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MEASURED EFFECTS OF GASEOUS FLOW SYSTEM DYNAMICS ON ACOUSTIC-MODE COMBUSTION INSTABILITY

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ABSTRACT

Experiments in which hydrogen injection geometry was changed in a T-burner combustor demonstrated that hydrogen flow system dynamics can influence acoustic-mode instability. Stability boundaries for the combustor were shifted by changing the hydrogen manifold volume and by changing the amount of propellant stream interaction. The results were compatible with stability boundaries calculated from a combustor response model if the time delay, which was assumed to exist between injection and combustion of the hydrogen, varied with propellant flow rates.

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SUMMARY

Combustion instability characteristics of a gaseous-hydrogen, liquid oxygen T-burner were experimentally determined in order to measure the influence of hydrogen flow system dynamics on acoustic-mode instability. Changes in the hydrogen injector geometry were made and the stability boundary as a function of propellant flow rates was determined for each configuration. The results were analyzed in terms of a linear, lumped-parameter analysis of the hydrogen flow system which is incorporated in an overall combustor stability criterion.

A change in the hydrogen manifold volume corresponding to a change in the gain of the flow system shifted the stability boundary and demonstrated that flow system dynamics can influence acoustic-mode instability. Changing from parallel jet to coaxial injection also altered stability emphasizing the importance of the combustion dynamics associated with propellant stream interaction. The results were compatible with stability boundaries calculated from a combustor response model if the time delay, which was assumed to exist between injection and combustion of the hydrogen, varied with propellant flow rates.

INTRODUCTION

Oscillations in propellant flow rate associated with feed system dynamics are known to be a driving mechanism for low-frequency, "chugging" modes of instability where chamber pressure in the combustor responds uniformly. The effects of flow rate oscillations on high-frequency, acoustic-mode instability have not been so well-defined. A particular case of interest is the dynamic flow response of a gaseous propellant such as hydrogen. An acoustic mode instability criterion based on hydrogen flow system response has been used to correlate the stability behavior of some hydrogen-oxygen engines (refs. 1 and 2). In those studies, a linearized, lumped-parameter analysis of the injector was combined with a stability criterion based on a sum of response factors or admittances for the hydrogen, oxygen, and nozzle. The response factor is defined as the magnitude of flow rate perturbations in phase with pressure perturbations. A time delay between the injection of a fuel mass element and its effective wave coupled combustion was introduced in the analysis.

In the present case, the stability characteristics of a gaseous-hydrogen, liquid oxygen T-burner were determined experimentally. The primary objective was to measure the effects of flow system dynamics on acoustic-mode instability produced by changes in injector geometry. A secondary objective was the comparison of the experimental results with the effects predicted by the lumped-parameter analysis.

COMBUSTOR RESPONSE MODEL

Flow System Dynamics

A summary of the linearized, lumped-parameter model of the flow system response is given below. The equations are those developed in reference 1 with the restriction that only an orifice entrance pressure drop is considered. Important variables and geometric parameters in the model are shown on the flow system schematic in figure 1. A constant flow rate of hydrogen is assumed to enter a manifold volume V. Gas is injected into the chamber through orifices of length L and area A. Oscillations in chamber pressure, P_c, produce flow rate oscillations at the orifice exit. The oscillations occur at an acoustic mode frequency ω determined by the chamber gas properties and geometry. Burning rate oscillations, $\dot{m}_b'$, are linked to flow rate oscillations at the orifice exit

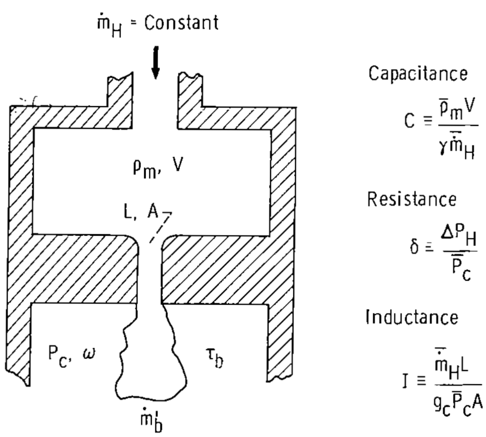


Figure 1. - Hydrogen flow system schematic.

by assuming that a simple time delay, τ_b, exists between injection and combustion. The parameter groupings in terms of electrical analogs given in figure 1 are: a capacitance associated with manifold compliance, a resistance associated with pressure drop in the orifice, and an inductance associated with the inertia of the slug of mass in the orifice. The model is basically a Helmholtz resonator with the additions of a constant mass flow entering the cavity and an oscillatory output delayed by τ_b. The resulting response is given by a gain:

$$\left|\frac{\dot{m}_b'}{P_c'}\right| = \frac{1}{\sqrt{R^2 + X^2}} \tag{1}$$

and a phase angle:

$$\varphi = \pi + \tan^{-1}\left(\frac{X}{R}\right) - \omega\tau_b \tag{2}$$

where:

$$R \equiv \frac{2\delta}{1 - \frac{\delta}{\gamma}} \tag{3}$$

$$X \equiv \omega_o I\left(\frac{\omega}{\omega_o} - \frac{\omega_o}{\omega}\right) \tag{4}$$

and the resonant frequency is:

$$\omega_o = \sqrt{\frac{1 + \delta}{CI\left(1 - \frac{\delta}{\gamma}\right)}} = \frac{a_m}{\sqrt{V \frac{L}{A}\left(1 - \frac{\delta}{\gamma}\right)}} \tag{5}$$

The response factor or in-phase portion of $\dot{m}_b'/P_c'$ for the hydrogen system is given by:

$$N_H = \left|\frac{\dot{m}_b'}{P_c'}\right| \cos\varphi \tag{6}$$

The expression for R given in equation (3) results from considering that the mass flow rate is proportional to $(\rho \, \Delta P_H)^{1/2}$. For a particular combustor geometry, the pressure ratio δ has an inverse dependence on the characteristic exhaust velocity efficiency η and the oxidant-fuel ratio O/F. An augmented or effective orifice length is often used but is neglected here because of the undetermined effect of steady flow through the orifices.

Stability Criterion

A combustor is considered neutrally stable when the summation of losses and gains of acoustic energy is zero. In reference 1 this criterion is expressed as a weighted sum of response factors:

$$\sum \mu_i N_i = 0 \tag{7}$$

In equation (7), the weighting factor μ_i is the fraction of the total mean flow rate involved in the i^{th} process. If the particular processes considered are associated with the separate injection flows of hydrogen and oxygen and the combined flow through a nozzle, equation (7) becomes:

$$\left(\frac{1}{1 + O/F}\right) N_H + \left(\frac{O/F}{1 + O/F}\right) N_O + N_N = 0 \tag{8}$$

EXPERIMENTAL STABILITY CHARACTERIZATION

T-Burner Combustor

The experiments were conducted with a hydrogen-oxygen T-burner shown schematically in figure 2. This center-vented geometry was chosen to minimize nozzle losses for the first longitudinal mode by placing the exhaust nozzle at a pressure node. Gaseous-hydrogen at room temperature and liquid oxygen were injected at one end of the chamber. The opposite end was solidly closed and a multi-orifice nozzle was located midway between the two ends.

During instability, measured pressure oscillations were 180° out of phase at the two ends; and the amplitudes at 2 inches (5.08 cm) either side of the nozzle were less than

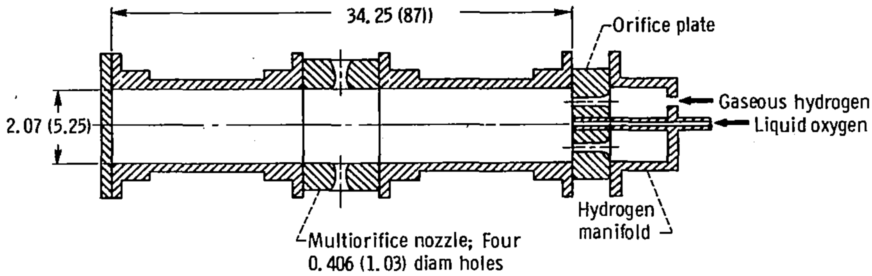
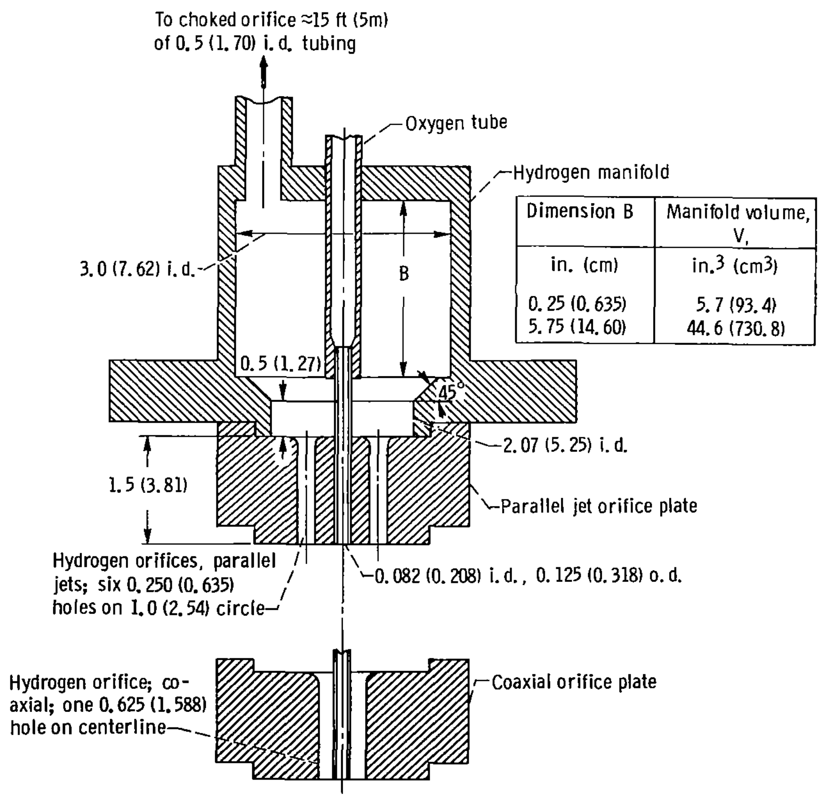


Figure 2. - Gaseous-hydrogen, liquid-oxygen T-burner. (All dimensions are in inches (cm). See fig. 3 for injector details.)

10 percent of the amplitude at the injector. These observations indicated a first longitudinal mode of oscillation as expected. The amplitudes at the closed end were two to three times the amplitudes at the injector end.

Injector Geometry Variations

The injector, shown in detail in figure 3, was assembled from three separate com-



Dimension B	Manifold volume, V,
in. (cm)	in.^{3} (cm^3)
0.25 (0.635)	5.7 (93.4)
5.75 (14.60)	44.6 (730.8)

Figure 3. - Injector details. (All dimensions are in inches (cm) unless otherwise noted.)

ponents. They were an orifice plate containing the hydrogen orifices which fixed the values of orifice length L and cross sectional area A; a manifold assembly which determined the volume V; and a single oxygen tube which was inserted through both pieces. The hydrogen was supplied to the manifold through a choked orifice to provide a constant input flow.

Injector geometry was varied in two ways while orifice length and area were held constant at L = 1.5 inches (3.81 cm) and A = 0.295 square inch (1.903 cm^2). Manifolds with volumes of either 5.7 cubic inches (93.4 cm^3) or 44.6 cubic inches (730.8 cm^3) were tested; and orifice plates with either six 0.250-inch (0.635-cm) diameter hydrogen orifices surrounding the oxygen jet or a single 0.625 inch (1.59-cm) diameter coaxial hydrogen orifice were used.

Tests of injectors which differed only in the size of the manifold provided a direct indication of the flow system's influence on stability. The frequency response for the two manifolds was calculated from equation (1) and is shown in figure 4. Specifying values of α, T_H, O/F, and η is equivalent to a specification of the resistance parameter δ. The larger volume which corresponds to the lower resonant frequency of 544 hertz has a much larger gain in the neighborhood of 300 hertz where the experiments were conducted.

Tests which compared combustor stability for the parallel jet and coaxial injection orifice plates indicated the influence of hydrogen-oxygen stream interaction. Runs in

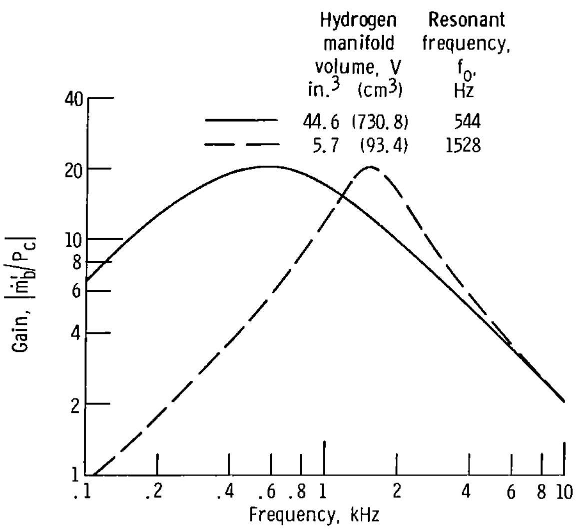


Figure 4. - Frequency response of hydrogen flow system for two manifold volumes. Hydrogen orifice area, A = 0.295 square inch (1.903 cm^2); orifice length, L = 1.5 inch (3.81 cm); oxidant to fuel flow rate ratio, 3.0; characteristic exhaust velocity efficiency, η = 85 percent; hydrogen orifice to exhaust nozzle area ratio, α = 0.569; hydrogen temperature, T = 520° R (289 K); specific heat ratio, γ = 1.4.

which orifice length, orifice area and manifold volume were constant were of particular significance in terms of the stability model. In those cases variations in stability behavior associated with propellant stream interaction must represent changes in oxygen response and/or delay time.

Determination of Stability Boundaries

Stability of each injector configuration was determined by varying propellant flow rates to determine a stability boundary by the method illustrated in figure 5. At a constant hydrogen flow rate, the value of oxygen flow rate where oscillation amplitude equaled 0.2 defined the stability boundary. The value of 0.2 represented a level slightly above the random chamber pressure oscillations measured at the closed end of the chamber. From such pairs of hydrogen and oxygen flow rate values at the stability boundary, stability maps in the flow rate plane were determined for each configuration.

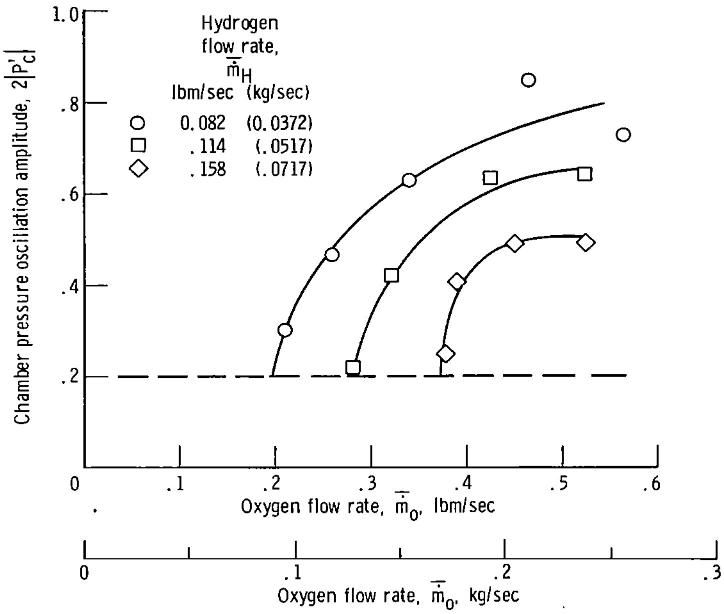


Figure 5. - Sample pressure amplitude plot used to determine stability boundary. Hydrogen manifold volume, 5.7 cubic inch (93.4 cm³); parallel jets.

RESULTS AND DISCUSSION

Manifold Volume Effects on Stability

The stability map for the small manifold volume and parallel jet injection is shown in figure 6. Lines of constant O/F and chamber pressure are included. The average values of characteristic exhaust velocity efficiency and frequency along the boundary were 85 percent and 300 hertz, respectively. In this case the stability boundary lies along a constant O/F line at a value of 2.5 and will be used as the basis for stability comparisons. Note that the combustor was unstable at values of O/F greater than 2.5.

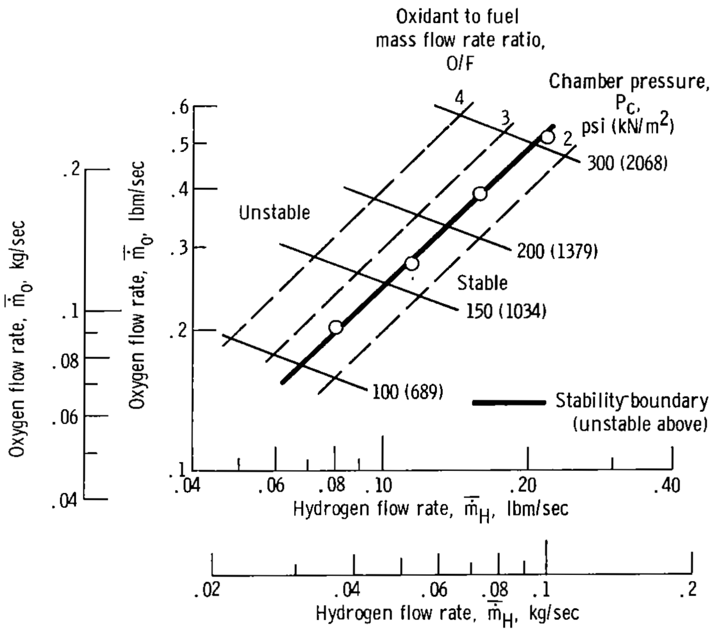


Figure 6. - Stability map for parallel jets. Hydrogen manifold volume, 5.7 cubic inches (93.4 cm^3).

Stability boundaries for the 5.7-cubic inch (93.4-cm^3) and 44.6-cubic inch (730.8-cm^3) manifold volumes with parallel jet injection are shown superimposed in figure 7. Enlarging the manifold volume shifted the stability boundary at lower hydrogen flows to higher values of oxygen flow rate and enlarged the range of stable operation. Since this result was produced by a change in upstream flow system geometry, it represents a direct experimental confirmation that flow system dynamics influence acoustic-mode stability behavior.

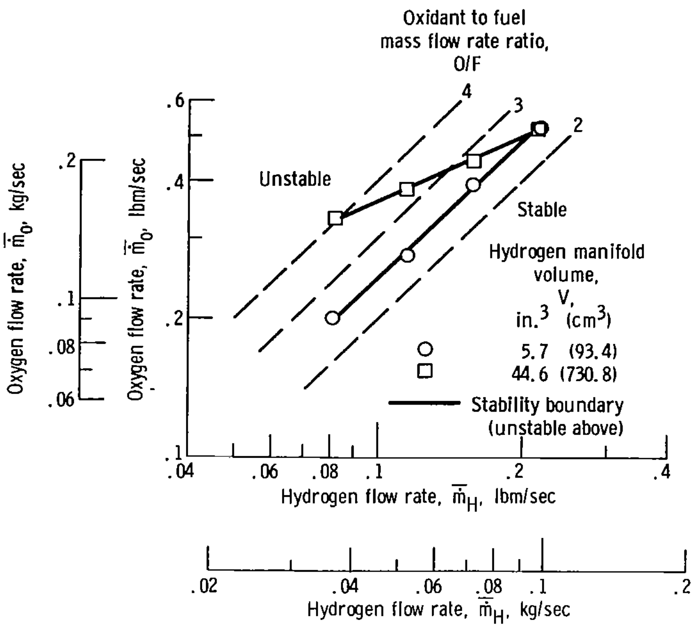


Figure 7. - Effect of manifold volume on stability. Parallel jets.

Comparison with Response Model

The stability boundary data for the two manifold volumes were compared with boundaries calculated from the response model and stability criterion summarized previously. The analysis had originally been applied to stability data obtained by varying hydrogen injection temperature at fixed propellant flow rates (refs. 1 and 2). Oxygen response, time delay, frequency and combustion efficiency were assumed to be constant. With these assumptions and the use of zero nozzle response due to the nozzle being located at a pressure node, agreement between calculated and measured boundaries was obtained for the small manifold volume. However, such a comparison failed to show agreement with the data for the large manifold volume in two respects. First, all stability boundaries were predicted to be constant O/F lines; and second, the predicted relation of the stable and unstable regions to the boundary was opposite to that observed.

Allowing the time delay τ_b to vary along the large volume boundary as shown in figure 8, produced agreement between calculated and observed behavior. The location of the stability boundary in the flow rate plane is seen to be very sensitive to the magnitude of τ_b. Oxygen response was held constant at a value of 0.81 determined by the common point on the two boundaries. The dashed lines in figure 8 are included to indicate that

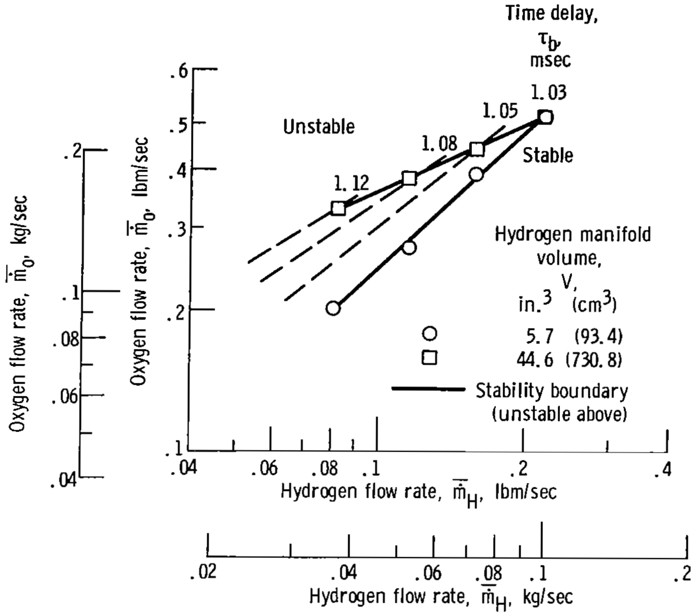


Figure 8. - Values of time delay between injection and combustion of hydrogen mass element determined from combustor response model with oxygen response constant. Oxygen response factor, 0.81; nozzle response factor, zero; frequency, 300 hertz; efficiency, 85 percent.

possible lines of constant τ_b implied by the analysis are not constant O/F lines parallel to the small volume boundary. Values of τ_b are an order of magnitude larger than those used in references 1 and 2 but the delay angle $\omega\tau_b$ is roughly the same. It should be noted that in practice the nozzle probably acts as a small loss due to its finite size, and, therefore, only approximate location at a pressure node (ref. 3). A small negative value of nozzle response would require an upward adjustment in oxygen response but little change in the values of time delay necessary to fit the data.

Propellant Stream Interaction Effects on Stability

The effect on stability of varying the amount of propellant stream interaction is shown in figure 9 for the small manifold volume. A change from low-interaction, parallel jet injection to the greater interaction existing with the coaxial geometry shifted the stability boundary toward higher oxygen flow rates. The average frequency and efficiency along the boundary were 375 hertz and 90 percent, respectively. In this case a change in oxygen response due to the interaction is expected along with variations in time delay. The combination of the large manifold volume with the coaxial faceplate was stable over

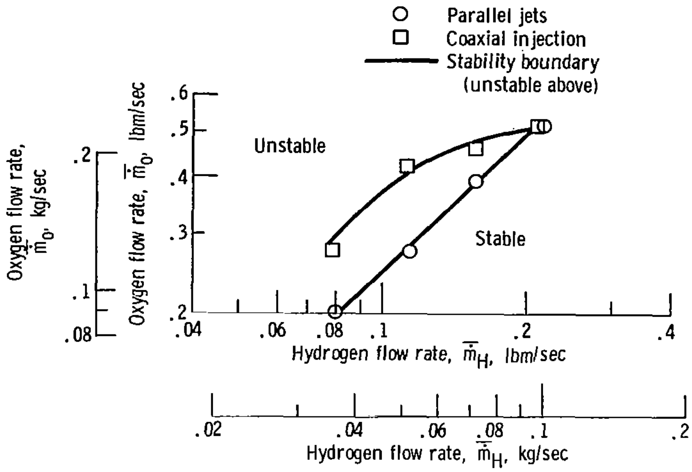


Figure 9. - Effect of propellant stream interaction on stability. Hydrogen manifold volume, 5.7 cubic inch (93.4 cm^3).

the entire range of flow rates tested. This result reconfirms the results of figure 7, which showed that a change in manifold volume alone altered the combustor's stability characteristics.

CONCLUDING REMARKS

For each configuration tested, stability decreased with an increase in O/F which represents a decrease in the resistance parameter δ. This same type of stability dependence on δ was reported in reference 2 for hydrogen-oxygen engines which were stability rated by varying hydrogen injection temperature. In terms of the response model, a decrease in δ lowers the resistance and thereby increases the gain of the flow system (see eq. (1)). Whether the increased gain is realized as driving or damping depends on the magnitude of the time delay τ_b. The predicted location of the stability boundary and the direction of increasing stability are further dependent on the mass weighting coefficient μ_i and the other responses N_i as indicated by equations (7) and (8). These considerations indicate that, for the data reported here, the response model requires rational methods of calculating time delay and oxygen response from a knowledge of operating parameters. Without a method of predicting oxygen response and time delay the analysis simply serves as a method of data correlation which emphasizes the role of flow system response.

SUMMARY OF RESULTS

The experimental investigation of the acoustic mode combustion instability behavior of a hydrogen-oxygen T-burner produced the following results and conclusions regarding the role of hydrogen injection dynamics:

1. Boundaries between stable and unstable operation as a function of propellant flow rates were shifted by a change in the size of the hydrogen manifold volume corresponding to a change in the gain of the flow system. This result demonstrated that hydrogen flow system dynamics can influence acoustic-mode instability.

2. The stability boundary was also shifted by changing from parallel jet to coaxial injection with hydrogen orifice area, orifice length and manifold volume held constant. This result emphasizes the importance of combustion dynamics associated with propellant stream interaction.

3. The results were compatible with stability boundaries calculated from a combustor response model if the time delay, which was assumed to exist between injection and combustion of the hydrogen, varied with propellant flow rates.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 11, 1968,
126-15-01-25-22.

APPENDIX - SYMBOLS

A	hydrogen orifice area, in.^{2}; m^2
a	isentropic speed of sound; in./sec; m/sec
C	capacitance parameter, $\overline{\rho}_m V/\gamma \overline{\dot{m}}_H$, sec
f	frequency, Hz
g_c	mass-force conversion factor, 386.09 (lbm)(in.)/(lbf)(sec^2); 1 (kg)(m)/(N)(sec)
I	inductance parameter, $\overline{\dot{m}}_H L/g_c \overline{P}_c A$, sec
L	orifice length, in.; m
$\dot{m}$	mass flow rate, lbm/sec; kg/sec
N	response factor, eq. (6), dimensionless
O/F	oxidant to fuel mass flow rate ratio
ΔP	pressure drop, lbf/in.^{2}; N/m^2
P_c	chamber pressure, lbf/in.^{2}; N/m^2
R	resistance, eq. (3), dimensionless
T	temperature, ^{o}R; K
V	hydrogen manifold volume, in.^{3}; m^3
X	reactance, eq. (4), rad
α	hydrogen orifice to exhaust nozzle area ratio
γ	specific heat ratio
δ	resistance parameter, $\Delta P_H/\overline{P}_c$, dimensionless
η	characteristic exhaust velocity efficiency, percent
μ	fraction of total mean flow rate, dimensionless
ρ	density, lbm/in.^{3}; kg/m^3
τ_b	time delay between injection and combustion of a hydrogen mass element, sec
φ	phase angle, rad
ω	angular frequency, rad/sec
ω_o	resonant angular frequency, rad/sec

Subscripts:

b burning hydrogen

H hydrogen

i i^{th} process

m hydrogen manifold

N nozzle

O oxygen

Superscripts:

$\bar{\ }$ time average

$'$ fractional perturbations about the mean, e.g., $P' = (P - \bar{P})/\bar{P}$

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