MEMORANDUM NO. 30-5

CRITERIA FOR OPTIMUM MIXTURE-RATIO DISTRIBUTION USING SEVERAL TYPES OF IMPINGING-STREAM INJECTOR ELEMENTS

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ABSTRACT

Empirical correlations are given relating the mixture-ratio distributions produced by various configurations of impinging-stream injectors and the ratios of density, velocity, and orifice cross-sectional area of the two fluids being mixed. Injector-element designs studied are two-on-one, two-on-two, and four-on-one.

I. INTRODUCTION

The primary function of the injector in a liquid rocket engine is to deliver the propellants to the combustion chamber in such a manner that complete and stable combustion in a minimum volume will be achieved. While a number of factors can influence the stability of combustion, the efficiency attained is primarily dependent on the uniformity of the mixture-ratio distribution produced by the injector.

Most engines are operated near to over-all mixture ratios corresponding to the maximum of the theoretical-performance curve. Since any deviation from this mixture ratio therefore results in lower performance, it is apparent that not only over-all but local mixture ratio must be accurately controlled if highest performance is to be attained. Combustion may be kinetically complete in relatively short distances over a wide range of mixture ratios for any particular propellant combination. However, at any over-all mixture ratio near maximum performance, the sum of energy released by complete combustion of propellants operating at various local mixture ratios will always be less than that produced by having all local mixture ratios equal to the over-all ratio. Any deviations in local mixture ratio produced by an injector element can be corrected only by turbulent mixing and diffusion in a relatively low-density accelerating fluid. In normal chamber configurations, such a process requires fairly long chamber lengths proportional to the size of the non-uniform local mixture-ratio regions. Therefore, unless a very large number of injector elements is used, the optimum mixture-ratio distribution produced by each element is one which is as uniform as possible throughout its entire spray. In order to achieve good uniformity, it is apparent that certain hydraulic and relative velocity conditions must be met.

II. THE USE OF IMPINGING STREAMS

One conventional method of mixing liquid propellants is through the use of impinging streams. However, in many injector designs, little attention is given to stream stability or relative stream momentum between fuel and oxidizer. It is frequently assumed that general spatial alignment of stream centerlines is all that is required to produce a uniform spray, and that fuel and oxidizer orifice pressure drops may therefore be arbitrarily assigned any convenient values.

It has been shown by Rupe (Ref. 1) that consistent distributions of mixture ratio can be obtained from impinging streams only if the free streams have stable velocity profiles. In addition, for uniform distribution, the velocity profiles should be symmetrical and have similar centerline to mean-stream pressure ratios. As described in Ref. 1, this can be most easily achieved through the use of a fully developed turbulent stream. One orifice configuration which will produce an adequate stable velocity profile consists of a contoured entry, a turbulence-inducing section, and an over-all length of about twenty hole-diameters. In addition, care must be taken to assure as uniform a flow as possible in the manifold feeding the orifices.

The tests summarized in this Memorandum were made using orifices of the type described above. Water and kerosene were used as the two fluids, and mixture-ratio distributions were determined from the volume ratio of collected samples. The sprays were sampled by a row of 1/4-in. diameter tubes discharging into graduated glass cylinders. The total mixture ratio was varied for each type of injector element until the ratio could be determined which produced the most uniform distribution throughout the entire spray. The effect of density ratio was checked by interchanging the water and kerosene, and sometimes by using carbon-tetrachloride in place of kerosene. The results obtained, therefore, apply specifically over a density ratio ρ_2/ρ_1 from 0.54 to 1.85.

It should be noted that the mixing criteria given here apply in particular to propellant systems which, because of their nature, permit appreciable liquid-phase mixing. These same criteria may also be valid for hypergolic combinations which have a slight delay between mixing and subsequent heat release. However, for extremely reactive propellants such as $N_2O_4-N_2H_4$, the mixture-ratio distributions are believed to be greatly affected by gas evolution at the impingement points (Ref. 2), so that uniform distributions cannot be easily obtained.

III. RESULTS

A. The One-on-One Element

The results of studies of a pair of impinging streams were reported by Rupe in Ref. 3. It was shown that the most uniform mixture-ratio distribution is obtained when the product of velocity-head ratio and diameter ratio of the two streams is unity; that is,

$$\frac{\rho_1 v_1^2 D_1}{\rho_2 v_2^2 D_2} = 1 \qquad (1)$$

where ρ is specific gravity, v is velocity, D is orifice diameter, and subscripts 1 and 2 denote the two fluids being mixed.

Since the stream momentum M is equal to the product of the velocity head and the orifice area A, and the area is proportional to the diameter squared, it can be shown that if the criterion of Eq. 1 is satisfied, the momenta of the two shown are related by

$$\frac{M_1}{M_2} = \frac{\rho_1 v_1^2 D_1^2}{\rho_2 v_2^2 D_2^2} = \frac{D_1}{D_2} \qquad (2)$$

Thus, for a pair of streams having diameter ratios between one and about three, the best mixture-ratio distribution is obtained when the stream-momentum ratio is equal to the stream-diameter ratio. Because the mixture ratio $\dot{w}_{ox}/\dot{w}_f$, and not the velocity ratio, is the parameter of interest in rocket-motor studies, the following more useful relationship can be derived from Eq. (2):

$$\frac{M_1}{M_2} = \frac{D_1}{D_2} = \frac{\dot{w}_1^2 \rho_2 D_2^2}{\dot{w}_2^2 \rho_1 D_1^2} \tag{3}$$

Or, if we let $\dot{w}_1$ = oxidizer flow rate and $\dot{w}_2$ = fuel flow rate, then

$$r^2 \frac{\rho_f}{\rho_{ox}} \left(\frac{D_f}{D_{ox}} \right)^3 = 1 \tag{4}$$

The doublet element is not always useful for some propellant combinations, particularly when only single or a very limited number of elements are desired. Distributions were studied, therefore, using several other element configurations having axially symmetrical resultant momentum lines. Only three such elements appeared to be of interest. They are planar triplets, two oxidizer streams and two fuel streams impinging at a common point, and four streams symmetrically impinging on one center stream.

B. The Two-on-Two Element

The two-on-two configuration has two opposed fuel streams at right angles to two opposed oxidizer streams, with both pairs impinging at the same angle. It is important that the centerlines of the jet meet at the same spatial point. For this element, the resultant spray is symmetrical across either pair of orifices regardless of mixture ratio. The smoothed mass distribution and volume-mixture-ratio distribution for a representative test close to optimum mixing of a two-on-two element are shown in Figs. 1 and 2. The cross penetration by the spray fan from each pair of jets is a characteristic of this orifice configuration. However, a relatively small amount of mass is involved at the outside of the spray, where fairly large deviations in mixture ratio occur. An additional feature of this type of element is the presence of a backspray. Approximately 10% of the mass is directed into a narrow cone to the rear of the impingement point. The combustion of this backspray has served to stabilize the main spray flame in certain cases (Ref. 4).

Since this injector element is symmetrical with respect to the two propellants, it would be expected that the constant on the right-hand side of Eq. (4) would be equal to unity, as in the case of a doublet. The experimental results confirmed this expectation, and the most uniform or optimum distribution occurred at the mixture ratio determined from the expression

$$r^2 \frac{\rho_f}{\rho_{ox}} \left(\frac{D_f}{D_{ox}}\right)^3 = k \tag{5}$$

where $k = 1$ for all impingement angles. The two-on-two elements studied during this program had area ratios from 1 to 3.5.

As in the case of the doublet, the optimum mixing criterion may require that two-on-two elements employ widely different orifice diameters for certain mixture ratios and propellant densities. The two-on-one and four-on-one elements were therefore investigated, since they permit the use of more nearly equal orifice diameters with mixture ratios greatly different from one. Because these two element types are not symmetrical with respect to propellants, the constant in any expression similar to Eq. (5) would not be expected to equal one, and furthermore, may be a function of the included impingement angle.

C. The Two-on-One Element

On the basis of limited tests with several two-on-one injector elements having various outer to center orifice-area ratios, the following equation was found to fit the data best for a 60-deg included impingement angle.

$$\left(\frac{\dot{w}_1}{\dot{w}_2}\right)^2 \frac{\rho_2}{\rho_1} \left(\frac{A_2}{2A_1}\right)^{1.75} = 0.66 \tag{6}$$

where the subscript 1 denotes the two outside streams and 2 the center stream, A_2 = area of the center orifice, A_1 = area of one of the outer orifices, and $\dot{w}_1$ = total flow through both outer orifices. Equation (6) reduces to the following form:

$$\frac{\rho_1 v_1^2}{\rho_2 v_2^2}\left(\frac{2A_1}{A_2}\right)^{0.25} = k' \quad (7)$$

(The total area ratios $(A_2/2A_1)$ covered experimentally had values from 0.3 to 1.0.) This can be compared to Eq. (1) for a doublet, which may be written

$$\frac{\rho_1 v_1^2}{\rho_2 v_2^2}\left(\frac{A_1}{A_2}\right)^{0.50} = k \quad (8)$$

In a limited investigation (see Ref. 5 for report), it was found that if a correlation equation of the form of Eq. 8 was used for triplet elements, the value of k was 0.625, as determined from elements having values of D_2/D_1 of 1.0 and 0.776. At a value of D_2/D_1 of 0.79, both correlation equations (7 and 8) give the same result but diverge for D_2/D_1 different from 0.79. For example, at D_2/D_1 of 1.41 (the maximum value of the ratio in the present study), the optimum mixture ratio predicted by Eq. 7 would be 15% different from that predicted by Eq. 8, with k of 0.625. At present, there are insufficient data to resolve this difference in the effect of the ratio of D_2/D_1; hence, probably neither equation should be used for values of D_2/D_1 very far from 0.79.

The triplet-element distribution is quite sensitive to deviations from optimum mixture ratio. The results for one element at three different volume-flow ratios are shown in Fig. 3. It can be seen that, even for volume ratios not too different from the optimum, the spray becomes very non-uniform with respect to mixture ratio. The effect of such distribution changes on the resulting combustion is shown and discussed in Ref. 2. For a 90-deg included impingement angle, the value of k' in Eq. (7) was found to be 0.42.

D. The Four-on-One Element

A series of tests with several four-on-one injector elements at 90-deg total impingement angle indicated that the most uniform distribution occurred when

$$\left(\frac{\dot{w}_1}{\dot{w}_2}\right)^2 \frac{\rho_2}{\rho_1} \left(\frac{A_2}{4A_1}\right)^{1.25} = 2.75 \tag{9}$$

where A_2 = area of the center stream, A_1 = area of one of the outer streams, the subscript 1 denotes the outer-stream parameters and 2 the center-stream parameters, and $\dot{w}_1$ = the total flow through all four outer orifices.

At 60-deg included impingement angle, the constant on the right-hand side of Eq. (9) that best correlates the data is equal to 2.90. Sufficient tests were not made, however, to determine the functional relation between this constant and the impingement angle. The total area ratios $(A_2/4A_2)$ studied were between 0.25 and 0.75.

IV. CONCLUSIONS

As shown in Ref. 3, an empirical correlation can be obtained by relating the mixture-ratio distribution produced by a pair of impinging streams and the ratios of density, velocity, and orifice cross-sectional area of the two fluids. The results given in this Memorandum indicate similar relationships for other types of impinging stream elements. The equations given for optimum mixture-ratio distribution show the following characteristics.

At a given mixture ratio, the element composed of two oxidizer streams on two fuel streams is optimized at the same velocity ratio of oxidizer to fuel as the doublet configuration. Like the doublet, this mixing criterion is independent of total included impingement angle, providing all four streams make the same angle with the axis of the spray.

The triplet element requires a lower oxidizer-to-fuel velocity ratio than the doublet for a given mixture ratio (where the center stream is assumed to be fuel).

The four-on-one element shows an opposite effect in that it requires a higher ratio of the velocity of the outer streams to the velocity of the center stream. Thus, the center stream of the triplet requires more momentum to penetrate the two outer streams, while the center stream of the four-on-one is, in effect, pulled into the outer streams.

It should be kept in mind that the results given are valid only for streams having symmetrical, turbulent velocity profiles. Because the mixture-ratio distribution of impinging-stream-injector elements can be made uniform near only one set of conditions, it is advisable to determine experimentally the distribution for any proposed injector element before incorporating it into a developmental engine.

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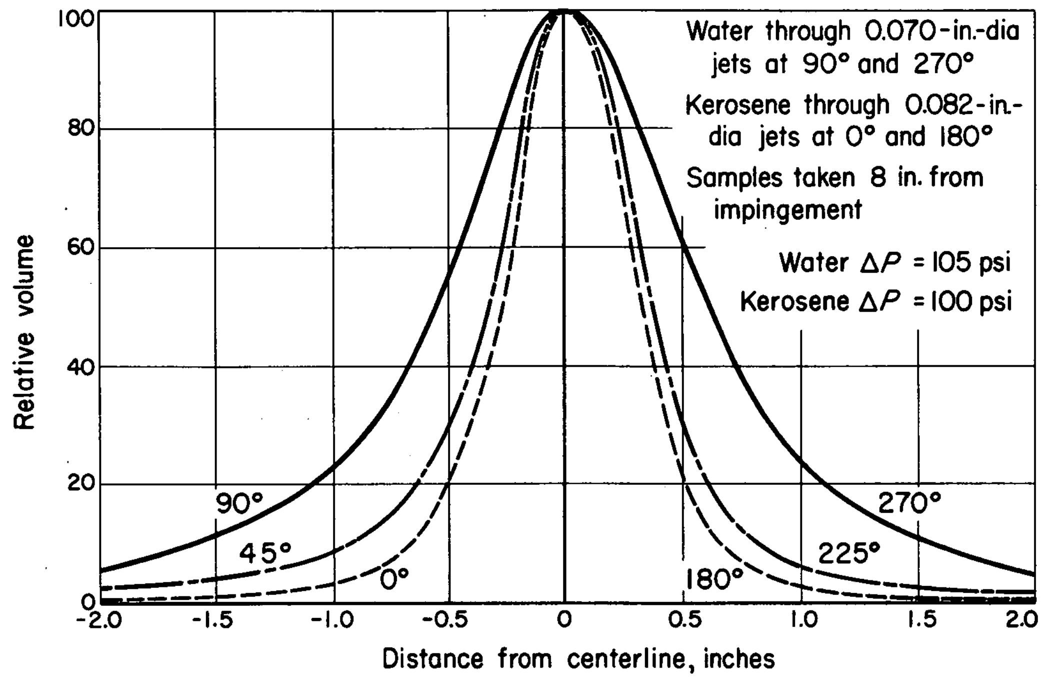

Fig. 1. Typical Quantity Distribution for Two-on-Two Injector

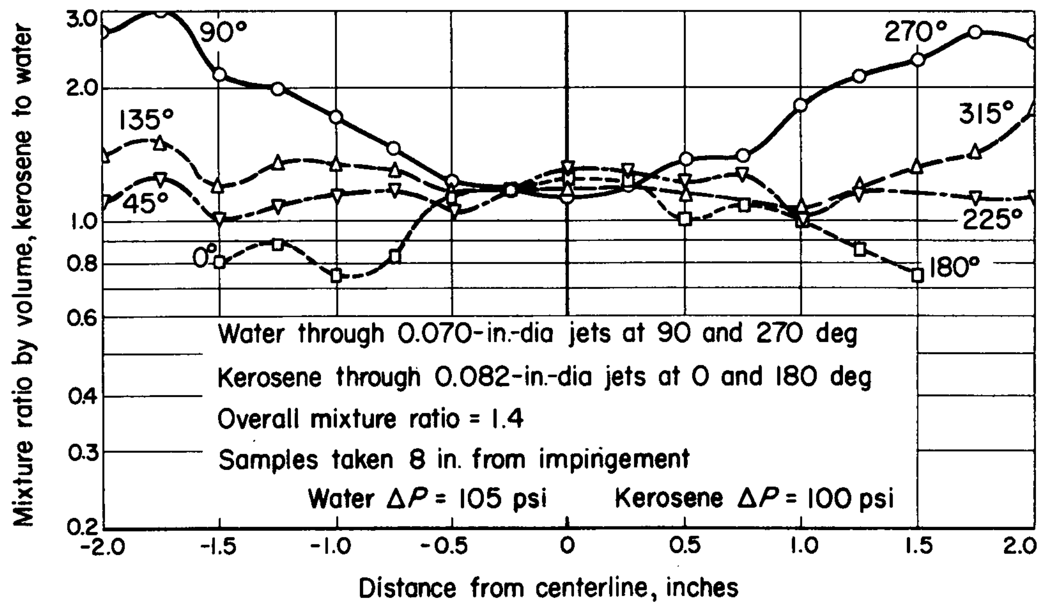

Fig. 2. Typical Mixture-Ratio Distribution for Two-on-Two Injector

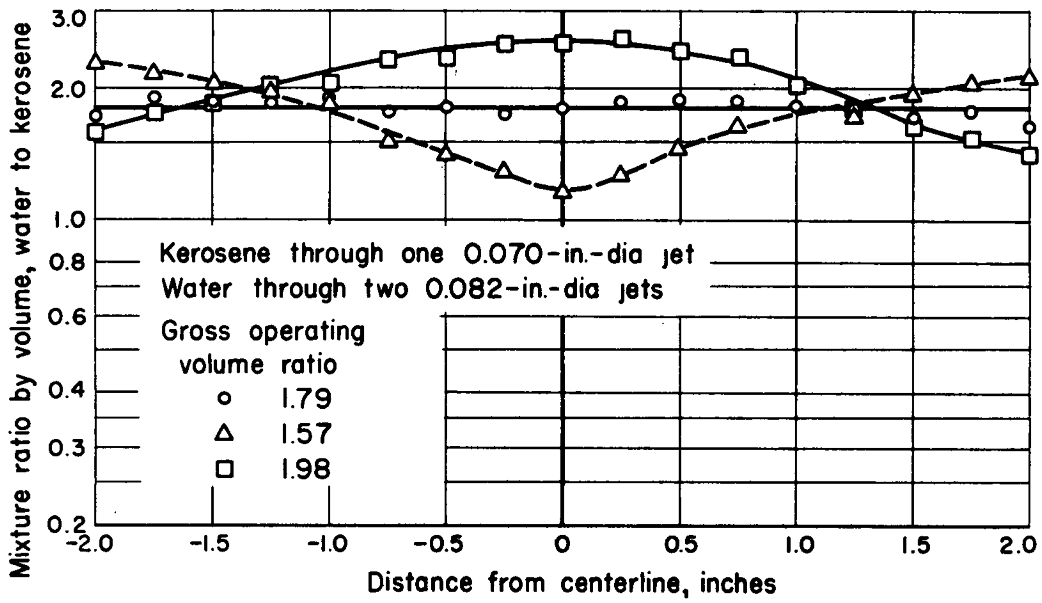

Fig. 3. Volume Mixture-Ratio Distributions for 60-deg Triplet Injector