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Orifice Diameter Ratio Effect on the Mixing Performances for Split Triplet Injectors

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The effect of orifice diameter ratio on the mixing qualities of unlike-doublet and split-triplet impinging elements is experimentally studied. The quality of mixing was checked by performing cold-flow tests with nonreacting immiscible simulant liquids. The local volume fractions are determined by direct measurement of the volume of each liquid. The test matrix comprises combinations of the orifice diameter ratios from 1 to 1.5, with the jet momentum ratios (oxidizer/fuel) in the range of 0.5–6. Results show that impinging elements of unequal orifice diameters exhibit substantially different mixing qualities. Maximum mixing efficiency occurs at higher momentum ratios with increasing diameter ratio. Relative jet velocity ratio for optimum mixing ranges from 0.65 to 0.78 and from 0.87 to 0.92 for unlike-doublet and split-triplet elements, respectively. The split-triplet element is superior to the unlike-doublet element in both the mixing efficiency and the mixing-controlled characteristic velocity in the test range of interest. The diameter ratio effect on the mixing of split-triplet element is less significant than that on the unlike-doublet element mixing. The mixing factor of the split-triplet element for maximum mixing efficiency is 0.75.

Nomenclature

C^* = characteristic velocity, m/s
D = orifice diameter, mm
L = orifice length, mm
M = mixing factor
M_l = local mass, kg
MR = momentum ratio, $[(\rho_O V_O^2 D_O^2)/(\rho_F V_F^2 D_F^2)]$
M_t = total mass, kg
m = mass flow rate, kg/s, or total number of samples, $n_1 + n_2$
mr = mixture ratio
n_1 = number of samples where $\gamma < R$
n_2 = number of samples where $\gamma > R$
R = input (injection) mixture ratio
V = speed of injected jet, m/s
W = total mass flow rate, kg/s
Γ = local mixture ratio for n_2
γ = local mixture ratio for n_1
η = efficiency
μ = dynamic viscosity, Pa · s
ρ = density, kg/m^3

Subscripts

c = center orifice
f = fuel
l = local
MME = maximum mixing efficiency
mix = mixing
o = oxidizer
out = outside individual orifice
s = simulant
t = total
theo = theoretical value

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Introduction

ONE of the techniques for attaining efficient mixing of liquid propellants is impinging two or more liquids at a common point. Unlike impinging elements are composed of oxidizer and fuel liquid streams that impinge at a given angle at a prescribed distance from the injector face. Impact waves caused by jet impingement act primarily for breakup and mixing of the liquids.[1] The liquid sheet is disintegrated intermittently, generating groups of drops and propagating in a wavelike expansion from the point of impingement. Formation of a fanlike elliptical liquid sheet in the perpendicular direction to the plane of the impinging jets results. Here, dissipative exchange of jet momentum due to high-velocity jet impingement provides simultaneous mechanical atomization and mixing in the immediate vicinity of the impingement point. The impingement process, properly controlled, aids in spatial distribution, as well as atomization of the liquids. In addition, one can accomplish a macroscopic mixing within the individual element's spray pattern.

Minimization of the physical size of the combustion chamber is required in designing a weight-efficient liquid rocket engine. Time is excessively short for diffusive or turbulent gas-phase mixing; thus, the propellants in the chamber are highly stratified and combustion occurs in a stream-tube pattern.[2] The combustion is widely liquid-phase mixing controlled, and its quality is largely determined by mixing uniformity of liquids in the spray. Accordingly, detailed and comprehensive understanding of the liquid-phase mixing is essential.

There have been numerous cold-flow experimental efforts on different aspect of impinging jet atomization.[3–6] Heidmann et al.[3] conducted an extensive study of impinging jets to investigate the effects on spray characteristics of orifice diameter, jet velocity, impingement angle, preimpingement length, and liquid properties. Liquid jet velocity and impingement angle were noticed to be main parameters controlling spray characteristics. Dombrowsky and Hooper[4] conducted cold-flow experimental investigations of various aspects of jet impingement and spray formation. The disintegration of a sheet produced by impinging jets and the formation of droplets were shown to be principally dependent on jet flow properties and impingement angle. Huang[5] examined the breakup of axisymmetric liquid sheets by impinging two directly opposed water jets. Spray formation was classified into two dissimilar breakup regimes connected by a transition regime in terms of Weber number. George[6] developed a correlation defining the relevance of the cold-flow data, such as drop sizes and impingement distance, to the hot-firing results, and mixing uniformity was found to be a function of the penetration of outer liquid jets into the central jet. A summary of the initial studies of liquid/liquid-mixing characteristics for unlike impinging elements is presented in Ref. 7. Rupe conducted a series of comprehensive experiments for the liquid phase mixing by impinging nonreactive and immiscible simulant jets.[8–11] Mixing efficiency was examined with a variety of injector geometries and flow properties, and distinct ranges of mixing variables for optimum mixing were presented. Nurick and McHale[12] investigated the effect of orifice configuration on mixing characteristics. Occurrence of cavitation was also discussed in terms of orifice length–diameter ratio (L/D). Sato[13] defined the relationship between combustion performance and the propellant spray mixing quality determined by cold-flow measurements.

The objective of this study is to examine the effect of orifice diameter ratio on the mixing qualities of unlike-doublet and split-triplet impinging elements. A mixing factor correlating a specific diameter ratio to maximum mixing efficiency of the split-triplet element is presented. A preferred range of the relative jet velocity ratio for maximum mixing efficiency of the split-triplet element is also presented and discussed.

Mixing Parameters

When two or more jets impinge, liquid jets are broken up into droplets immediately in the zone near the impingement point.[5] Spatial distributions of mass are largely determined by the extent of penetration and corresponding momentum transfer (or exchange) by the liquid jet.[14] Disintegration of liquid sheets generally results from the formation of unstable waves of aerodynamic and hydrodynamic origin. In this respect, the extent of mixing has frequently been represented in terms of several parameters associated with liquid jet velocity, such as mass ratio, momentum ratio (MR), Rupe number, or even the velocity itself (see Ref. 15). Rupe number N_R defined as the fraction of one jet velocity head $\{1/[1+(\rho_F V_F^2 D_F)/(\rho_O V_O^2 D_O)]\}$. At higher jet Reynolds numbers, the hydrodynamic impact waves due to momentum exchange are predominant over the entire liquid sheet, and the exchange of jet momentum provides direct mechanical mixing.[14] Therefore, the liquid jet MR, defined simply as the ratio of the oxidizer to fuel jet momentum $[(\rho_O V_O^2 D_O^2)/(\rho_F V_F^2 D_F^2)]$, can be effectively used as a physical mixing parameter to describe the extent of jet penetration. In the present study, the extent of mixing is expressed in terms of jet velocity and MR.

Combustion efficiency is largely determined by the uniformity of liquid-phase mixing, thus, even distribution of mass has critical importance for more complete heat release. The ideal spray can be assumed to be one in which the local mixture ratio is constant and equal to the injection mixture ratio. Therefore, the extent of mixing can be determined by comparing the departure of the local mixture ratio of an actual spray with that of the ideal spray. Based on this, Hohen et al.[16] proposed a statistical treatment of the local liquid-phase mixing data to estimate the mixing quality of the impinging injectors:

$$\eta_{\text{mix}} = 100 \times \left[1 - \left\{\sum_1^{n_1} \frac{M_l \cdot (R-\gamma)}{M_t \cdot R} + \sum_1^{n_2} \frac{M_l \cdot (R-\Gamma)}{M_t \cdot (R-1)}\right\}\right] \tag{1}$$

In Eq. (1), η_{mix} (percent) indicates the deviation of the local propellant mixture ratio from the injection mixture ratio. It represents the mixing quality on a macroscopic level as determined experimentally by a finite number of lattice cells, distributed on a collector head, intercepting the spray.

The characteristic velocity that is obtained in a combustor reflects the effective energy level of the propellants and the design quality of injector. A primary purpose of determining the mixing characteristics of bipropellant streams using the cold-flow technique is to gain confidence so that a predictable injector hot-firing performance will be achieved, at least on a relative basis, assuming a known propellant vaporization rate. Because the mixing efficiency defined in Eq. (1) only describes the extent of mixing in the spray in reference to the ideal spray, a mixing-controlled characteristic velocity C^*_{mix} (meters per second) is indispensable to describe the injector hot-firing performance associated with mixing quality[15]:

$$C^*_{\text{mix}} = \sum_1^m C^*_{\text{theo},l} \cdot M_l \Big/ M_t \tag{2}$$

In Eq. (2), C^*_{theo} is the theoretical characteristic velocity, which is equivalent to combustion performance with ideal mixing ($\eta_{\text{mix}} = 100$ %) and complete vaporization.[17] Note that, for simplicity, the definition of C^*_{mix} in Eq. (2) was made on the assumption that cold-flow mixing approximates real propellant mixing in the combusting environment.

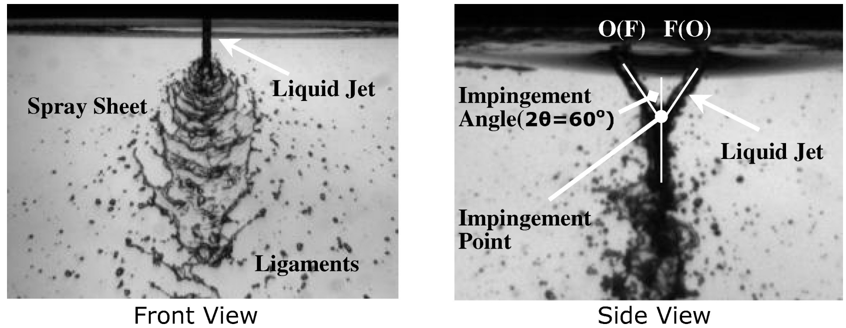
Experimental Apparatus

A schematic of unlike-doublet and split-triplet elements and resultant spray is shown in Fig. 1. The configuration of jet impingement and spray formation by the split-triplet element is similar to that by the triplet element; the only difference is an additional center orifice to reduce the disparity between the fuel and oxidizer orifice sizes. A pair of parallel jets inside impinges on a pair of lateral jets injected at an included angle of 60 deg. Two successive impinging processes are incorporated in the spray formation by the split-triplet element. Two first impingements are made in unlike-doublet fashion and generate a pair of secondary liquid streams (possibly in the form of spray, jets, or liquid sheets) (Fig. 1b). Larger impingement angles result in a higher impact-induced turbulence and, hence, higher turbulent mixing. Therefore, the extent of mixing after the first impingement with an impingement angle of 30 deg is expected to be lower than that by an unlike doublet with an impingement angle of 60 deg. Stream-on-stream secondary impingement instead of coherent liquid jet impingement is made at the second impingement point. Because flow properties of the two secondary liquid streams are identical, secondary impingement is carried out as in like-doublet fashion (Fig. 1b). In all impinging elements tested, the included angle between two lateral jets and the orifice length/diameter ratio (L/D) were fixed at 60 deg and 6, respectively.

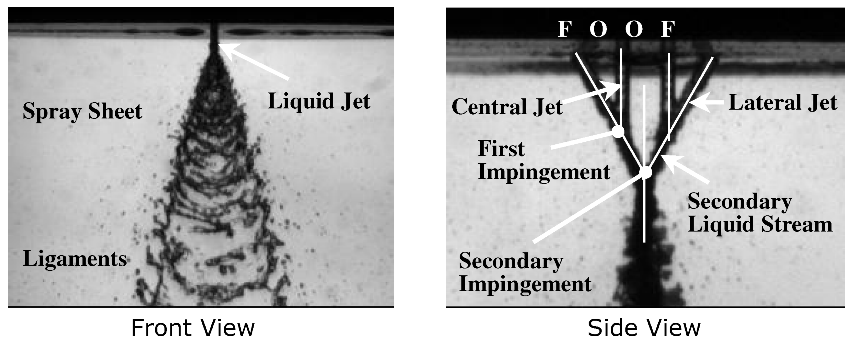
The flow characteristics of the liquid streams before impingement have a significant effect on the mixing process.[18] The liquid jet streams considered here are turbulent and dynamically similar. If the cold jets involve unique hydraulic flow characteristics, the relevance to hot-firing results is questionable. Studies of high-velocity jets issuing from short L/D injectors must consider the potential for cavitation within the injector. In addition, typical orifice discharge coefficients are somewhat above the sharp-edged thin-orifice value of 0.61, but rarely above 0.9, unless extraordinary measures are taken to contour the inlet.[19] To this end, the orifice entrance was properly tempered to provide the liquid streams without bubble and pressure head loss. Preliminary flow tests to estimate the orifice hydraulics were conducted, and the orifice discharge coefficients were measured to be in the range of 0.8–0.9; no evidence of cavitation was found.

A schematic of test setup to measure the local mass is shown in Fig. 2. The system consists of sections. The procedure to control and measure the flow follow that described in Ref. 20. Advanced servo-circuits were used to minimize the feed pressure fluctuation, hence, preventing fluctuations of liquid mass flow rates. This precision system limits the feed tank pressure fluctuation within 6.895 kPa.

The instrument for the measurement of the mixing in spray is a patternator. The spray was picked up by a 14 × 14 cm quadrilateral plain-faced collector evenly divided into 400 (20 × 20) square cross-sectional lattice cells. One end of the test cell was connected to a transparent test tube so that liquid through each flow passage is collected, and its level is visually read. Because the propellant simulants (water for oxidizer and kerosene for fuel) are immiscible, the volume of each of the two simulants collected at any given location is readily determined. The ratio of the volumes of each



a) Unlike-doublet element with the impingement angle $2\theta = 60$ deg



b) Split-triplet element with included angle between the lateral jets of 60 deg

Fig. 1 Jet impingement and spray formation.

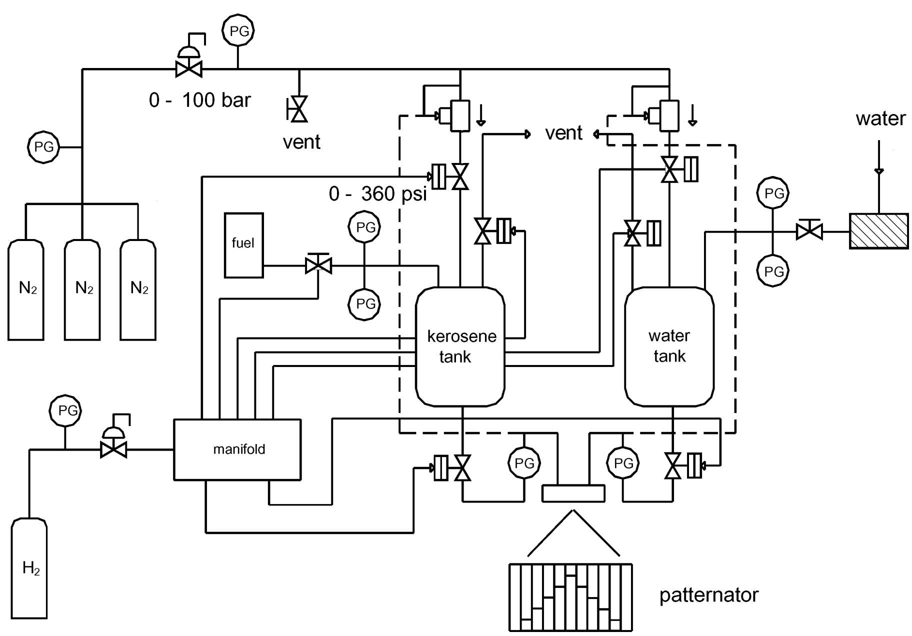


Fig. 2 Schematic of patternation test.

liquid in a test tube represents the local mixture ratio at its location in the spray. Mixing measurements at all parametric conditions were made at 6.2-cm downstream of the impingement point, where the spray formation is completed. Average collection efficiency was measured to be over 90%.

Results and Discussion

Macroscopic mixing qualities of the unlike-doublet and the split-triplet impinging elements were measured systematically to investigate the effect of diameter ratio on the extent of mixing. To prevent the distortion of the resulting spray due to dimensional disparity and corresponding degradation of mixing, the diameter ratio over 1.5 is hardly used in the industry. To this end, three oxidizer orifice diameters D_o of 0.4, 0.5, and 0.6 mm, which correspond to the orifice diameter ratios of 1, 1.25, and 1.5, respectively, were tested while maintaining the fuel orifice diameter fixed at 0.4 mm.

Rupe[10] concluded that the extent of mixing for a given circular orifice combination reaches a maximum when the product of the ratios of the velocity heads and stream diameters is equal to unity. This condition can be uniquely defined when flow properties of every liquid stream participating in the impingement including the jet diameter are the same, and thus, the dynamic similarity between the liquid streams is perfect. This unique condition provides the baseline for the estimation of mixing. In this respect, the MRs of the jets were varied in a range 0.5–6.0. For the conditions of the

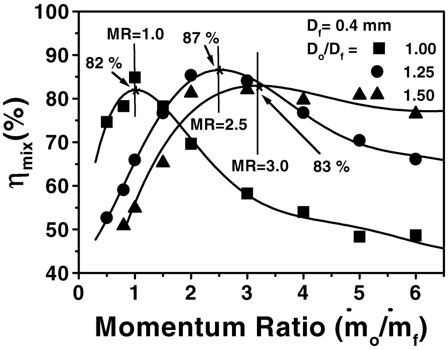


Fig. 3 Effect of diameter ratio on the mixing efficiency of unlike-doublet element.

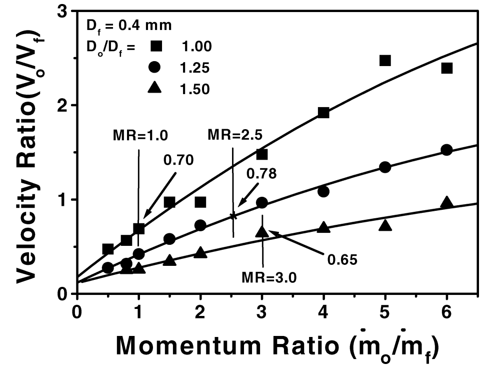


Fig. 4 Jet velocity ratio variation in terms of MR.

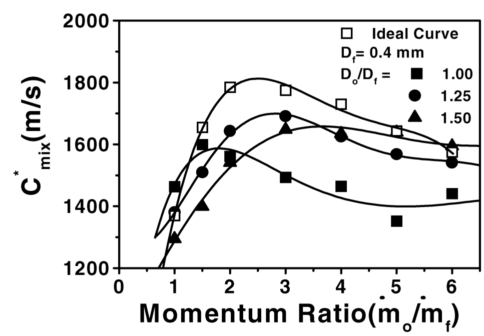


Fig. 5 Effect of diameter ratio on the mixing characteristic velocity of unlike-doublet element.

present study, the Reynolds number for the liquid jets, based on orifice diameter, ranges from 2.5×10^3 to 1.2×10^4. In this range, the jet stream is turbulent, and the turbulent dispersion plays a key role in the spray formation.

Unlike-Doublet Impinging Element

Figure 3 shows the measured mixing efficiency η_{mix} of the unlike-doublet impinging element as a function of MR for three of the orifice diameter ratios. When the diameter ratio is unity, the η_{mix} curve show its peak occurring at the optimum MR of unity (MR = 1). Previous experimental and theoretical studies revealed the general feature of unlike impinging elements that optimum mixing occurs when the jet momentum and the orifice diameters are equalized.[3,7] As the MR arrives at unity, the extent of penetration by both jets is equalized, and state of mixing becomes optimum. However, most practical impinging jets operate in the range of higher MR. In these systems, the extent of mixing decreases with an increase in the jet MR. When the oxidizer jet momentum is superior to the fuel jet momentum (MR > 1), a significantly different mass distribution is obtained. Experimental results show that, at low jet velocities, the two jets basically bounce off of each other after impingement; however, at high jet velocities, they cross through each other.[1] In the case of different jet velocities, the jet of lower velocity is bounced off and spread, whereas the jet of higher velocity transmits and passes through the counter jet. Thus, the deployment of the mixture ratios becomes uneven, and mixing is degraded with increasing MR (Fig. 3).

The diameter ratio for optimum mixing η_{mix} is frequently nonunitary because of the system operation requirements, such that most propellant combinations utilize larger oxidizer orifices to equalize fuel and oxidizer pressure drops. Mass distribution significantly changes with the diameter ratio. The maximum local mass flow shifts along the impinging plane in the direction of the high-momentum stream. As this shift takes place, symmetry about the major spray axis can no longer be maintained. This dimensional disparity distorts the resulting spray shape and could impair mixing and atomization. In Fig. 3, the general trend is for MR for maximum mixing efficiency to increase with increasing diameter ratio. With constant mass flow rate, jet momentum is inversely proportional to the orifice diameter, and the oxidizer stream with enlarged jet diameter more severely distorts the spray and degrades mixing with disparate deployment of fuel and oxidizer masses.[4]

Experiments also have shown that, when the diameter ratio differs significantly from 1.22, the level of mixing attainable with an unlike impinging doublet suffers dramatically.[7] It is evident in Fig. 3, however, that peak heights of η_{mix} curves remain almost unchanged regardless of the diameter ratios, and degradation of mixing due to the disparity between two jets is distinctly relieved with diameter ratio augmentation. This is possibly because, under a given jet momentum, the jet velocity is inversely proportional to the orifice diameter. In general, the spray characteristics and corresponding mixing quality are more strongly affected as the oxidizer jet velocity (velocity ratio) is increased.

Figure 4 shows the measured velocity ratio of the unlike-doublet impinging element as a function of MR for three of the orifice diameter ratios. The general trend is for velocity ratio to increase with increasing in MR because, inherently, the MR is proportional to the velocity ratio squared. The higher the diameter ratio, the lower the velocity ratio. Therefore, the disparity of flow properties between two jets is reduced, and the extent of mixing is enhanced with increasing diameter ratio. In addition, the available energy is utilized in a more efficient manner as the jet diameter increases, or the increase in kinetic energy available for mixing and Reynolds number influences both the scale and magnitude of stream turbulence to increase mixing.[10] Smaller orifice diameter may be another reason for this peculiar behavior. Studies have shown that the smaller the element, the higher the level of mixing; however, for orifice sizes below 0.03 in., little improvement is seen.[6] Note that, in Fig. 4, velocity ratios at which the maximum mixing efficiency occurs remain in a narrow range of 0.65–0.78 for the diameter ratios of interest.

Figure 5 shows a comparison of the mixing-controlled characteristic velocities, C^*_{mix} of unlike-doublet elements as a function of MR for three of the orifice diameter ratios. As was already mentioned, the characteristic velocity reflects the effective energy level of the propellants and the design quality of injector. This performance parameter directly relates the degree of mixing to its contribution on the combustion performance. Here, the local mixing-controlled characteristic velocity was calculated by fast chemistry code.[17] Nonreacting kerosene/water liquids simulate the kerosene/liquid oxygen (LOX) propellant combination, and the chamber pressure is assumed to be 200 psi. Changes in the jet Reynolds number and the stream dynamics due to simulating liquids were incorporated in correlations with jet momentum. Because the mixing quality depends on the injection parameters, whereas the characteristic velocity is a function of the mixture ratio, their peak values occur at different MRs. For instance, maximum η_{mix} due to the unlike-doublet element with unitary diameter ratio of unity occurs at the MR of unity (Fig. 3), whereas C^*_{mix} reaches its maximum at the MR near 2.3 (Fig. 5). Curves of measured C^*_{mix} in Fig. 5 show a generally similar tendency to an ideal curve, but the MRs at which the maximum C^*_{mix} occurs are deviated from the stochiometry significantly. At higher MR, C^*_{mix} by the elements of unequal orifice diameters is much greater than that of the unitary diameter ratio element. At the MR of unity, a perfect mixing condition, C^*_{mix} by the equal sized

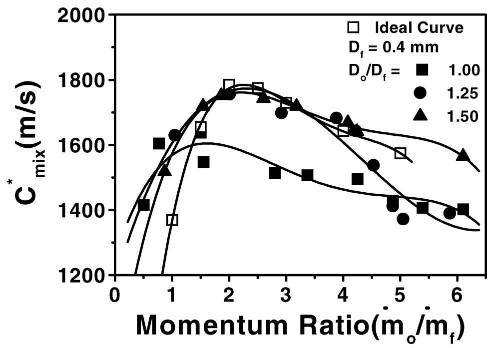


Fig. 6 Effect of diameter ratio on the mixing characteristic velocity variation of the split-triplet element.

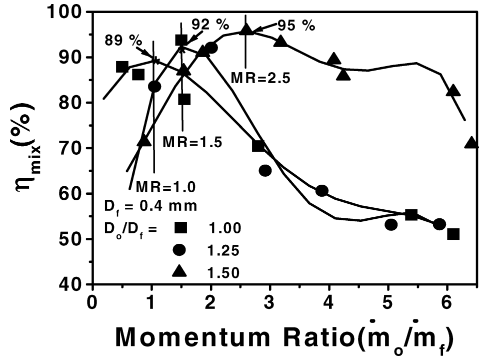


Fig. 7 Effect of diameter ratio on the mixing efficiency of unlike-split-triplet element.

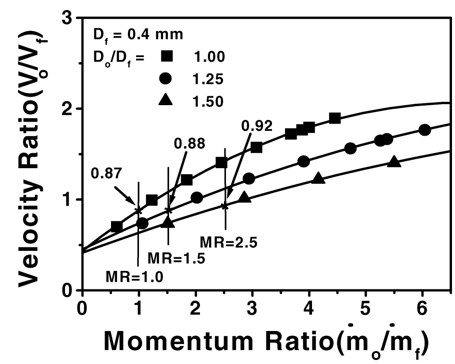


Fig. 8 Jet velocity ratio varies with MR.

orifices becomes greater; however, the difference in C^*_{mix} between the equal and unequal orifice diameters is less significant than that of the mixing efficiency (Fig. 3).

Note that the characteristic velocity is not always proportional to the extent of mixing. This implies that, even with an assumption of mixing-controlled combustion, the extent of combustion should not be predicted by the mixing efficiency only. This discrepancy is primarily because the homogeneity of the mixture ratio distribution was calculated by averaging local values in a linear and arithmetic manner and the adiabatic flame temperature is inherently nonlinear against almost all thermodynamic properties. For instance, when the input mixture ratio is considerably different from the stoichiometry, deviation of the local values from the input mixture ratio causes degradation of mixing. However, the thermodynamic relation may possibly predict a higher gas temperature because a given local mixture ratio is closer to stoichiometry. Accordingly, the averaged value of mass-weighted characteristic velocities may erroneously be larger than that arrived at from the input mixture ratio. This can falsely bring about characteristic velocity efficiency greater than 100%.

Unlike-Split-Triplet Impinging Element

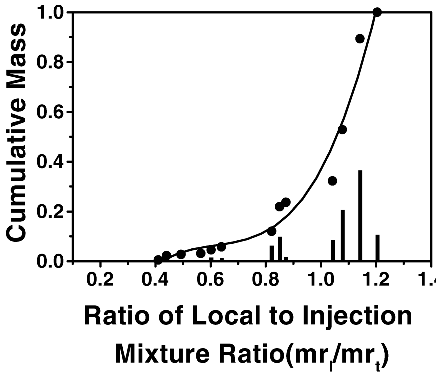
Figure 7 shows depicts the measured mixing efficiency η_{mix} of the split-triplet impinging element. Here, MR increases with increasing central oxidizer jet momentum, while maintaining the lateral fuel jet momentum unchanged. Similar to the unlike-doublet case shown in Fig. 3, the maximum η_{mix} of the split-triplet element of unitary diameter ratio occurs at the MR of unity. Any increase from this condition reduces the mixing extent. When the oxidizer jet momentum is superior to the fuel jet momentum, gradually decreasing η_{mix} due to uneven mass distribution and degradation of mixing is apparent in Fig. 7. As the oxidizer jet momentum is further increased (MR > 1), penetration by the central oxidizer jet becomes superior. Fuel liquid stream is rapidly atomized and dispersed, but the oxidizer stream with higher initial momentum still preserves momentum sufficient to sustain itself as a coherent liquid stream and follows its own initial trajectory. In addition, increasing the oxidizer jet momentum enhances the liquid crossing. Consequently, oxidizer fluids are more concentrated in the center of the spray field, whereas the fuel mass is more dispersed away from the center, resulting in the degradation of mixing. Notice that, when the diameter ratio is unity, the mixing efficiencies of the unlike doublet show a sharper decrease (Fig. 3), whereas the degradation of the split-triplet mixing is more gradual (Fig. 7) with increasing MR. The reason for the improved efficiency is that the spray formed by the split-triplet impingement is always symmetrical about both the major and minor spray axis. In addition, two oxidizer streams of higher jet velocity that crossed through the fuel stream of lower velocity impinge again on each other in a like-doublet fashion. The secondary atomization plays a primary role in the enhancement of mixing extent of the split-triplet element.

In Fig. 7, the general trend is for MR for maximum mixing efficiency to increase with increasing diameter ratio. This repeats the general tendency of the unlike impinging elements shown in Fig. 3. However, in contrast to the unlike-doublet case (Fig. 3), a gradual increase in peak height is evident. The maximum η_{mix} occurs at a certain MR at which the oxidizer jet is well conditioned for optimum mixing. In contrast to the η_{mix} tendency shown in Fig. 3, where improvement of η_{mix} is substantial at higher MR with increasing diameter ratios, η_{mix} is relatively insensitive to the diameter ratio in the range of 1–1.25. However, when the diameter ratio is further increased to 1.5, the increase in η_{mix} becomes significant at higher MRs. Similar to the unlike-doublet case, maximum mixing efficiencies all occur in a narrow range of jet velocity ratios of 0.87–0.92 regardless of the diameter ratio of interest (Fig. 8). Regardless of the diameter ratios, the split-triplet element (89 ~ 95%) is superior to the unlike-doublet element (82 ~ 87%) in maximum mixing efficiency.

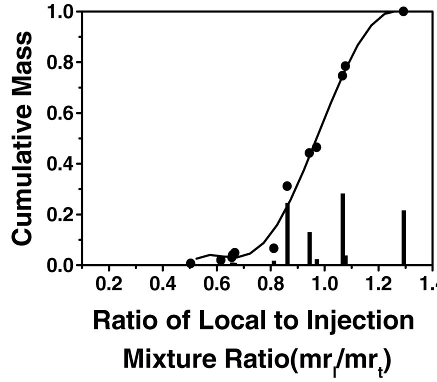
A mixing factor correlating a specific diameter ratio to maximum mixing efficiency of the split triplet element was estimated. In Ref. 7, a correlation is presented relating the circular orifice area (diameter) ratio for maximum mixing efficiency for unlike impinging elements when designed for an included impingement angle of 60 deg. The correlation was based on the results of the cold-flow studies of element mixing efficiency. This correlation is

$$(D_c/D_{\text{out}})^2_{\text{MME}} = M\left[\rho_{\text{out}}\big/\rho_c(W_c/W_{\text{out}})^2\right]^{0.7} \tag{3}$$

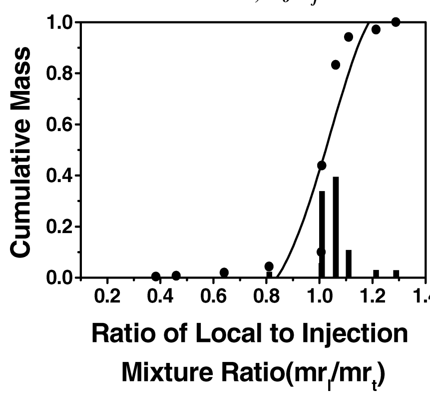
In the range of the orifice diameter ratios of interest, the mixing factor M in Eq. (3) for unlike-doublet element is 1.0, 0.76, and 0.7 for the diameter ratios of 1.0, 1.25, and 1.5, respectively. This is in accordance with previous experimental result that the level of mixing attainable with an unlike impinging doublet is optimum at the diameter ratio of unity and suffers dramatically when the diameter ratio differs significantly from 1.22 (Ref. 7). In the split-triplet case, the mixing factor for maximum mixing efficiency is 0.73, 0.77, and 0.44 for the diameter ratios of 1.0, 1.25, and 1.5, respectively. The mixing factor for maximum mixing efficiency is approximately from 0.75 up to the diameter ratio of 1.25. The mixing quality attainable is also significantly degraded when the diameter ratio is further increased over 1.25. Apparently, the diameter ratio effect on the mixing of split-triplet element is less significant than in the unlike-doublet element case.



a) $D_o/D_f = 1.00$



b) $D_o/D_f = 1.25$



c) $D_o/D_f = 1.50$

Fig. 9 Cumulative mass in terms of the ratio of local to injection mixture ratio in the case of optimum mixing of the split-triplet element, D_f=0.4mm.

Figure 6 shows the mixing-controlled characteristic velocities of the split-triplet element as a function of MR for three of the orifice diameter ratios. The characteristic velocities for the diameter ratio of 1.25 and 1.5 are almost equal to or higher than ideal C^*_{mix}, whereas the C^*_{mix} due to the diameter ratio of unity is much lower over the entire range of MR.

In the present study, no performance losses due to incomplete liquid vaporization, gas-phase mixing, and chemical reaction were considered: thus, the combustion is totally controlled by the liquid-phase mixing. However, the effect of atomization on mixing performance may be estimated in an indirect way. Consider one limiting situation that all liquids are concentrated in one cell only and the opposite that liquids are evenly distributed in every cell on the collector head. In the former, the spray is simply the twofold result of the initial liquid jets, whereas, in the latter, the spray completely covers the collector head with a uniform mixture ratio profile. In these two limiting situations, mixing efficiencies are erroneously the same ($\eta_{\mathrm{mix}} = 100\%$), by definition of Eqs. (1). This specific example reveals that the profile of mixture ratio distribution must be considered simultaneously with the estimation of mixing quality.

Figure 9 shows cumulative mass of the split-triplet spray in terms of the number frequency of the cells of a same local mixture ratio. On the horizontal axis, local mixture ratios are normalized by the injection mixture ratio, and the vertical bar and symbol represent the sum of the local masses and the cumulative mass fraction to the applicable mixture ratio, respectively. When there is a higher number of vertical bars concentrated at the ratio of local to injection mixture ratio of unity, the cells are about the same in the local mixture ratio close to the injection mixture ratio, that is, the mixing is more uniform. Therefore, the steeper the slope, the more uniform is the mixture ratio distribution. When the diameter ratio is 1.5 (Fig. 9c), cumulative mass frequency shows a faster increase than that of the diameter ratios of 1 (Fig. 9a) and 1.25 (Figs. 9b). This result is in accordance with the earlier result of higher mixing efficiency and mixing-controlled characteristic velocity with increasing diameter ratio (Figs. 6 and 7).

Conclusions

The effect of orifice diameter ratio on the mixing qualities of unlike-doublet and split-triplet impinging injectors was studied experimentally. Measurements of local mass distributions were made for different MRs and different orifice diameter ratios. Nonreacting kerosene/water liquids simulate the kerosene/LOX propellant combination. The effect of orifice diameter ratio on mixing-controlled combustion efficiencies and characteristic velocity were represented in terms of the oxidizer/fuel jet MR. General conclusions are as follows.

1) For both unlike-doublet and split-triplet elements, the general trend is for MR for maximum mixing efficiency to increase with increasing diameter ratio. Maximum mixing efficiency of the unlike-doublet element remains unchanged regardless of the diameter ratios, but in the split-triplet case, it gradually increases with increasing in diameter ratio.

2) Relative jet velocity ratio (V_o/V_f) for the maximum mixing efficiency occurs in a narrow range of $0.65 \sim 0.78$ for unlike-doublet and $0.87 \sim 0.92$ for split-triplet elements.

3) The diameter ratio effect on the mixing of split-triplet element is less significant than on unlike-doublet element mixing. The mixing attains its optimum at the orifice diameter ratio 1.25 and 1.5 for unlike-doublet and split-triplet elements, respectively.

4) Split-triplet element is superior to unlike-doublet element in both mixing efficiency and mixing-controlled combustion velocity in the test range of interest. The measured maximum mixing efficiency ranges $82 \sim 87\%$ and $89 \sim 95\%$ for unlike-doublet and split-triplet elements, respectively. The mixing factor for optimum mixing of the split-triplet element is 0.75.

References

[1]Ashgriz, N., Brocklehurst, W., and Tally, D., "Mixing Mechanisms in a Pair of Impinging Jets," *Journal of Propulsion and Power*, Vol. 17, No. 3, 2001, pp. 736–749.

[2] Sutton, G. P., and Biblarz, O., *Rocket Propulsion Elements*, 7th ed., Wiley, New York, 2001, pp. 343, 344.

[3] Heidmann, M. F., Priem, R. J., and Humphrey, J. C., "A Study of Sprays Formed by Two Impinging Jets," NACA TN-3855, March 1957.

[4] Dombrowski, N., and Hooper, P. C., "A Study of the Sprays Formed by Impinging Jets in Laminar and Turbulent Flow," *Journal of Fluid Mechanics*, Vol. 18, Pt. 3, 1963, pp. 392–400.

[5] Huang, J. P., "The Break-Up of Axisymmetric Liquid Sheets," *Journal of Fluid Mechanics*, Vol. 43, Pt. 2, 1970, pp. 305–319.

[6] George, D. J., "Rocket Injector Hot Firing and Cold Flow Spray Fields," AIAA Paper 73-1192, Nov. 1973.

[7] *Liquid Rocket Engine Injectors*, SP-8089, NASA Space Vehicle Design Criteria, 1986.

[8] Rupe, J. H., "The Liquid Phase Mixing of A Pair of Impinging Streams," Jet Propulsion Lab., Progress Rept. 20-195, California Inst. of Technology, Pasadena, CA, Aug. 1953.

[9] Rupe, J. H., "A Correlation Between the Dynamic Properties of a Pair of Impinging Streams and the Uniformity of Mixture Ratio Distribution in the Resulting Spray," Jet Propulsion Lab., Progress Rept. 20-209, California Inst. of Technology, Pasadena, CA, 1956.

[10] Rupe, J. H., "Experimental Studies of the Hydrodynamics of Liquid Propellant Injector," Jet Propulsion Lab., External Publ. 388, California Inst. of Technology, Pasadena, CA, June 1957.

[11] Rupe, J. H., "An Experimental Correlation of the Nonreactive Properties of Injection Schemes and Combustion Effects in a Liquid Propellant Rocket Engine," Jet Propulsion Lab., TR 32-255, California Inst. of Technology, Pasadena, CA, July 1965.

[12] Nurick, W. H., and McHale, R. M., "Noncircular Orifice Holes and Advanced Fabrication Techniques for Liquid Rocket Injectors, Phase I Final Report," NASA CR-108570, Rocketdyne Div., North American Rockwell Corp., Oct. 1974.

[13] Sato, K., "A Study of N2O4/Amine Injector Elements Part 1. Cold Flow Test," National Aerospace Lab. of Japan, Rept. TR-899, 1986, pp. 1–13.

[14] Powel, W. B., "ICRPG Liquid Propellant Thrust Chamber Performance Evaluation Methodology," *Journal of Spacecraft and Rockets*, Vol. 1, No. 1, 1970, pp. 597–599.

[15] Wrobel, J. R., "Some Effects of Gas Stratification on Chocked Nozzle Flows," *Journal of Spacecraft and Rockets*, Vol. 2, No. 6, 1965.

[16] Hohen, F. W., Rupe, J. H., and Sotter, J. G., "Liquid-Phase Mixing of Bipropellant Doublets," Jet Propulsion Lab., Rept. TR 32-1546, California Inst. of Technology, Pasadena, CA, April 1972.

[17] Gordon, S., and McBride, B. J., "Computer Program for Calculation of Complex Chemical Equilibrium Composition, Rocket Performance, Incident and Reflected Shocks and Champman–Jouguet Detonations," SP-273, NASA, 1971.

[18] Won, Y. D., Cho, Y. H., Lee, S. W., and Yoon, W. S., "Effect of Momentum Ratio on the Mixing Performance of Unlike Split Triplet Injectors," *Journal of Propulsion and Power*, Vol. 18, No. 4, 2002, pp. 847–854.

[19] Anderson, W. E., Ryan, H. M., Pal, S., and Santoro, R. J., "Fundamental Studies of Impinging Liquid Jets," AIAA Paper 92-0458, Jan. 1992.

[20] Reibling, R. W., and Powel, W. B., "The Hydraulic Characteristics of Flow Through Miniature Slot Orifices," Jet Propulsion Lab., Rept. TR 32-1397, California Inst. of Technology, Pasadena, CA, Sept. 1969.

[21] Nurick, W. H., and Clapp, S. D., "An Experimental Technique for Measurement of Injector Spray Mixing," *Journal of Spacecraft and Rockets*, Vol. 6, No. 11, 1969.