as other studies have shown, the Mach disk is essentially the limit of penetration height for underexpanded injectants in supersonic flow.[2] It is desirable, therefore, that any injection scheme minimize the dependence on the displacement of the Mach disk since it functions as a momentum sink. The time dependency of the pulsating injectant is the second aspect by which increased penetration depth may be obtained. A finite time interval must pass before the Mach disk is established in the flow. During this interval, the pulsating injectant will be able to penetrate the flow with little hindrance from this shock effect. On the other hand, the Mach disk is an established phenomenon of steady injection for highly underexpanded jets, and therefore limits the penetration benefits of increased momentum flux ratio for steady injection.

Conclusions

Pulsing of injectants into a supersonic crossflow through a sonic nozzle provides greater flow penetration than steady injection when the peak exit pressure of the unsteady jet is matched to the steady injection pressure. Matching these pressures also gives equivalent momentum flux for both types of injection, demonstrating that penetration can be increased without increasing R. It is desirable to increase penetration without an accompanying increase in R since high momentum flux ratio is an indication of strengthened shock structure and consequent losses for a sonic injectant in a supersonic flow. The increased penetration of the pulsating injectant is derived from the impulse due to the temporal acceleration through the converging nozzle, further acceleration as the highly underexpanded gas exits the injector orifice and expands in the freestream, and freedom from the Mach disk effect until the Mach disk is established a finite time interval from the inception of the pulse. As shown by other studies, higher values of R give proportionately better penetration. The benefit of increased steady injection pressure is not unlimited however. Although a slightly underexpanded jet can be beneficial,[2] highly underexpanded jets produce a strong Mach disk which depletes much of the injectant momentum. For this reason, nonconventional injection methods including pulsed injection need further exploration. Total pressure measurements and variation of the pulse width $\tau = \alpha/f$ through independent changes of α and f will be considered further as part of an ongoing study.

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