blamed on poor h_i estimation, some of the error is undoubtedly due to the following idealizations in the mathematical model: treatment as a "quasi"-steady process; isentropic flow in the nozzle (which of course means the nozzle has a discharge coefficient of unity and a zero over-all loss coefficient); all flask temperature and pressure gradients were neglected; use of the Beattie-Bridgeman equation; and use of the finite differencing scheme. With respect to the experiment, the thermocouple must be capable of following a temperature which can drop at almost 100°F/sec in a relatively stagnant medium. This is a rather difficult task even for the smallest of thermocouples. The manufacturer's data states that the thermocouple used in the tests requires about 13 msec to reach 63.2% of an imposed step change in temperature for a flow velocity of 65 fps. Clearly, as this velocity is diminished, the time required for the same temperature variation will rise. Thus, in the early portion of the blowdown, differences can be attributed to the thermocouple lag. No precaution was taken to avoid radiation heat-transfer interchange between the thermocouple and the wall; a rough steady-state analysis shows that the temperature correction for radiation is large enough to account for the differences in temperatures toward the end of the blowdown.

Appendix

The following stems from the work of Johnson,[5,6] let:

$$Z = Z(\rho,T) = 1 + \sum_{i=1}^{I} A_i(T)\rho^i = 1 + \sum_i \left(\sum_{j=0}^{J} a_{ij}/T^j\right)\rho^i \quad \text{(A1)}$$

then

$$f_1(\rho,T) \equiv Z - 1 = \sum_i A_i(T)\rho^i \quad \text{(A2)}$$

$$f_2(\rho,T) \equiv T(\partial Z/\partial T)_\rho = -\sum_i \sum_j j(a_{ij}/T^j)\rho^i \quad \text{(A3)}$$

$$f_3(\rho,T) \equiv Z - 1 + \rho(\partial Z/\partial \rho)_T = \sum_i (1+i)A_i(T)\rho^i \quad \text{(A4)}$$

$$f_4(\rho,T) \equiv \int_0^\rho \left[Z - 1 + T\left(\frac{\partial Z}{\partial T}\right)_\rho\right]\frac{d\rho}{\rho} = \sum_i \sum_j (j-1)\left(\frac{a_{ij}}{T^j}\right)\left(\frac{\rho^i}{i}\right) \quad \text{(A5)}$$

$$f_5(\rho,T) \equiv \int_0^\rho f_2(\rho,T)\frac{d\rho}{\rho} = -\sum_i \sum_j j\left(\frac{a_{ij}}{T^j}\right)\rho^i \quad \text{(A6)}$$

$$f_6(\rho,T) \equiv T(\partial f_4/\partial T)\rho = \sum_i \sum_j (j-1)j(a_{ij}/T^j)(\rho^i/i) \quad \text{(A7)}$$

$$g_1(T_2,T_1) \equiv \int_{T_1}^{T_2}\left(\frac{c_{p,0}}{R} - 1\right)\frac{dT}{T} = (c_0 - 1)\ln\left(\frac{T_2}{T_1}\right) + \sum_{k=1}^{K}\left(\frac{c_k}{k}\right)(T_2{}^k - T_1{}^k) \quad \text{(A8)}$$

$$g_2(T_2,T_1) \equiv \int_{T_1}^{T_2}\left(\frac{C_{p0}}{R} - 1\right)dT = (c_0 - 1)(T_2 - T_1) + \sum c_k\frac{(T_2{}^k - T_1{}^k)}{(k+1)} \quad \text{(A9)}$$

$$g_3(T_2,T_1) \equiv \int_{T_1}^{T_2}\left(\frac{c_{p,0}}{R}\right)\frac{dT}{T} = g_1(T_2,T_1) + \ln\left(\frac{T_2}{T_1}\right) \quad \text{(A10)}$$

where

$$\frac{c_{p,0}(T)}{R} = c_0 + \sum_{k=1}^{K} c_k T^k \quad \text{(A11)}$$

Integrating first along a path of constant T_1 then along a path of constant ρ and finally along a constant T_2 we may write

$$(s_2 - s_1)/R = \int_{1\to 2}\{(c_vT)/(RT) - [Z + T(\partial Z/\partial T)_\rho]d\rho/\rho\} = g_1(T_2,T_1) + \ln(\rho_1/\rho_2) - f_4(\rho_2,T_2) + f_4(\rho_1,T_1) \quad \text{(A12)}$$

$$(u_2 - u_1)/R = \int_{1\to 2}[(c_vdT)/(RT) - T^2(\partial Z/\partial T)_\rho d\rho/\rho = g_2(T_2,T_1) + T_1f_5(\rho_1,T_1) - T_2f_5(\rho_2,T_2) \quad \text{(A13)}$$

$$(h_2 - h_1)/R = (u_2 - u_1)/R + P_2/(\rho_2R) - P_1/(\rho_1R) = (u_2 - u_1)/R + Z_2T_2 - Z_1T_1 \quad \text{(A14)}$$

furthermore

$$c_v/R = T(\partial s/\partial T)_\rho/R = c_{p,0}/R - 1 - f_6(\rho_1T) \quad \text{(A15)}$$

$$c_p/R = c_v/R - T(\partial s/\partial \rho)_T(\partial \rho/\partial T)_\rho/R = c_v/R + (1 + f_1 + f_2)^2/(1 + f_3) \quad \text{(A16)}$$

$$\gamma = (c_p/R)/(c_v/R) \quad \text{(A17)}$$

$$a^2 = (\partial P/\partial \rho)_S = (\partial P/\partial \rho)_T + (\partial P/\partial T)_\rho(\partial T/\partial \rho)_S = [1 + f_3 + (1 + f_1 + f_2)^2/(c_{p,0}/R - 1 - f_6)]RT \quad \text{(A18)}$$

References

[1] Reynolds, W. C. and Kays, W. M., "Blowdown and Charging Processes in a Single Gas Receiver with Heat Transfer," *Transactions of the ASME*, Vol. 80, 1958, pp. 1160–1168.
[2] Tsien, H. S., "One Dimensional Flows of a Gas Characterized by van der Waal's Equation of State," *Journal of Math and Physics*, Vol. 25, No. 6, 1947, pp. 301–324.
[3] Tao, L. N., "Gas Dynamic Behavior of Real Gases," *Journal of Aero Sciences*, Nov. 1955, pp. 763–774 and 794.
[4] Johnson, R. C., "Calculation of Real-Gas Effects in Flow Through Critical-Flow Nozzles," *Transactions of the ASME: Journal of Basic Engineering*, Sept. 1964, pp. 519–526.
[5] Johnson, R. C., "Real-Gas Effects in Critical-Flow-Through Nozzles and Tabulated Thermodynamic Properties," TN D-2565, Jan. 1965, NASA.
[6] Hilsenrath, J. et al., *Tables of Thermodynamic and Transport Properties*, Pergamon Press, New York, 1960 (NBS Circular 564).
[7] McAdams, W. H., *Heat Transmission*, 3rd ed., McGraw-Hill, New York, 1954, p. 180.

Effect of Orifice Length-to-Diameter Ratio on Mixing in the Spray from a Pair of Unlike Impinging Jets

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Nomenclature

d = orifice diameter

$$E_m = 1 - \left[\left(\sum_0^n c\dot{w}_t(R - r)\Big/\dot{W}_tR\right) + \left(\sum_0^{\bar{n}} c\dot{w}_t(R - \bar{r})\Big/\dot{W}_t(R - 1)\right)\right],$$

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where $c = A_s/A_t$, A_s = area of stream tube being sampled; A_t is the area of collection tube; R and r are the metered-in (over-all) and local values of mass fraction of oxidizer simulant, respectively; $\dot{W}_t$ and $\dot{w}_t$ are the metered-in (over-all) and local values of mass flowrate of fuel and oxidizer simulants; $\bar{r}$ is used for all $r \geqq R$; n is the number of samples with $\bar{r} < R$; and $\bar{n}$ is the number of samples with $r \geqq R$

I = included impingement angle
L = length of orifice or jet
Re = Reynolds number
$\bar{v}$ = average fluid velocity
We = Weber number
η = efficiency
ρ = liquid density
ϕ = jet diameter ratio divided by jet momentum ratio, defined by Eq. (3)

Subscripts

1 = liquid 1 (water)
2 = liquid 2 (n-hexane)
c^* = characteristic velocity
I_{sp} = specific impulse
j,o = jet and orifice, respectively

Introduction

ONE index of the uniformity of mixture ratio in the spray produced by a liquid-propellant rocket engine injector is the now widely known mixing factor E_m first introduced by Rupe in 1953.[1] This factor is essentially the difference between unity and a summation of the mass-weighted differences between local values of mixture ratio and the over-all, or metered-in, mixture ratio (see Nomenclature). Hence, it is a measure of the uniformity of an injector's mixture ratio distribution; $E_m = 1.0$ corresponds to perfectly uniform mixing, while $E_m = 0$ implies no mixing. For mixing-limited combustion processes, where the stream-separation effects described in Ref. 2 do not occur, reasonably good correlations, such as those of Ref. 3, exist between the

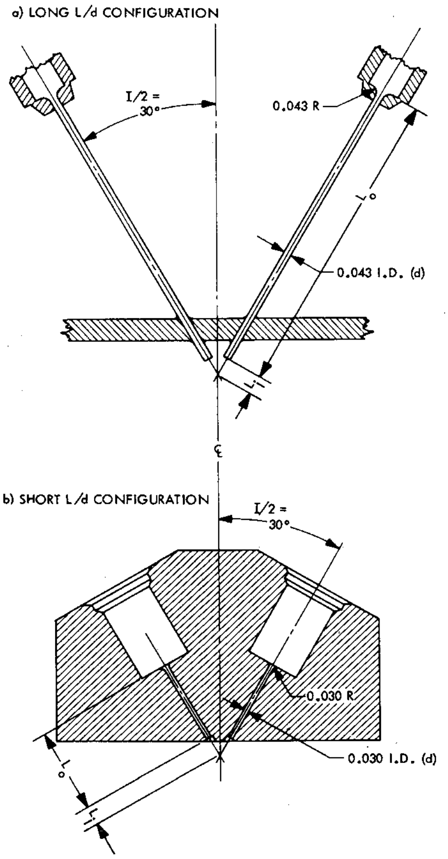


Fig. 1 Injection elements (not to scale).

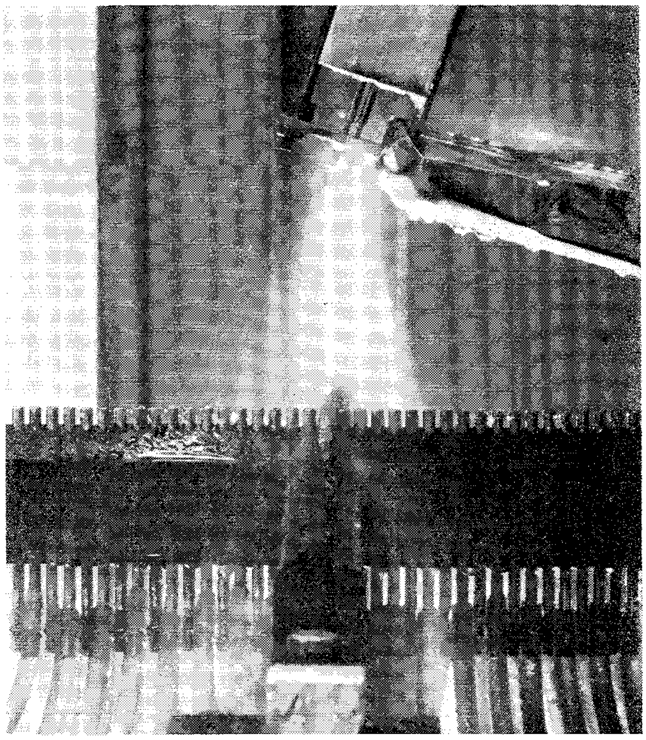


Fig. 2 Jet Propulsion Laboratory injector spray collection apparatus.

engine performance efficiency $\eta_{I_{sp}}$ or η_{c^*} (measured under combustion conditions) and the mixing factor E_m (measured using nonreactive, propellant simulants).

The problem of maximizing E_m has been studied by a number of workers for a variety of impinging-jet injection elements, and the experimental results are summarized in Ref. 4.

For the special case of the widely used unlike doublet element, it can be expected from dimensional analysis that for conditions of invariable jet alignment, geometrically similar collection devices and geometrically similar spatial relationships between injector and collector, E_m may depend on as many as twelve independent variables:

$$E_m = f\{Re_1, Re_2, We_1, We_2, (L_0/d)_1, (L_0/d)_2, (L_j/d)_1, (L_j/d)_2, \times (\rho_1/\rho_2), (\bar{v}_1/\bar{v}_2), (d_1/d_2), I\} \quad (1)$$

However, Rupe introduced experimental evidence[1,5] to reduce the number of first-order degrees of freedom, and was led to the functional relation

$$E_m = f\{\varphi;\ (L_0/d)_1;\ (L_0/d)_2;\ (L_j/d)_1;\ (L_j/d)_2;\ I\} \quad (2)$$

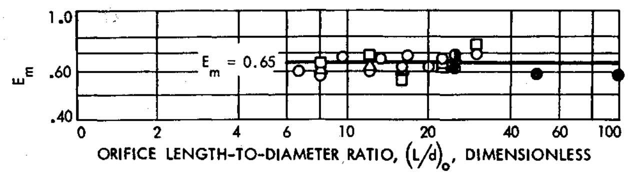
where

$$\varphi \equiv (\rho_1/\rho_2)(\bar{v}_1/\bar{v}_2)^2(d_1/d_2) \quad (3)$$

So far as is known, the effects on E_m of changing the velocity profiles of the impinging jets by decreasing the values of the L/d terms have never been experimentally determined. The brief experimental program described herein was conducted to determine the L_0/d effects, if any, at constant φ and I.

Apparatus and Procedures

Figure 1 shows the two unlike impinging-jet elements tested. For both, $I = 60°$, and $L_j/d = 5.0$; also, $d_1 = d_2$ for each, and orifice alignment was rigidly fixed to hold constant any misalignment effects[6] on the measured values of E_m. The first element consisted of two stainless-steel tubes brazed into corresponding holes drilled into a mild-steel plate; L_0/d was varied from an initial value of 100 to a minimum of 25 by progressively cutting off the upstream ends of the tubes, reradiusing the entrances, and re-silver-



SYMBOL	Re_{H_2O}	$Re_{hex.}$	We_{H_2O}	$We_{hex.}$	ϕ
▲	60,000	149,500	217.0	438.0	1.0
○	35,600	88,500	149.0	298.0	1.0
△	25,000	62,100	104.6	210.0	1.0
◑	35,600	88,500	128.0	261.0	1.0
●	14,600	36,300	53.5	106.0	1.0
□	14,600	36,300	61.2	123.0	1.0

Fig. 3 Effect of orifice length-to-diameter ratio on the mixing factor.

soldering the inlet fittings in place. The second element comprised two holes drilled in an aluminum block; L_0/d was varied from 30 to 6.7 by progressively lengthening the counterbored inlet manifolds. The inlets of all orifices were contoured with a radius equal to their inside diameter. All orifices were fed by long, straight lengths of supply tubing, free from elbows, fittings, or other sources of gross flow disturbances. There were no cross-flow velocity components.

A constant weight mixture ratio of 1.23 ($\varphi = 1.0$) was used, because this value was predicted by the work of Ref. 5 to yield maximum values of E_m in an unlike doublet element with water (liquid 1) and n-hexane (2). The Reynolds number ranges were $14{,}600 \leq Re_1 \leq 60{,}000$, and $36{,}300 \leq Re_2 \leq 149{,}500$. The resulting sprays were collected in the Jet Propulsion Laboratory injector spray collection apparatus (Fig. 2) at a constant distance of 2.5 in. between the impingement point and the collector, and the data were electronically processed to calculate corresponding values of E_m.

Results and Discussion

Figure 3 shows that E_m was essentially constant (0.65 ± 0.10), regardless of L_0/d or Re. The spread of the data is within the estimated accuracy of the combined flow measurement and spray collection processes. Thus, over the range of L_0/d studied, the efficiency of mixing in the spray from a pair of immiscible, nonreactive, unlike impinging jets is apparently independent of the degree of development of the jet velocity profiles at the orifice exit. High values of L_0/d are not prerequisite to good mixing. To some extent, E_m must also be independent of the relaxation of the velocity profile with distance in the freejets, and, therefore, of L_i/d. Tentatively, then, Eq. (2) may be written as

$$E_m = f\{\varphi, I\} \tag{4}$$

The average absolute value of E_m found in the present work (0.65) differs from those reported by Rupe (0.75) in Ref. 5 and Gerbracht (0.76) in Ref. 6 at identical values of $\varphi(1.0)$ and $I(60°)$ and with orifices of comparable diameters. Both Rupe and Gerbracht collected their sprays at a distance of 6 in. from the impingement point, in contrast to the 2.5 in. used here. It has been widely observed that E_m increases with the collection distance, probably because of air entrainment under the nonreactive conditions. When a collection distance of 6 in. was used with the present apparatus (Fig. 1b), E_m rose to 0.77, in agreement with Refs. 5 and 6.

It should be borne in mind that the values of E_m reported are time-averaged values. It is possible that these results may not apply in certain production injectors, where entrance geometry and hydraulics cannot be controlled to the same degree. Finally, although most injectors currently used in the industry do not have orifices with values of L_0/d less than about 5, it would be of interest to construct an apparatus to investigate mixing behavior in the specific range $0 \leq L_0/d < 7$, which was not covered here.

References

[1] Rupe, J. H., "The Liquid-Phase Mixing of a Pair of Impinging Streams," Progress Report 20-195, Aug. 6, 1953, Jet Propulsion Lab., Pasadena, Calif.

[2] Evans, D. D., Stanford, H. B., and Riebling, R. W., "The Effect of Injector-Element Scale on the Mixing and Combustion of Nitrogen Tetroxide-Hydrazine Propellants," TR 32-1178, Nov. 1, 1967, Jet Propulsion Lab., Pasadena, Calif.

[3] Dickerson, R., Tate, K., and Barsic, N., "Correlation of Spray Injector Parameters with Rocket Engine Performance," AFPRL-TR-68-147, June 1968, Rocketdyne, Canoga Park, Calif.

[4] Riebling, R. W., "Criteria for Optimum Propellant Mixing in Impinging-Jet Injection Elements," *Journal of Spacecraft and Rockets*, Vol. 4, No. 6, June, 1967, p. 817.

[5] 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," Progress Report 20-209, March 28, 1956, Jet Propulsion Lab., Pasadena, Calif.

[6] Gerbracht, F. G., "Injector Hydraulics," *Space Programs Summary 37-47*, Vol. III, p. 149, Jet Propulsion Lab., Pasadena, Calif., October 31, 1967.