rejection per kw_e of present nuclear power generators. Alternatively, a cycle efficiency of perhaps 45% could be obtainable with these MHD systems using only an air-cooled convector radiator as a heat sink. Such a power source would require no cooling water and might minimize the power plant's effect on the local ecology.

Development of the proposed nuclear turbo-MHD power system will require significant progress in the technology of MHD generators, super-conducting magnetic systems, and high-temperature reactors. Present technology programs are aimed at establishing the feasibility of both the generators[13,14] and magnets,[12] but have not yet been expanded to explore in depth the feasibility and characteristics of the required very high-temperature reactors.

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Atomization and Mixing Characteristics of Gas/Liquid Coaxial Injector Elements

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The results of a cold-flow characterization study of the mixing and atomization characteristics of several gas/liquid circular coaxial elements are discussed. Mixing and atomization data are presented which show the effect of element geometry as well as element operating conditions. The studies were conducted in unique pressurized facilities in order that hot-fire injector dynamics could be modeled. Local values of gas and liquid mass flux are presented which qualitatively and quantitatively show the mixing quality of the two-phase spray fields. Single parameter correlations for both the mixing and atomization data were obtained. The atomization experiments produced drop size distributions that correlated with the normalized Rosin-Rammler distribution function.

Introduction

THIS paper presents the results of the initial phase of an experimental program (NAS3-12051) to characterize the circular coaxial injector concept for gas/liquid rocket motor applications. The primary objective of the effort was to establish high performance and associated design criteria for the propellant combination of gaseous methane/liquid FLOX (82.6% F_2, 17.4% O_2) at chamber pressures on the order of 500 psia.

In general, gas/liquid coaxial injector element concepts consist of a central liquid (usually oxidizer) jet which is surrounded by an annulus of high-velocity gas (usually fuel). In this study both the geometric and operating variables of the coaxial element were systematically investigated to determine their effects on the mixing and atomization characteristics of the element.

To establish the required design criteria for full-scale gas/liquid coaxial injectors, an investigation utilizing single-element injectors was conducted. This approach involved the determination of both the propellant mixing and atomization characteristics of coaxial elements using cold-flow

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simulation techniques. Such data provide essential input to standard combustion model computer programs which are used for the a priori calculation of combustion efficiencies, i.e., performance.

Method of Approach

The basic premise underlying the cold-flow studies reported herein is that the over-all characteristic velocity efficiency (i.e., performance) of a rocket motor can be represented by the product of a mixing-limited efficiency ($\eta_{c^*,\text{mix}}$), and a vaporization-limited efficiency ($\eta_{c^*,\text{vap}}$), i.e.:

$$\eta_{c^*} = \eta_{c^*,\text{mix}} \times \eta_{c^*,\text{vap}} \tag{1}$$

where η_{c^*} = over-all c^* efficiency, $\eta_{c^*,\text{mix}} = c^*$ efficiency that would be obtained if propellant vaporization were entirely complete, and the only losses were due to nonuniform propellant mixing, $\eta_{c^*,\text{vap}} = c^*$ efficiency that would be obtained if propellant mixing were completely uniform, and the only losses were due to incomplete propellant vaporization.

This approach has been used successfully in a number of liquid/liquid propellant studies[1,2] and more recently has been successfully extended to gas/liquid injector systems.[3] Mixing efficiencies are determined by cold-flow determination of resulting mass and mixture ratio distributions; vaporization efficiencies are determined with a computerized vaporization-limited combustion model, the input of which includes mean drop sizes as well as drop size distribution.

Mixing Efficiency

Wrobel presented an analysis of mixing losses in which the flow within the combustion chamber was hypothetically subdivided into "i" stream tubes, each containing propellant at some mixture ratio which was uniform within that stream tube.[4] No mass or energy was considered to cross stream boundaries. Propellant vaporization, mixing, and combustion were treated as being complete upstream of the start of nozzle convergence. Within the nozzle, the flow was considered to be one-dimensional and isentropic. At each axial station, the static pressure was considered uniform for all stream tubes and boundary-layer effects were neglected. The resulting equation relating the mixing-limited c^* efficiency to the local mass and mixture ratio distribution can be approximated by

$$\eta_{c^*,\text{mix}} = \sum_i \frac{\dot{w}_i}{\dot{w}_T} \frac{c^*_i}{c^*_{\text{theo}}} \tag{2}$$

where the effective c^* is simply a mass-weighted average of the local c^*'s for the individual stream tubes. Then, for any propellant mixture ratio distribution, Eq. (2) provides a simple means for determining the c^* efficiency loss due to "mixing."

Most investigators agree that the distributions developed by spray mixing near the injector will not be appreciably changed downstream by turbulent mixing of the gases. As a consequence, if the initial spray distribution formed by an injector can be experimentally determined, $\eta_{c^*,\text{mix}}$ can be computed by Eq. (2).

The mixing quality of a spray field can be expressed by an index (E_m), which defines the mass-weighted deviation of local mixture ratio from the initially injected over-all mixture ratio[5]

$$E_m = \left[1 - \sum_i^N \frac{\dot{w}_i}{\dot{w}_T} \frac{(R - r_i)}{R} - \sum_i^N \frac{\dot{w}_i}{\dot{w}_T} \frac{(R - \bar{r}_i)}{R - 1}\right] 100 \tag{3}$$

where E_m = mixing index, $\dot{w}_i/\dot{w}_T$ = mass fraction in the stream tube, R = ratio of total oxidizer mass to total oxidizer and fuel mass, r_i = ratio of oxidizer mass to total oxidizer and fuel mass in an individual stream tube for $r_i < R$, $\bar{r}_i$ = ratio of oxidizer mass to total oxidizer and fuel mass in an individual stream tube for $r_i > R$

The mixing factor (E_m) is not uniquely defined by $\eta_{c^*,\text{mix}}$. The correspondence is strongly affected by the particular propellant combination and the nominal injected mixture ratio. For a given propellant system, the relationship between E_m and $\eta_{c^*,\text{mix}}$ can be determined with a simple stream tube analysis by assuming $\eta_{c^*,\text{vap}} = 100\%$.[2] A discussion on the relationship between $\eta_{c^*,\text{mix}}$ and E_m was recently presented by Nurick.[6] E_m will be employed herein to describe the average mixing uniformity of a given spray field so that the results may be applied in general to gas/liquid systems.

Vaporization Efficiency

The vaporization efficiency of a particular gas/liquid injector-chamber system can be calculated by means of computerized analytical models with empirical data as essential input.[7] The model formulation is based on the development of mathematical expressions for the various physical processes involved in the combustion of liquid droplet sprays in a gas/liquid rocket engine. The model considers the oxidizer to be injected as a spray containing ranges of discrete droplet size groups, each possessing a given average diameter. The total spray mass is distributed among the various groups according to an experimental mass distribution function.

The model is solved in numerical form by high-speed digital computers. It requires input of the "upstream boundary condition," which completely describes the initial conditions of spray (droplet sizes, drop size distribution, drop velocities, and temperature), and gas (composition, flowrate, and pressure) at the location where computation is started. Chamber geometry must also be specified.

For analysis of performance, primary results of interest from the model are the percentage of propellant combusted upstream of the nozzle throat. If the mass distribution (mixing) is perfectly uniform, this leads directly to a c^* efficiency according to the following equation:

$$\eta_{c^*,\text{vap}} = \left(\frac{\dot{w}_B}{\dot{w}_I}\right)\left(\frac{c^*_B}{c^*_I}\right) \tag{4}$$

where, $\dot{w}_B$ = flowrate of burned gas at the geometric throat, $\dot{w}_I$ = injection flowrate of fuel plus oxidizer, c^*_B = theoretical c^* corresponding to the composition of the burned gas at the geometric throat, c^*_I = theoretical c^* corresponding to the injection mixture ratio of liquid fuel and oxidizer

Rather than report $\eta_{c^*,\text{vap}}$ for the studies presented herein, the resulting mass median drop size ($\bar{D}$) will be presented as a function of the pertinent variables. Thus, by employing a computerized combustion model these results can be utilized to predict $\eta_{c^*,\text{vap}}$ for numerous gas/liquid propellant systems.

Experimental Apparatus

Mixing Measurement System

To simulate the dynamic conditions of a hot fire gas/liquid propellant system, mixing experiments were conducted in a pressurized environment with single-element injectors. Conducting the experiments in a pressurized environment permitted exact modeling of the hot-fire gas phase density, which heretofore has not been possible in ambient pressure experiments. A mixture of gaseous nitrogen/oxygen and water was used as nonreactive propellant simulants. Local values of gas and liquid mass flux for the calculation of E_m were determined with a specially designed two-phase impact probe[8]: A schematic of the experimental system that was employed for the characterization of the dense gas/liquid spray fields is shown in Fig. 1. The apparatus consisted essentially of a pressurized test section in which the impact

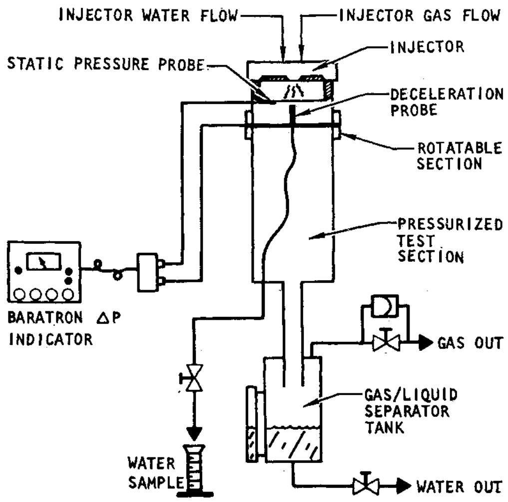


Fig. 1 Schematic of pressurized mixing facility.

probe was positioned in $r - \theta$ coordinates. The impact pressure in the probe was measured with an MKS Baratron Type-77 Electronic Pressure Meter.

Drop Size Measurement System

To simulate the dynamic injection conditions of hot-fire propellant systems, the atomization experiments were also conducted in a pressurized facility. In this case, gaseous nitrogen and molten wax were used as fuel/oxidizer simulants, respectively. In this molten wax technique, the wax droplets freeze prior to collection and are subsequently subject to sieve analysis.[9] Heretofore, gas/liquid molten wax tests have been conducted at atmospheric pressure. However, these tests did not adequately model the gas-phase density of the hot-fire system.

The $\bar{D}$ data of the molten wax technique must be corrected for differences between the physical properties of molten wax and the oxidizer of interest (FLOX, LOX, etc.). Except for absolute viscosity and density, molten wax (Shell-270) simulates reasonably well the physical properties of most oxidizers. The wax data can be corrected for these differences in physical properties employing the empirical relations of Ingebo.[10]

A schematic of the pressurized atomization facility that was employed in these studies is presented schematically in Fig. 2. The system consisted of a 600-gallon cylindrical tank in which a single-element injector model was mounted. Molten wax and heated GN_2 were supplied to the injector from a system that was heated with circulating hot oil. All lines and valves in the wax supply system were oil jacketed to prevent wax freezing. Heated GN_2 was supplied to the injector at a temperature above the melting point of the wax (~200°F) in order that the resulting wax droplets did not freeze prior to the completion of the liquid jet breakup and atomization processes.

Experimental Studies

Element Selection and Modeling Criteria

The nominal thrust level of the circular coaxial element that was chosen for characterization was 70-lbf FLOX/CH_4(g) at optimum sea level expansion. The primary element design variables which were studied were the liquid oxidizer orifice size, the gaseous fuel (or annulus) orifice size, the amount of recess of the oxidizer post, and the effects of oxidizer post chamfering. The element operating variables which were independently investigated were the injected gas velocities, injected liquid velocities, injected mass flow ratios ($\dot{w}_{liq}/\dot{w}_{gas}$), and the gas-phase density.

The element design which was chosen for characterization is presented schematically in Fig. 3. To investigate the effects of liquid velocity, three configurations were employed; their respective dimensions are also shown in Fig. 3. For all three configurations, the oxidizer post exit was chamfered at a nominal half-angle of 6°; this is below the value at which separation occurs.[11]

The nominal design values selected for the hot-fire element operating conditions for the FLOX/CH_4(g) propellant system were as follows: $P_c = 500$ psia ($\rho_g = 1.45$ lbm/ft^3); Thrust = 70 lbf/element at sea level; Oxidizer/Fuel Mixture Ratio ≡ $MR = 5.25$; Fuel Temperature = 530 R; FLOX Density = 89 lbm/ft^3.

In cold-flow simulation of these hot-fire conditions, it was possible to model all of the above mentioned variables (i.e., ρ_{gas}, V_{gas}, etc.) except the density of oxidizer. Water ($\rho = 62.4$ lbm/ft^3) was employed as oxidizer simulant in the mixing experiments and Shell-270 wax ($\rho = 47.1$ lbm/ft^3) was used as oxidizer simulant in the atomization experiments.

Element Mixing Studies

Parametric mixing experiments were conducted to determine the independent effects of gas velocity, liquid velocity, throttling (gas density), element mixture ratio, and oxidizer post recess on the mixing characteristics of coaxial elements. For brevity, individual plots showing the effects of all the aforementioned parameters will not be presented herein. Rather, the effects of several key parameters will be presented.

The throttling characteristics of the three sizes of elements ($D_L = 0.136$ in., 0.108 in., 0.070 in.) are presented in Fig. 4. These data were obtained for a nominal oxidizer post recess of approximately one liquid jet diameter. The experiments were performed at constant mixture ratio and the total propellant flowrate was proportional to the simulated gas-phase density (i.e., the tests simulated throttling a hot-fire injector at constant mixture ratio). The data show a significant decrease in mixing-limited performance as the element

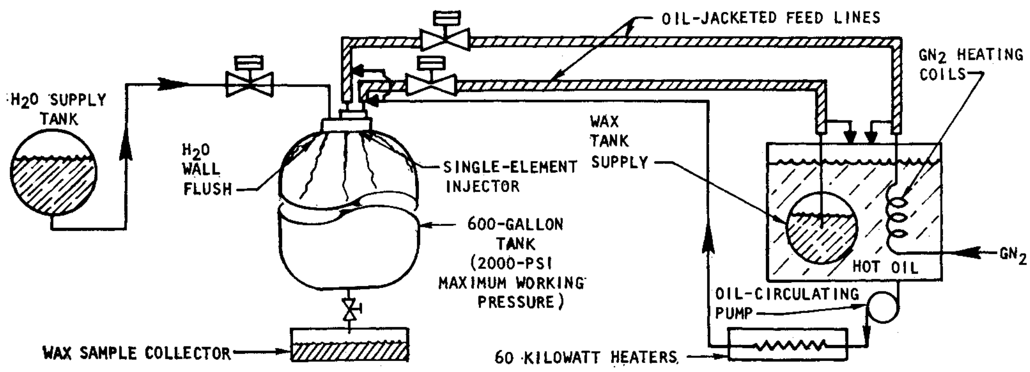
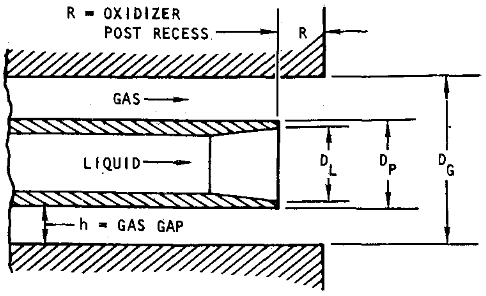


Fig. 2 Schematic of pressurized atomization facility.



ELEMENT CONFIGURATIONS (NOMINAL DIMENSIONS)			
NO.	D_L (IN.)	D_P (IN.)	D_G (IN.)
1	0.136	0.146	0.182
2	0.108	0.122	0.166
3	0.070	0.080	0.136

Fig. 3 Nominal element configurations.

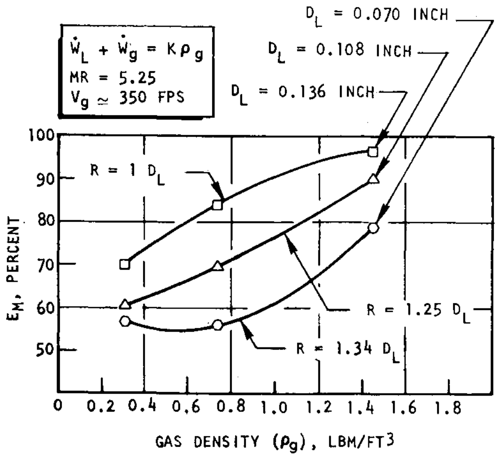


Fig. 4 Throttling characteristics.

was throttled (i.e., ρ_g decreases). Note, however, the high mixing performance ($E_m = 95.6\%$) of the recessed element at the design condition ($\rho_g = 1.45$ lbm/ft^3, $MR = 5.25$). For the FLOX/CH_4(g) propellant system at 500 psia, that value of E_m corresponds to $\eta_{c^*,\text{mix}} = 99.9\%$.

The independent effects of oxidizer post recess were determined for a gas-phase density of 1.45 lbm/ft^3 and $MR = 5.25$. Figure 5 presents the mixing test results for the three element configurations. As indicated, a distinct optimum for the $D_L = 0.136$-in. configuration was found at a recess of approximately one liquid jet diameter. Increasing the post recess from 2–4 D_L resulted in essentially the same mixing performance. The $D_L = 0.108$-in. configuration exhibited a similar trend but oxidizer post recess did not affect the $D_L = 0.070$-in. configuration over the range investigated.

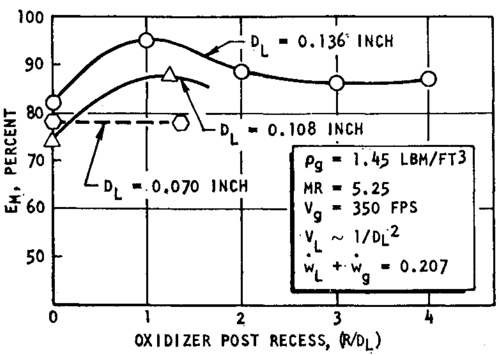


Fig. 5 Effects of oxidizer post recess.

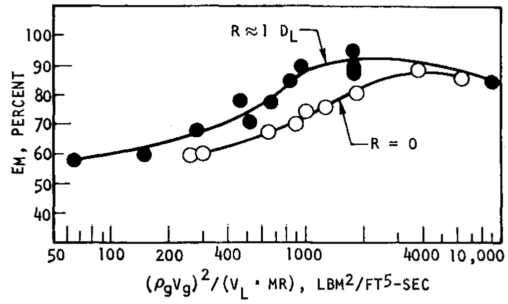


Fig. 6 Correlation of cold-flow mixing data.

Correlation of Cold-Flow Mixing Data

The mixing results of the cold-flow study were analyzed to determine if a single parameter could be found to correlate the results in terms of pertinent variables. The correlating parameter was formulated by considering the dynamic and operating variables that could be expected to control the stripping of the liquid jet by the high-velocity gas. The variables included the momentum flux of the high-velocity gas ($\rho_g V_g^2$), an operating variable proportional to the residence time of the liquid jet (V_L), the variable density of the gas phase (ρ_g), and the ratio of liquid mass to gas mass (MR). These variables were formulated into a single parameter by considering the qualitative trends of the data. Figure 6 presents a correlation of the mixing data (E_m) with the parameter $(\rho_g V_g)^2/(V_L \cdot MR)$. As indicated, the parameter provides a reasonable correlation of the mixing data.

Element Atomization Studies

Parametric atomization studies analogous to the mixing experiments were conducted with the three element configurations. All experiments were conducted in the pressurized atomization facility employing molten wax and gaseous nitrogen as nonreactive propellant simulants.

The throttling characteristics of the three configurations are presented in Fig. 7 for both recessed- and flush-post configurations. The experiments were performed at $MR = 5.25$ and the total propellant flowrate was proportional to the simulated gas-phase density, as would be the case under hot-firing conditions. As indicated, for the $D_L =$ 0.136-in. and 0.108-in. configurations, the mean drop size decreased as the element was throttled. For the $D_L =$ 0.070-in. element, throttling did not significantly affect the resultant mean drop size. It should be noted that the liquid jet velocity, V_L, was proportional both to the gas phase density and the liquid jet diameter.

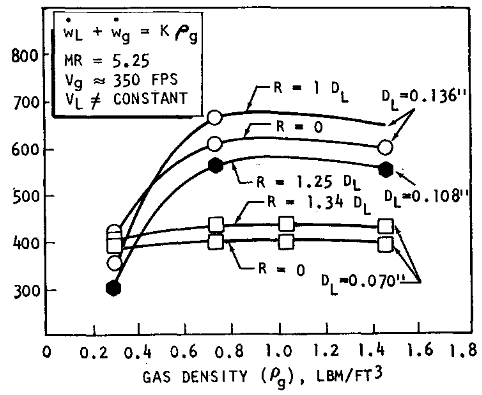


Fig. 7 Throttling characteristics.

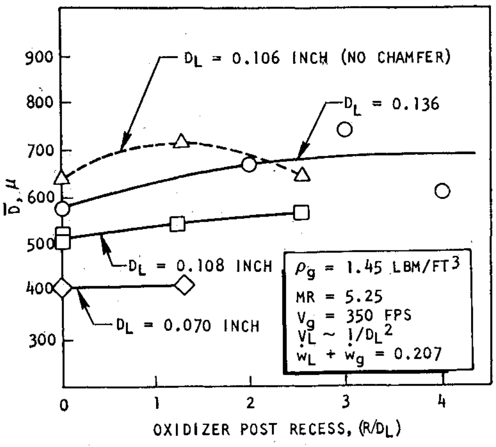


Fig. 8 Effect of oxidizer post recess.

The independent effects of FLOX post recess were determined for the design point of $\rho_g = 1.45$ lbm/ft^3 and $MR = 5.25$. Figure 8 presents the results of the atomization experiments for several element geometries. The solid curves are for elements with liquid jet diameters of 0.136 in., 0.108 in., and 0.070 in., all of which were designed with a 6° chamfer (diffuser section) at the exit of the oxidizer post. As indicated, increasing post recess either had negligible effect or resulted in increasing drop size as the post was recessed to practical depths (Recess/$D_L \simeq 2.5$).

These results (Fig. 8) are not in accord with previously reported coaxial element atomization data, which indicate a significant decrease in drop size as the oxidizer post is recessed.[3] However, the referenced study investigated large-thrust-per-element injectors (≈ 2000 lbf) and the elements which were employed did not have a chamfer at the exit of the oxidizer post.

To determine whether or not the post exist chamfer was the reason for the discrepancy between the data, an element was fabricated that was identical to the $D_L = 0.136$-in. element except that the post chamfer was eliminated. As indicated in Fig. 8 (dashed line), this element produced drop sizes that were slightly larger than the $D_L = 0.136$-in. element and significantly larger than the $D_L = 0.108$-in. configuration. Recessing the nonchamfered oxidizer post again did not result in decreased drop sizes. Note that the experiment with the $D_L = 0.108$-in. configuration with zero post recess was repeated and the results were 500 and 527 μ, respectively. Thus it appears that large-thrust-per-element coaxial injectors are more sensitive to oxidizer post recess than small-thrust-per-element coaxial injectors.

A typical normalized drop size distribution curve from the pressurized atomization experiments is presented in Fig. 9. These data are for an experiment with the $D_L =$

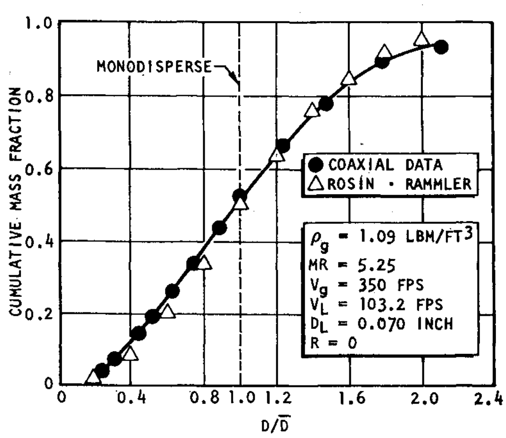


Fig. 9 Normalized drop size distribution data.

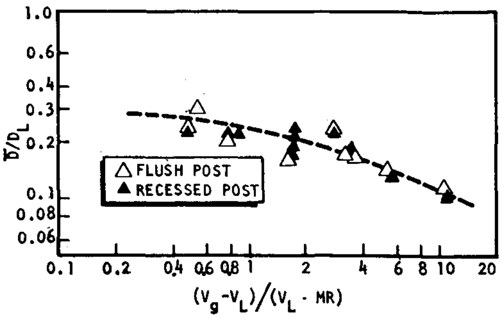


Fig. 10 Correlation of cold-flow atomization data.

0.070-in. element configuration at zero post recess ($\rho_g = 1.09$ lbm/ft^3, $MR = 5.25$) which produced a $\bar{D}$ of 398 microns.

Also shown in the figure is the normalized Rosin-Rammler drop size distribution function.[12] Note agreement with the coaxial injector data for values of $D/\bar{D} > 1.0$. Use of realistic drop size distribution functions for $D/\bar{D} > 1.0$ in combustion model programs is critical since these drop size ranges significantly influence $\eta_{c^*,\mathrm{vap}}$.

Correlation of Cold-Flow Atomization Data

An attempt was made to correlate the atomization data by utilizing the parameter $(\rho_g V_g)^2/(MR \cdot V_L)$ which correlated the mixing data (Fig. 6). However, no reasonable correlation was obtained. The most successful correlation of the atomization data was obtained by replacing the numerator of the mixing correlation parameter by a term proportional to the shear rate at the gas-liquid interface (i.e., $V_g - V_L$). Resultant mean drop sizes were nondimensionalized by D_L. Figure 10 presents the parameter D/D_L as a function of $(V_g - V_L)/(V_L \cdot MR)$. As indicated, the parameters provide a reasonable correlation of the atomization data.

Discussion of Results

Data Verification

Verification and correlation of the cold-flow data presented herein will be determined in the later phases of the subject experimental program (NAS3-12051) utilizing single-element hot-firing injector/chambers. However, the trends of cold-flow data can be examined qualitatively in terms of the operating characteristics of full-scale coaxial gas/liquid injector systems.

Full-scale FLOX/CH_4(g) studies[13,14] indicate that over-all engine performance (η_{c^*}) decreases as the engine is throttled from its design condition. Cold-flow data presented herein show that mixing performance decreases (Fig. 4) as the element is throttled while the mean drop size also decreases (i.e., $\eta_{c^*,\mathrm{vap}}$ increases, Fig. 7). However, the beneficial effects during throttling of a reduced drop size are overcompensated by a decrease in the mixing efficiency ($\eta_{c^*,\mathrm{mix}}$). The net predicted effect is a decrease in the over-all c^* performance of the element.

The referenced studies also indicate that injector performance decreases as the injected mixture ratio is increased. The cold-flow data of this study show that E_m decreases ($\eta_{c^*,\mathrm{mix}}$ decreases) and mean drop size increases ($\eta_{c^*,\mathrm{ap}}$ decreases) with increasing mixture ratio. Thus, the cold-flow data are in qualitative agreement with the data of full-scale injector studies.

Physical Interpretation of Mixing Quality

The mixing quality (E_m) of several typical spray fields can be examined by comparison of local values of gas and liquid mass flux. Figure 11 presents the "normalized" gas and

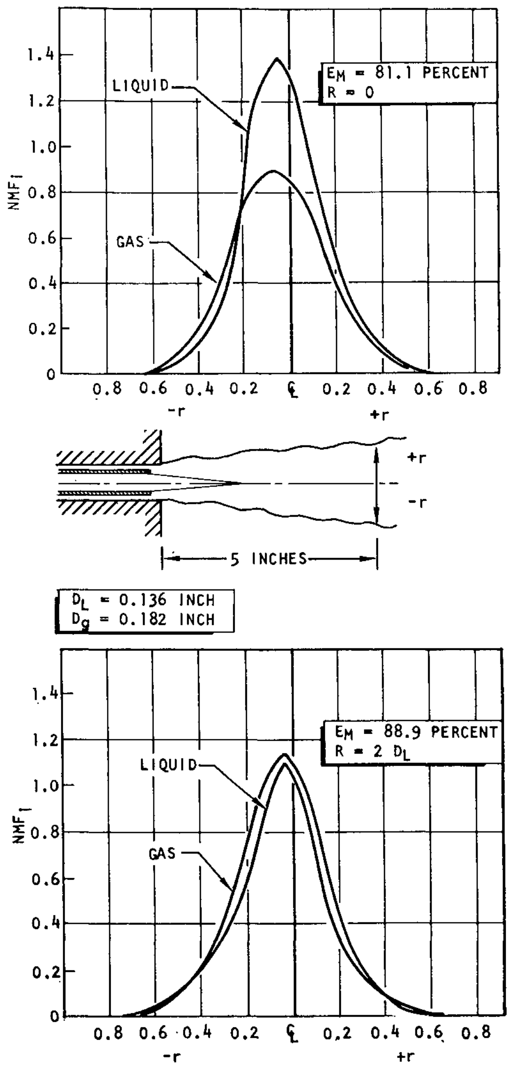


Fig. 11 Gas and liquid mass flux profiles.

liquid mass fluxes ($NMF_i = (\dot{w}_i/A_i)_{local}/\dot{w}_{i,tot}$, i = gas or liquid) for the series of experiments that utilized the No. 1 element configuration to determine the effect of oxidizer post recess ($R = 0$ and $R = 2D_L$). Note that the mass flux is "normalized" only with respect to total flowrate and not with respect to area.

Plotting the "normalized" mass fluxes allows for a visual determination of the uniformity of the spray field. That is, if local values for the "normalized" liquid and gas mass flux coincide, then at that point the local mixture ratio is equal to the injected mixture ratio. If the liquid values are higher than the gas, then the local mixture ratio is greater than the injected mixture ratio, and vice versa. For complete mixing (i.e., $E_m = 100\%$) the curves would coincide both spacially and in magnitude.

At the condition of zero post recess, the local mixture ratios are higher than the injected mixture ratio near the centerline of the spray field. In one outer zone of the spray field ($-r > 0.2$ in.), the mixture ratios are less than the injected mixture ratios. The net result of the combination of the profiles is a degradation in the mixing quality of the spray field (i.e., $E_m = 81.1\%$). When the oxidizer post was recessed to a value of $2D_L$, the flux profiles more nearly coincided throughout the spray field. Thus, higher mixing quality ($E_m = 88.9\%$) was obtained.

Examination of cold-flow data as shown in Fig. 11 provides the experimentor not only with information in regard to the mixing characteristics of the element, but also information in regard to the chamber wall heat-transfer characteristics of the element. By examination of mass and mixture ratio profiles in the outer zones of the spray field, the relative chamber wall heat-transfer characteristics of elements can be assessed. These data are useful for the selection of injector peripheral elements for enhanced injector/chamber compatibility.

Summary

An experimental program has been conducted with single-element coaxial injectors, which shows the independent effects of element design and operating variables upon the mixing and atomization processes. The mixing and atomization experiments were conducted in unique pressurized facilities so that the hot-fire injector dynamics could be more closely modeled than has heretofore been possible. Reasonable single-parameter correlations of both the mixing and atomization data were obtained. The experimental drop size distributions were found to be correlated by the normalized Rosin-Rammler distribution functions.

To date, direct verification of the cold-flow data has not been completed. However, the cold-flow data are in qualitative agreement with the operating characteristics of full-scale gas/liquid injector systems.

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