# Fluid Dynamic Characterization of Sudden-Expansion Ramjet Combustor Flowfields

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**Experimental studies pertinent to axisymmetric, sudden-expansion dump combustor configurations for integral rocket-ramjet missiles have been performed under cold flow test conditions. These studies have included surface flow visualization, measurements of total and static pressures, and gas sampling within a representative combustor duct. Flow visualization tests, using a surface oil flow technique, vividly demonstrated the complex nature of the flow recirculation region downstream of the dump station. Gas concentration measurements of simulated fuel-air mixing were made in the combustor duct using an on-line gas analysis system with a quadrupole mass spectrometer. Combustor flowfield studies were made for test configurations with and without mechanical flameholding devices. Direct correlations between cold flow mixing data and measurements of combustion efficiency from direct-connect ramburner tests were made as a function of combustor length-to-diameter ratio.**

## Introduction

In recent years, a new airbreathing propulsion technology has been evolving for missiles whose applications dictate rather severe volume constraints. The novel concept embodied in this advanced generation of strategic and tactical missiles is the integral rocket-ramjet.[1,2] This missile propulsion concept requires the rocket booster and the ramjet engine to operate as a completely integrated system. Thus, one is required to design a ramjet engine that can operate as a solid propellant rocket in its initial stage of flight. Since the ramjet combustor must initially serve as housing for the rocket propellant, it cannot be ideally configured in terms of fuel injection and combustor geometry for operation in the ramjet mode. The basic combustor configuration, illustrated in Fig. 1, is the so-called sudden-expansion dump combustor. In this type of combustor, fuel injection occurs in the air inlet duct upstream of the dump station. Primary flame stabilization is provided by the flow recirculation region just downstream of the dump station. Additional flame stabilization can be obtained, at the expense of total pressure loss, with mechanical flameholding devices at the air inlet/combustor interface.

As indicated by the simple sketch in Fig. 1, the dump combustor flowfield is a complex fluid mechanical mélange of turbulent fuel-air mixing, flow separation, flow recirculation, shear flow attachment, acoustic coupling, etc. The objective of the present experimental effort was to obtain further insight and fundamental understanding of the overall characteristics of this type of flowfield. Emphasis has been placed on the performance of detailed fluid dynamic studies using a basic dump combustor configuration, typical of those of current interest in the development of integral rocket-ramjet propulsion systems. Some of the basic parameters of interest relative to combustor flowfield characterization are dump station step height, combustor length-to-diameter ratio (L/D), and inlet flow Mach number. One of the principal considerations in the performance of these experiments was to acquire a comprehensive and consistent set of data which would be of significant use to both the combustor modeler and combustor test engineer. Of primary concern in the performance of any cold flow analog of combustion flowfield phenomena is the general applicability of test results to the reactive flow system. Inasmuch as possible, direct correlations of data from cold flow and reactive flow experiments have to be made in order to try to establish some level of validity and usefulness for the cold flow results. As will be discussed in a later section, such an attempt has been made in this paper.

## Experimental Hardware

The experimental test facility, used in the performance of this research effort, is a modified version of an existing supersonic combustion research facility.[3,4] A schematic illustration of the modified configuration for dump combustor research is shown in Fig. 2. The basic test facility consists of a high-pressure air supply system, a gas-fired ceramic-brick heater, air plenum chamber, air inlet section with eight circumferential fuel injection ports, dump combustor section with three interchangeable exhaust nozzles, and exhaust duct. A photographic view of the dump combustor test configuration is shown in Fig. 3. Overall dimensional data for the dump combustor test geometry are given in Table 1. The L/D for the combustor duct is 3.92. The array of fuel injection ports in the air inlet are located 2.5 in. upstream of the dump station and were connected orthogonally in two groups of four to separate gas-feed systems. The orifice diameter of each injection port was nominally 0.035 in.

### General Instrumentation

As can be seen in Figs. 2 and 3, the combustor duct contains opposing wall ports at two axial positions which provide access to the internal flowfield. A variety of contoured wall

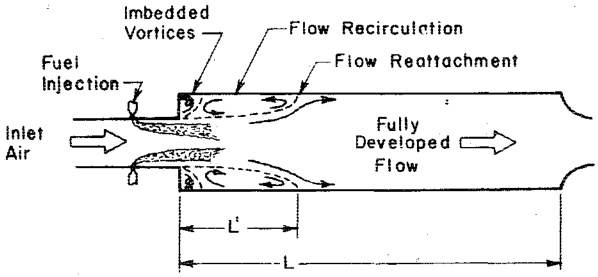


**Fig. 1 Schematic illustration of dump combustor flowfield.**

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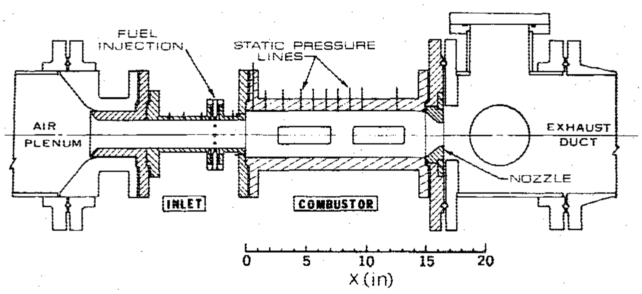



**Fig. 2 Sudden-expansion dump combustor test configuration.**

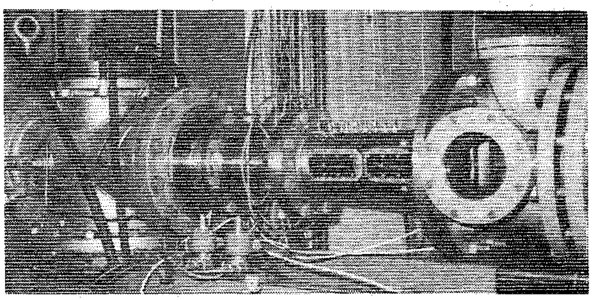


**Fig. 3 Photographic view of test hardware.**

plugs provide the capability to mount and traverse various types of probes at six positions along the duct axis. In addition, wall static pressures are measured at eighteen different locations (see Fig. 2) on the air inlet and dump combustor sections. The total pressures in the air plenum and in the gas-feed lines for the fuel injectors are also measured. All pressure measurements are made using differential-pressure-diaphragm transducers with nominal operating ranges of 0-100 psia. The voltages from these transducers are fed through signal conditioning units into a hybrid analog-digital data acquisition system which operates on-line in real time.

#### Gas-Sampling System

An on-line gas-sampling system was developed and utilized in this effort to obtain detailed gas concentration profiles for simulated fuel-air mixing in the sudden-expansion dump combustor.[4,5] The gas-sampling system consisted of a traversing sample probe, which was electromechanically operated, and a quadrupole mass spectrometer (QMS) system for analyzing gas samples collected by the probe. The QMS system was interfaced with the on-line analog-digital data acquisition system. Two types of gas-sampling probes were used to obtain gas concentration data from within the dump combustor duct. One of these probes was a simple static pressure probe with four orthogonal orifices (0.010 in. diam) located on the probe body which was 0.063 in. o.d. The advantage of using this type of sampling probe under the present test conditions was that the pressure in the probe line remained essentially constant over the total traversing range of the probe. The second type of sampling probe used was the conventional impact, or total pressure, variety. This probe had an inlet orifice diameter of 0.020 in. and a probe o.d. of 0.125 in. This probe provided better spatial resolution than the first probe, but was subjected to large changes in total pressure in the combustor flowfield, especially in the region just downstream of the dump station. A third probe was used for gas sampling at the exit of the combustor exhaust nozzle. It was also a single-orifice impact type with a sampling orifice diameter of 0.010 in. The position of this probe remained fixed on the axis of the dump combustor and was used alternatively with the traversing probe by means of a rotating valve connection in the probe line leading to the QMS system.

## Test Results

As already noted in the Introduction, the intent of this effort was to perform a comprehensive series of experimental tests for the purpose of obtaining a broad research data base pertinent to the fluid dynamic nature of sudden-expansion dump combustors. Most of the attention was directed toward the study of a simple dump combustor configuration without mechanical devices which might be used for enhanced flame stabilization. The nominal test conditions for these baseline experiments are given in Table 2. Tests were also conducted with various devices installed in the air inlet just ahead of the dump station. These experiments were made to obtain comparative test data, primarily in the area of simulated fuel-air mixing, as a basis for making preliminary performance evaluations for several flameholder configurations of interest. Results from these tests will be discussed briefly following the general presentation of test results for the baseline sudden-expansion dump combustor configuration.

#### Flow Visualization

Since the primary objective of this particular effort was to characterize, in an overall sense, the complex nature of an axisymmetric sudden-expansion flowfield, it was considered essential to perform some type of flow visualization. The present test facility arrangement did not lend itself to the use of water or liquid dye injection as fluid flow tracers. Such flow visualization techniques have been used by several investigators in studying recirculating flowfields produced by discontinuous area changes in two-dimensional and axisymmetric flow channels.[6-9]

The technique utilized was that of surface oil flow. The oil was a high-viscosity silicone type which had been tinted with titanium dioxide. Surface oil flow experiments were performed by placing an array of small oil "dots" on the inside surfaces of four contoured wall plugs. These plugs were then mounted in the access ports of the dump combustor, just prior to the performance of a test run. Typical flow visualization results which were obtained from cold flow tests are shown in Fig. 4. To properly interpret the oil flow patterns of Fig. 4a, one should imagine that the axisymmetric dump combustor configuration has been cut along a vertical plane, with the resulting half-sections being folded open from the top.

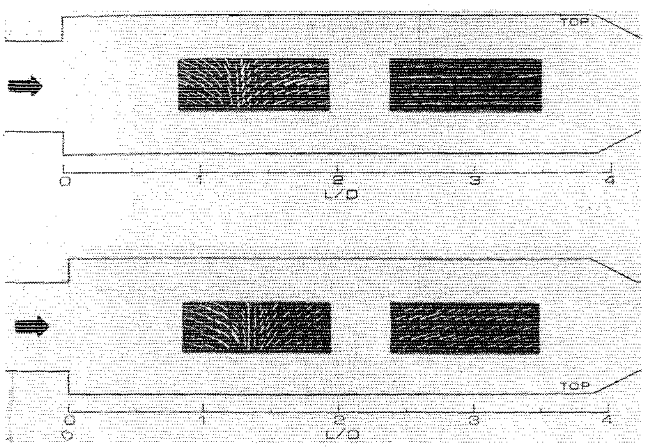
As can be seen in Fig. 4a, the region of flow recirculation and reattachment is quite well-defined. It is also obvious from these results that the recirculating flow, if viewed in the downstream direction, is rotating about the duct axis in a clockwise direction. Since the surface area of a front wall plug did not cover the complete axial length of the recirculation region, several tests were performed with oil "dots" applied in the front portion of the combustor duct, as shown in Fig. 4b. This photographic view was taken through an open front wall port, looking diagonally across the combustor duct into the dump station region. In Fig. 4b, a composite flow

**Table 1 Dump combustor test geometry**

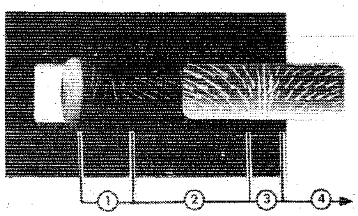
| Component | Length, in. | Diameter, in. | Area ratio relative to combustor |
|---|---|---|---|
| Inlet | 12.5 | 2.50 | 0.42 |
| Combustor | 15.1 | 3.84 | 1.00 |
| | 1.5 | 2.00 | 0.27 |
| Nozzles | 1.5 | 2.50 | 0.42 |
| | 1.5 | 3.00 | 0.61 |

**Table 2 Nominal conditions for inlet air**

| Parameter | $D^* = 2.0$ in. | $D^* = 2.5$ in. | $D^* = 3.0$ in. |
|---|---|---|---|
| Total pressure, psia | 30.5 | 30.5 | 30.5 |
| Static pressure, psia | 27.0 | 22.0 | 16.0 |
| Mach number | 0.42 | 0.70 | 1.0 |
| Velocity, f/s | 450 | 720 | 1010 |
| Mass flow, lbm/s | 2.2 | 3.4 | 3.4 |




a) Overall flow pattern.




b) Dump station flow pattern.

**Fig. 4 Surface oil flow visualization results.**

visualization result has been obtained by combining the oil flow pattern for the dump station region with that for the front wall plug. Four distinct flow regions have been denoted on Fig. 4b. These are: 1) the circumferential rotational flow region near the dump station, 2) the axial recirculation flow region, 3) the flow attachment region, and 4) the downstream-developed flow region. Measurements of overall recirculation zone lengths $L'$ were made from surface oil flow visualization results for the three test cases given in Table 2. Values for $L'$ of 5.1, 5.4, and 6.0 in. were determined for tests with combustor nozzle diam of 2.0, 2.5, and 3.0 in., respectively, at an inlet air total pressure of 30 psia. The accuracy of these measurements is felt to be on the order of $\pm 0.1$ in. for the first two, and about $\pm 0.2$ in. for the latter.

Based on results from the present effort, along with data from Refs. 7-9, the variation of recirculation zone length with sudden-expansion step height $h$ for axisymmetric configurations was found to occur as shown in Fig. 5, where the combustor duct diameter has been used as a normalizing parameter. As shown in Fig. 5, it is possible to bracket the data with two linear relationships for the variation of recirculation zone length with step height. These empirical relations can be expressed as

$$L' = 7.9\, h \tag{1}$$

and

$$L' = 9.2\, h \tag{2}$$

The slight change in the dependency of recirculation zone length on step height between Eqs. (1) and (2) is due, it is felt, to the secondary influence of inlet flow Mach number or perhaps Reynolds number. Equation (1) is considered applicable at lower inlet flow Mach numbers of about 0.5, whereas Eq. (2) would be used for higher inlet flow Mach numbers near 0.9. The Reynolds number (based on the inlet diameter) for the inlet test conditions given in Table 2 ranges from approximately $1.3 \times 10^6$ at $D^* = 2$ in. up to $2.2 \times 10^6$ at $D^* = 3.0$ in.

Although the surface oil flow results obtained in the present effort are qualitative in nature and limited to the flowfield at

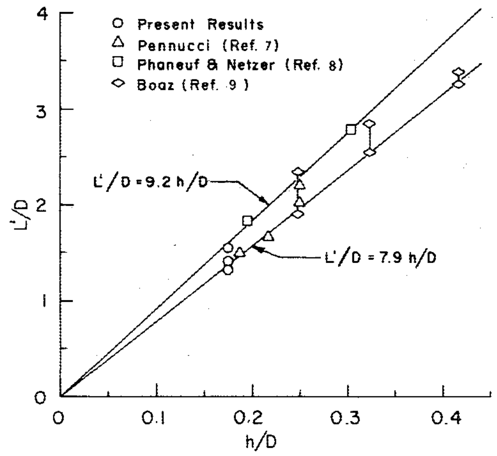



**Fig. 5 Variation of recirculation zone length with dump station step height.**

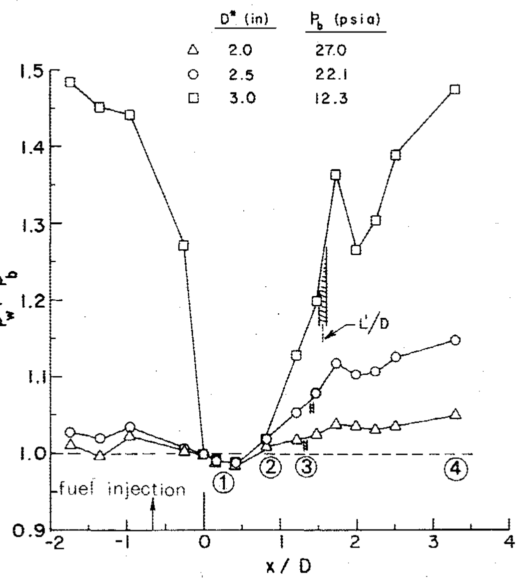



**Fig. 6 Normalized wall static pressure results.**

the wall surface of the combustor duct, these results do provide significant insight as to the overall nature of the dump combustor flowfield. Furthermore, it is felt that the recirculation zone length is more clearly defined by the surface oil flow technique than by water droplet or liquid dye injection into highly turbulent flowfields.

### Pressure Measurements

As mentioned previously, wall static pressures were measured at eighteen positions on the air inlet and combustor sections. Four of these positions were located orthogonally on the sudden-expansion wall surface at a radial distance midway between the radii of the air inlet section and the combustor duct. A very slight, but repeatable and regular, static pressure variation of approximately $\pm 0.15$ psia was observed for a full 360 deg sweep around the base wall surface. The average value of the four measured base static pressures has been used as a normalizing parameter in plotting the axial distributions of wall static pressure, which are given in Fig. 6 for the three different combustor nozzle options. In tests with the 2.0 and 2.5 in. combustor nozzles, the inlet airflow was subsonic and the nozzle flow was choked. For the 3.0 in. combustor nozzle, flow choking occurred in the air inlet section, thus resulting in a characteristically different wall static pressure profile. Although the latter case is not regarded as being particularly typical of nominal operating conditions for the ramjet combustor, it does represent a condition that might occur in

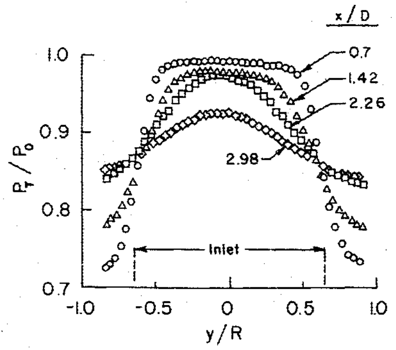



**Fig. 7 Normalized total pressure profiles for $D^* = 2.5$ in. and $P_0 = 30.5$ psia.**

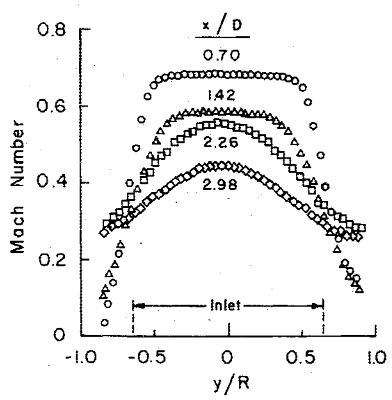



**Fig. 8 Flow Mach number profiles for $D^* = 2.5$ in.**

certain isolated situations. The very large axial variation of wall static pressure in both the air inlet section and the combustor must indeed be taken into consideration when attempting to analyze and predict ramjet performance for the case of high-subsonic inlet Mach number.

It is of interest to note in Fig. 6 that the position of maximum wall static pressure occurs well downstream of the flow reattachment region for each of the three test cases. There does, however, appear to be a slight characteristic increase in axial static pressure gradient, which seems to occur in the vicinity of the flow reattachment region. This is then followed by a change from a positive to a negative pressure gradient and back again to positive as one proceeds further downstream along the duct wall. The four flow regions, which were indicated on the composite flow visualization result in Fig. 4b, are also denoted in Fig. 6. There appears to be a slight initial decrease in wall static pressure in region 1, followed by a nearly linear increase through regions 2 and 3, with the slight increase in pressure gradient occurring as previously noted.

Since it is impossible to present and discuss adequately all of the results obtained for the three different combustor nozzles, the remainder of the paper will be confined to a detailed consideration of test results which were obtained using the 2.5 in. nozzle. It is felt that the important features of the axisymmetric sudden-expansion dump combustor flowfield will be adequately demonstrated by these data.

Radial profiles of normalized total pressure are shown in Fig. 7 for various axial locations in the combustor duct. Flow Mach number profiles, which were determined from measurements of total and static pressures, are given in Fig. 8. It should be noted that the profiles for $x/D = 0.70$ and $x/D = 1.42$ are both upstream of the flow attachment position and, hence, pass through the flow recirculation region. The large radial gradient in total pressure and flow Mach number in the viscous shear layer region, which is bounded by the inner inviscid core flow from the inlet and the outer flow

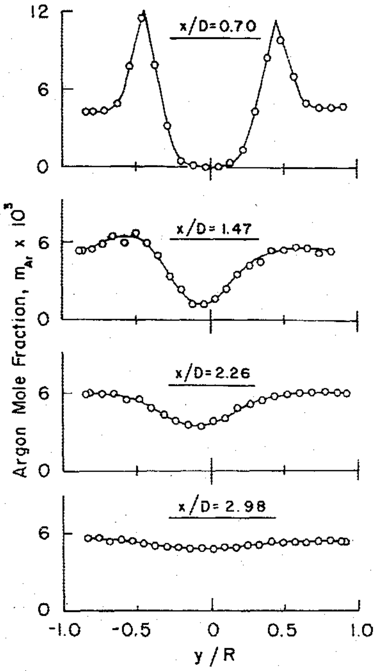



**Fig. 9 Argon concentration profiles for $D^* = 2.5$ in. and $P_{0F} = 129$ psia.**

recirculation region, is obvious from these profiles in Figs. 7 and 8. As will be pointed out later, these results, along with data obtained from flow visualization and gas-sampling tests, will be used to form a composite flowfield structure for the region downstream of the dump station.

#### Gas-Sampling Results

Gas-sampling measurements were performed as part of this research effort for the purposes of 1) demonstrating the operational capabilities of the on-line real-time gas analysis system described earlier, and 2) obtaining preliminary cold flow mixing data for a basic fuel injection arrangement pertinent to dump combustor development for integral rocket-ramjets. Pure argon (commercial grade) was used as a tracer gas substitute for injected fuel in these preliminary mixing experiments. The presence of a known percentage (0.934%) of argon in atmospheric air, which is compressed and used as test air, provides a "built-in" calibration standard in this situation.

Radial and axial concentration profiles of injected argon are shown in Figs. 9-11 for experimental tests with $D^* = 2.5$ in. The radial profiles of argon mole fraction, shown in Fig. 9, were obtained at a nominal argon injection pressure of 129 psia using the side-orifice (i.e., static pressure type) sampling probe described earlier. The radial line of probe traverse for all gas-sampling measurements was always taken in a plane intersecting two of the eight circumferential fuel injection orifices. Gas-sampling measurements with the total pressure type sampling probe were found to be in excellent overall agreement with those obtained using the side-orifice probe. A slight discrepancy was observed in the regions of peak argon concentration at $x/D = 0.7$, which can be attributed to the sudden decrease in total pressure felt by the one sampling probe but not by the other at this radial position. Since a sudden change of pressure in the sampling line to the QMS might induce a transient in instrument sensitivity, the side-orifice sampling probe is considered to be more reliable in this particular region of the flowfield.

As can be seen in Fig. 9, the injected argon concentration is essentially uniform (i.e., fully mixed) at the last downstream axial position of $x/D = 2.98$. The approach to a fully mixed condition for the simulated fuel-air flowfield is further indicated by the results given in Fig. 10 for the centerline

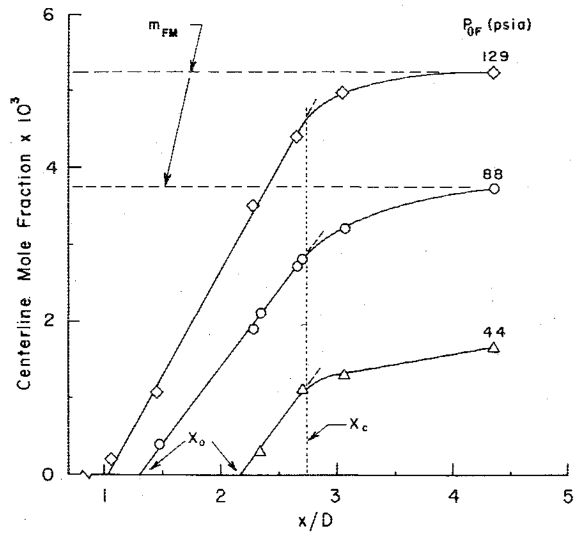



Fig. 10 Centerline argon concentration results for $D^* = 2.5$ in.

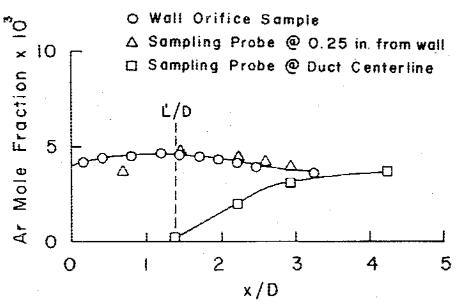



Fig. 11 Axial variation of argon concentration along combustor wall and centerline.

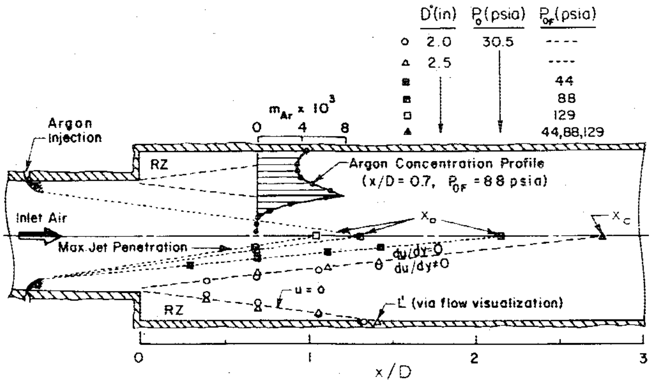



Fig. 12 Composite flowfield characterization for sudden-expansion dump combustor.

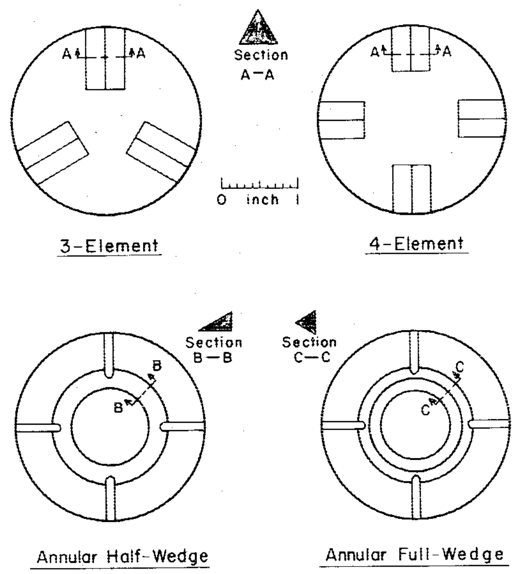



Fig. 13 Flameholder configurations.

concentration of injected argon. There are several interesting features about these data which should be noted. The first of these is the linear increase of argon concentration along the duct centerline from the axial position denoted as $x_0$ up to the position denoted as $x_c$. This region is interpreted as one of purely diffusional mixing of the injected argon in the inviscid core region of the inlet airflow. The departure from linearity, which occurs at the axial location indicated as $x_c$, is obviously independent of argon injection pressure, and thus signals a change in the primary dump combustor flowfield. Beyond this point, the centerline concentration of argon increases at a slower rate and approaches a fully mixed condition in an asymptotic manner.

The gas concentration data shown in Fig. 11 provide further insight into the simulated fuel-air mixing pattern for the sudden-expansion dump combustor. As can be seen from this plot, the argon concentration in the primary flow recirculation region is essentially uniform and quite high as compared to the duct centerline. As before, the approach to a fully mixed condition in the downstream region of the combustor duct is indicated. The wall-orifice gas samples were obtained by connecting the QMS sampling line to the individual static pressure ports along the combustor duct wall.

**Basic Flowfield Characterization**

A composite plot showing dump combustor flowfield characteristics which have been derived from the various test data obtained in this effort is shown in Fig. 12. In the lower half of this plot, interfaces are delineated for the regions of inviscid core flow ($du/dy = 0$), shear flow ($du/dy \neq 0$), and reverse flow ($RZ$) for the dump combustor flowfield just downstream of the dump station. Also, the approximate jet penetration boundaries for the injected argon are indicated for the three injection pressures. A radial concentration profile for injected argon (measured at $x/D = 0.7$) is given in the upper half of Fig. 12. The correlation of this profile with the flowfield interfaces is indicated by lines of projection to the actual traversing plane. The maximum concentration of injected argon occurs at a radial position corresponding to the interface between the inviscid core flow region and the shear flow region. As one moves from this position toward the duct wall, the argon concentration appears to decay to a nearly constant level in the flow recirculation zone. It is apparent from the composite plot in Fig. 12 that the sudden-expansion dump combustor flowfield is indeed complex in nature and, undoubtedly, will be difficult to model mathematically. The significance of these basic flowfield tests results as related to ramburner performance will be discussed later in this section.

**Tests with Flameholders**

Since it may be necessary to use mechanical flameholding devices to augment flame stabilization and combustor performance in short $L/D$ (<5) dump combustors, experimental tests were also conducted with several representative flameholder configurations installed in the basic dump combustor hardware. Schematic illustrations of the flameholder configurations tested are shown in Fig. 13. These devices are mounted in the air inlet section just ahead of the dump station. The rear surface of each flameholder element actually lies in the sudden-expansion plane at the inlet/combustor interface. The geometric blockage to the air inlet was held constant at a nominal 25% of total inlet area for all flameholder configurations.

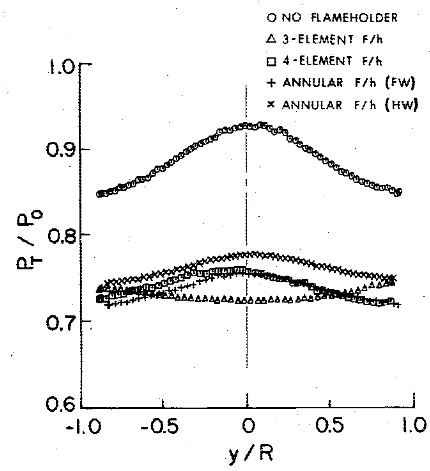



Fig. 14 Normalized total pressure profiles for $x/D = 2.98$.

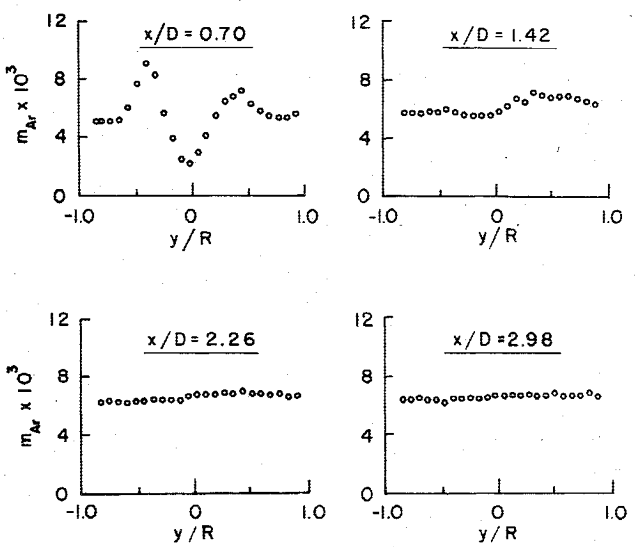



Fig. 15 Argon concentration profiles for annular FW flameholder.

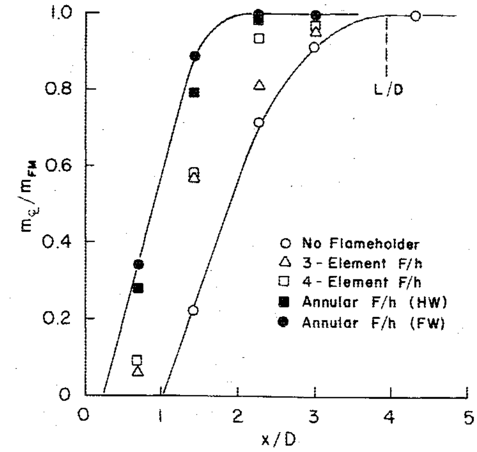



Fig. 16 Normalized argon concentration results for tests with and without flameholders.

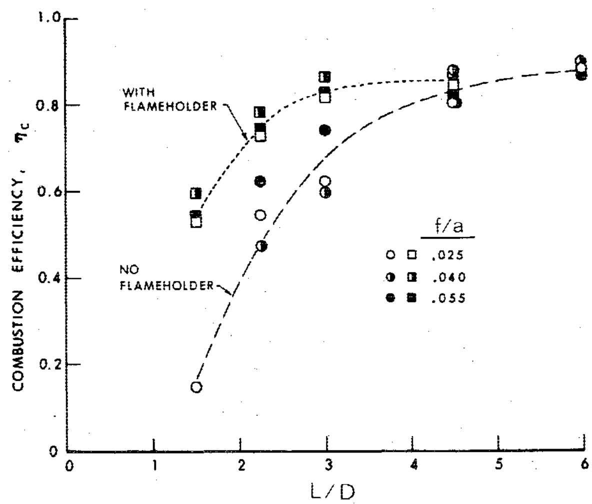



Fig. 17 Ramburner performance as a function of combustor L/D (Ref. 11).

Some of the results obtained from tests with flameholders are given in Figs. 14-16. All of the tests with flameholders were performed using the 2.5 in. combustor nozzle. In Fig. 14, the effect of flameholders on total pressure recovery in the dump combustor is indicated for the axial position corresponding to $x/D = 2.98$. As can be seen, there is an additional total pressure loss of approximately 15%, as compared to the case with no flameholder. It is also of interest to note that the three-element flameholder configuration appears to result in a slightly higher loss than for the other three configurations.

The primary motivation in testing the various flameholder configurations was to determine their effect on simulated fuel-air mixing in the dump combustor. Radial concentration profiles of injected argon for tests with the annular full-wedge (FW) configuration are shown in Fig. 15. The considerable enhancement of simulated fuel-air mixing (Fig. 9) is demonstrated by the fact that an essentially fully mixed condition is achieved in approximately 1.5 duct diameters. A relative comparison of simulated fuel-air mixing for all test configurations is made in Fig. 16. In this figure, the fully mixed mole fraction of injected argon (Fig. 10) has been used as a normalizing parameter for establishing centerline mixing profiles for the various test cases. As can be seen in Fig. 16, the axial length required to achieve complete mixedness is reduced by a factor of at least two for the test case involving the annular FW flameholder as compared to the case with no flameholder.

### Correlation with Ramburner Performance

The ultimate question one is faced with in the interpretation of cold flow data, such as obtained in this effort, is their significance relative to actual combustor performance. Clearly, there are limitations as to the degree of applicability which can be reasonably assumed. The usefulness of simulated combustor flowfield results, as a basis for gaining insight relative to the reacting flowfield, can only be established by direct confrontation of experimental data.

Therefore, an attempt has been made to correlate some of the present results with combustor performance data from direct-connect ramburner tests which have been reported by Stull et al.[10,11] Plots of combustion efficiency, as a function of combustor L/D, are given in Fig. 17 for ramburner tests with and without a flameholder. The results of Fig. 17 were obtained for a baseline test configuration having a 2.5 in. diameter air inlet and 5.0 in. diameter combustor sections of various lengths. Liquid hydrocarbon fuel (JP-4) was injected through eight circumferential wall injectors at a distance of one inlet duct diameter upstream of the dump station. Determination of combustion efficiency was based on the ratio of ramburner stagnation temperature rise (computed from ramburner thrust measurements) to the ideal total temperature rise (computed from equilibrium chemistry calculations for the measured fuel-air ratio, f/a).

Even though the combustor test configurations used by Stull and his co-workers are not completely compatible with the present hardware, the similarities are such as to provide a

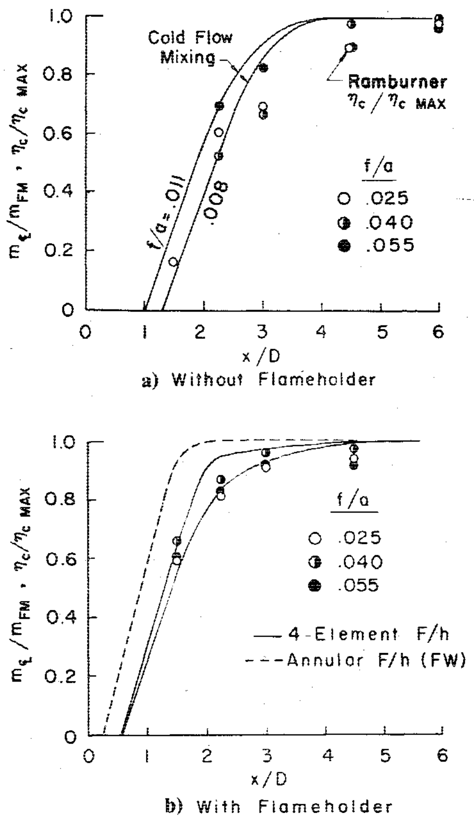



Fig. 18 Correlation of cold flow mixing with ramburner performance.

reasonable basis for correlation of test results. In particular, it was of interest to make a correlation between simulated fuel-air mixing under cold flow conditions and ramburner performance as a function of combustor L/D. Such a correlation is made in Fig. 18, where the normalized centerline concentration of injected argon is compared with the combustion efficiency results of Fig. 17, which have also been normalized on the basis of the maximum combustion efficiency achieved at the highest combustor L/D of 6. A value of 0.9 was assumed as the maximum combustion efficiency for this case. It is quite apparent in Fig. 18 that the trends in ramburner performance as a function of combustor L/D can be correlated with respect to the simulated fuel-air mixing profiles from the cold flow tests.

## Conclusions

Basic flowfield studies pertinent to axisymmetric, sudden-expansion ramjet combustor configurations have been performed under cold flow conditions. The results obtained from this effort provide the basis for the following conclusions:

1) The flowfield just downstream of the dump station in the region of primary flow recirculation and reattachment is quite complex. The circumferential flow rotation observed in this region is not considered to be attributable to inlet flow swirl.

2) Simulated fuel-air mixing data for the baseline dump combustor configuration indicated the need for a combustor L/D in excess of 4 to obtain complete mixing. The addition of an annular wedge-shaped flameholder at the dump station reduced the axial length required to achieve complete mixing by a factor of more than 2, but with an increased loss in total pressure.

3) Direct correlation between cold flow mixing and ramburner combustion efficiency has been made as a function of combustor L/D. The usefulness of cold flow mixing data in predicting overall combustor performance trends for mixing-limited configurations is apparent.

4) The detailed fluid dynamic flowfield characterization resulting from this investigation has provided additional insight into the complexities of dump combustor configurations, which will be particularly useful to those pursuing the task of mathematical modeling in this area of research and development.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