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Optimum Mixing of Hypergolic Propellants in an Unlike Doublet Injector Element

John Houseman*
Jet Propulsion Laboratory, Pasadena, Calif.

Introduction

THIS communication discusses a newly found optimum mixing condition for an unlike doublet injector element with hypergolic propellants. The fluid dynamics of the impingement region of an injector element can be altered appreciably by liquid phase chemical reactions at the interface of the propellants. This effect can be used to considerable advantage to obtain better mixing of the propellants than would be possible without chemical effects. However, the extent of the liquid phase reaction must be controlled by careful selection of the injector operating conditions since too much reaction results in poor mixing of the propellants.

The unlike doublet is a common injector element in liquid rocket engines and its function is to produce a spray of well-mixed droplets of fuel and oxidizer. Typically, an unlike doublet consists of two cylindrical jets of liquid propellant that impinge on each other at an angle of from 45° to 90°. A liquid sheet is formed at 90° to the plane of the jet centerlines. With normal turbulent jets the sheet extends for only a few jet diameters and then breaks up into fine droplets. The degree of mixing is a function of several operating parameters and an optimum mixing criterion has been formulated by Rupe[1] after an extensive study of the spray produced by chemically nonreactive streams. The most uniform spray is produced when the products of fluid density, jet velocity squared, and jet diameter are equal for both streams. Even under those conditions, the spray contains an oxidizer-rich region on the side of the fuel orifice and a fuel-rich region on the side of the oxidizer orifice. It appears as if a fraction of each jet has penetrated through the impingement area to reach the other side of the main liquid sheet that is produced. This penetration effect is an accepted and well-documented facet of jet impingement. However, it has never been demonstrated experimentally with actual propellants until now.

With the advent of hypergolic propellants, another mechanism for spray formation was postulated, namely separation.

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* Member of the Technical Staff.

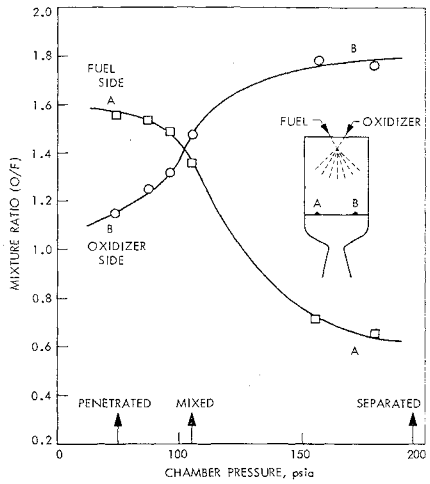

Fig. 1 Transition from the penetrated to the separated mode of jet impingement.

With very reactive propellants, liquid phase reactions in the impingement region of the jets can cause so much gas formation that the streams never mix but remain separated. This separation phenomenon results in an oxidizer-rich spray on the side of the oxidizer orifice and a fuel-rich spray on the side of the fuel ornifice. The gas formation in the impingement zone deflects the jets away from the impingement region. Thus, separation produces exactly the opposite effect of penetration. Evans, Stanford, and Riebling[2] have shown the relation between separation and reduced rocket engine performance. Burrows[3] and Breen et al.[4] have made photographic observations of jet separation. Tentative criteria to predict the presence or absence of jet separation have been advanced by Kushida and Houseman[5] on the basis of theoretical analysis.

The following possible mechanisms for the formation of gas in the impingement region are now envisioned:

1) The liquid phase reactions produce gaseous products.

2) The liquid phase reactions generate so much heat locally that the propellant begins to boil.[5]

3) The fuel and oxidizer jets are separated by a thin film of mixed gas. The reaction in this gas film generates a sufficient amount of heat to vaporize enough oxidizer and fuel on both sides of the film to maintain the film.[5]

A study of these combustion effects in sprays was undertaken to determine the range of applicability of nonreactive spray data to hypergolic propellant systems. An interim objective of this study is presented in this paper, namely, direct experimental data that show the existence of both the penetrated and separated mechanism of spray formation for hydrazine and nitrogen tetroxide propellants. These different mechanisms have been identified by measuring the chemical composition of the combustion gases resulting from the propellant spray. It is shown for small orifices that there is a gradual transition from penetration to separation as the flow rate and chamber pressure are increased. It is proposed that the transition zone between penetration and separation represents a new optimum mixing condition for hypergolic propellants.

Experimental Results

An unlike doublet injector element was mounted in a 3-in.-diam rocket chamber, as shown schematically in Fig. 1. A water-cooled sampling probe extends across the chamber 5 in. downstream from the jet impingement point. The probe can be traversed across the chamber and carries a sampling tip through which the combustion gases are continuously withdrawn for on-line analysis with a quadrupole mass spectrometer.

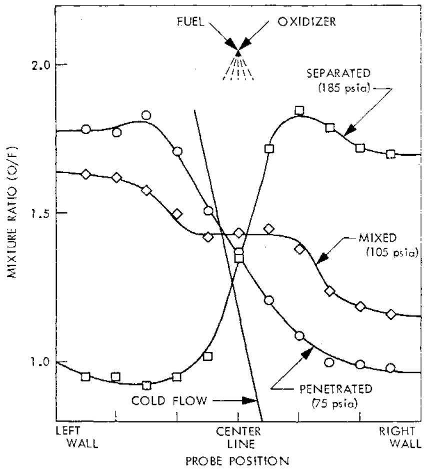

Fig. 2 Mixture ratio profiles for various modes of jet impingement.

In order to obtain jets with reproducible hydraulic properties, orifices with a length-to-diameter ratio of 100 were used, resulting in fully developed turbulent jets. Free jet length before impingement was 4 diam. The chamber-to-throat area contraction ratio was 100.

All tests were conducted at an input mixture ratio of oxidizer to fuel of 1.2 by weight, which is the optimum mixing condition according to the Rupe criterion for nitrogen tetroxide and hydrazine for equal jet diameters.

In a series of 5-sec firings, the propellant tank pressures were increased from about 200 to 900 psig, resulting in increased chamber pressures due to increased propellant flow rates. The chamber gas was sampled at two probe positions, namely 0.5 in. off the right-hand wall (oxidizer side B) and 0.5 in. off the left-hand wall (fuel side A). The results with 0.029-in.-diam orifices and 40°F propellants are shown in Fig. 1. At low chamber pressures, the fuel side has the highest mixture ratio, indicating an oxidizer-rich spray, while the oxidizer side is fuel-rich. As the chamber pressure increases, the mixture ratios on the oxidizer side and on the fuel side become equal. When the chamber pressure is increased further, the previous situation is reversed, resulting in a high mixture ratio on the oxidizer side and a low mixture ratio on the fuel side. In other words, the system moves from the penetrated form of spray formation to the separated form as the chamber pressure is increased by increasing the propellant flow rates. The best mixing of propellants occurs when the oxidizer side and the fuel side of the chamber have the same mixture ratio, i.e., at approximately 105 psia. Even though all the data points on Fig. 1 comply with the Rupe optimum mixing criterion, it is apparent that there is a new optimum within this range of data points due to chemical effects. The best mixing occurs at the cross-over point from penetration to separation. Apparently, a small amount of gas generation is beneficial to mixing, provided it does not disrupt the basic impingement process.

More detailed gas sampling was carried out for the penetrated, mixed, and separated sprays at propellant flow rates corresponding to chamber pressures of 75, 105, and 185 psia. Figure 2 shows the mixture ratio gradients across the spray for the different cases. The cold flow line in Fig. 2 is the steep gradient normally obtained in tests with simulated propellants in which the liquid spray is collected. The penetrated line shows the same behavior, but since the spray is now converted into combustion gas, it spreads to fill the chamber and the gradient is not as steep. In this case, the old assumption that nonreactive spray data can be applied to actual propellant systems[1] has thus been demonstrated. The mixed line shows a uniform area in the center of the chamber, but still retains some of the penetrated behavior near the walls. Apparently the crossover condition was not quite obtained in this series of tests. The separated line shows the opposite behavior to the penetrated one and has a steep gradient in the reverse direction.

The injector was turned at 30° intervals relative to the sampling probe, and five other sets of profiles were measured to obtain the complete two-dimensional mixture ratio distributions across the chamber shown in Fig. 3. Note that the dark oxidizer-rich area on the left-hand side of the penetrated case has moved to the right-hand side for the separated case. The mixed case shows a large area in the center of the chamber that is well mixed. The area that is outside the 1.0 to 1.6 mixture ratio range is quite small compared to the case of either penetration or separation. The separated case shows the largest chamber area outside the 1.0 to 1.6 mixture ratio range and obviously produces the poorest mixing. Indeed, the mixed case shows the best mixing of propellants and represents the optimum condition for high combustion efficiency.

It may be observed that the measured mixture ratios average out at 1.3–1.4, rather than the input value of 1.2. This is due to limitations of the sampling procedure, namely loss of ammonia in the sample, resulting in a calculated mixture ratio that is too high. However, this does not affect the conclusions regarding mixing uniformity since they are based on relative changes in mixture ratio rather than on the absolute values.

The data show that large concentration gradients exist in the combustion chamber at a distance of 5 in. downstream from the impingement point. Very little lateral mixing has taken place during an average residence time of about 3 msec, based on a typical 150 fps gas velocity. The data therefore support the stream tube theory of very limited lateral mixing between stream tubes.

The results shown were obtained with 0.029-in.-diam orifices with 40°F propellants. Preliminary results indicate that 0.020-in.-diam orifices always operate in the penetrated mode, while 0.073-in.-diam orifices always operate in the

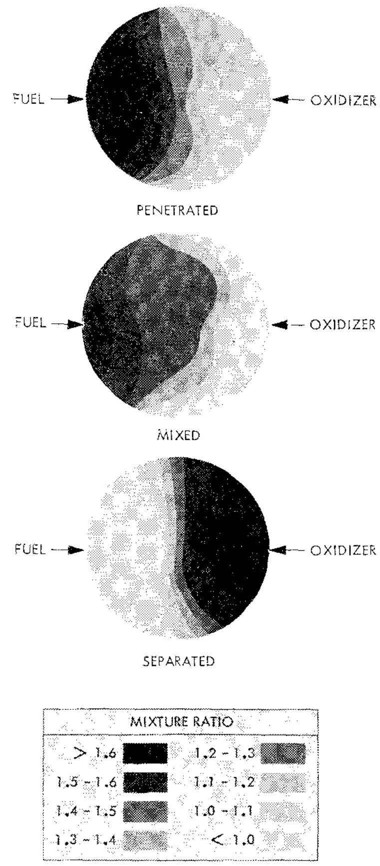

Fig. 3 Mixture ratio contours across the combustion chamber.

separated mode. The scale effect is obviously one of the key parameters.

The c^* efficiencies for the penetrated, mixed, and separated cases averaged out at 93, 97, and 93%, respectively. These figures were not corrected for heat transfer or discharge coefficient, but such corrections would not change the relative standing by more than 1%. At this level of c^*, the 4% difference between the mixed mode and the other modes represents a significant change. Operation under mixed mode conditions results in a uniform propellant spray and optimum combustion efficiency.

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Effect of Vortices on Delta Wing Lee-Side Heating at Mach 6

ALLEN H. WHITEHEAD JR.*
NASA Langley Research Center, Hampton, Va.

Nomenclature

L = model chord length
M_∞ = freestream Mach number
p/p_∞ = ratio of local static pressure to freestream static pressure
R_∞ = freestream Reynolds number
St_∞ = local Stanton number based on freestream conditions
x = distance down centerline from apex
α = angle of attack
θ = surface angle from centerline through apex

Subscripts

L = model length
x = distance down centerline from apex

RECENT investigations[1–3] have indicated pressure and heating levels on the lee surface of a delta wing considerably above that predicted using two-dimensional expansion methods. Examination of the lee-surface flowfield in these studies revealed that this localized high heating and pressure in the central region of the wing is induced by coiled vortex sheets present above the surface when conditions are conducive to separation. Hypersonic experiments indicate that separation and the associated vortex system can initiate either at the leading edge or at the base of an inboard shock

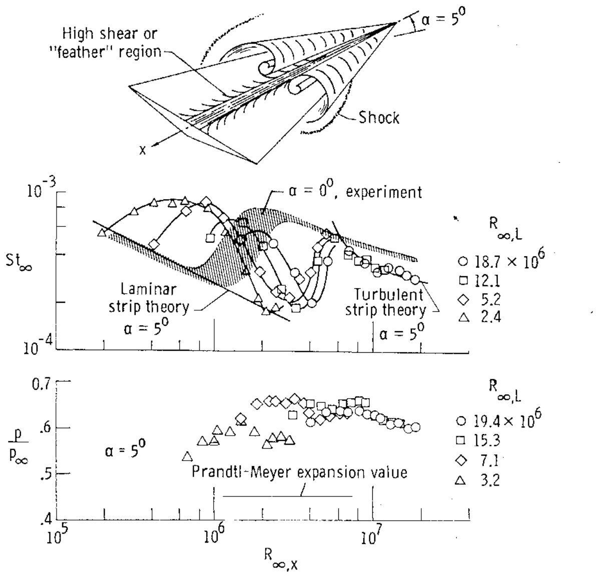

Fig. 1 Flowfield, centerline heating, and pressure distribution on lee surface of 75° swept wing; $M_\infty = 6$, $\alpha = 5°$ (unless otherwise labeled), $L = 26.1$ in.

system. The major difference in the flowfield when the flow separates at the leading edge is that the vortex structure appears further outboard than when the vortex initiates at the base of an inboard separation. The nature of the flow in the centerline region is dependent on the spanwise location of the vortex.[1] In previous hypersonic experiments on the lee surface the flow was separated inboard of the leading edge.[1,2] The present investigation was undertaken to determine if severe heating persists over the lee surface when the flow separates at the leading edge. Furthermore, the present study, conducted in the Langley 20-in. Mach 6 tunnel, extends over a much wider Reynolds number range than previous tests.

The present delta wing was sting-mounted and had a sharp leading edge (<0.003 in.) with a sweep of 75° and a 14.6° wedge angle (measured normal to the leading edge). The leading-edge shock was calculated to be detached at all angles of attack. An oil-flow technique was used to indicate direction and relative magnitude of the surface shear forces, and to indicate the location of separation and reattachment. In this method, random dots of an oil and lampblack mixture are applied to the model surface prior to the run. The vapor-screen technique gave additional evidence of the vortical structure above the lee surface. Temperature data were reduced to Stanton numbers by methods similar to those described in Ref. 4 and assuming a turbulent recovery factor of 0.895. Local Mach numbers used in determining turbulent recovery temperatures were obtained from measured static and freestream total pressures.

Previous tests show peak heating on the lee surface of a delta wing coincident with a high shear area in the centerline region identified by a feather-like oil flow trace.[1] This high shear region was also revealed in the present experiments by the oil flow results as indicated by the sketch of Fig. 1.

The effect of a Reynolds number variation from 2.4 to 18.7 million on the lee-surface centerline heating is shown in the lower portion of Fig. 1. The data depart initially from laminar theory[5] and then rise to a peak whose value and location are unit Reynolds number dependent. The heating decreases beyond this peak to near-laminar values with further increases in $R_{\infty,x}$. An abrupt rise in heating then occurs and, subsequently, the data achieve the level and trend expected of a turbulent boundary layer. The peak Stanton number values obtained on the centerline at the low Reynolds numbers are almost double the values found on the centerline

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* Aerospace Engineer, Applied Fluid Mechanics Section, Aero-Physics Division. Associate Member AIAA.