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PERFORMANCE AND STABILITY CHARACTERISTICS OF NITROGEN TETROXIDE - HYDRAZINE COMBUSTORS

by Martin Hersch

Lewis Research Center
Cleveland, Ohio

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ABSTRACT

Studies were conducted to determine the effects of various design and operating parameters on storable propellant rocket combustion. An injector incorporating like-on-like doublets forming parallel sheets achieved 95 percent of theoretical performance and gave best stability. Triplet injectors with unlike impingement had poorest stability characteristics. Increasing combustor length improved performance for parallel sheet but not for triplet injection. Effects of contraction ratio, propellant flow rate, and chamber pressure on performance were small. It was concluded that unlike impingement of hypergolic propellants may be an initiating cause of high-frequency instability.

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SUMMARY

Characteristic exhaust velocity and stability characteristics were investigated for small scale combustors burning N_2O_4 and N_2H_4. Variables investigated were injector configuration, combustor length, contraction ratio, propellant flow rate, and chamber pressure. The nominal oxidant-fuel mixture weight ratio was 3. Combustor length varied from 3 to 21 inches (7.62 to 53.3 cm). Chamber pressure varied from 70 to 280 psia (4.82×10^5 to 1.93×10^6 N/m^2). Four injector configurations were used: like-on-like doublets forming parallel sheets, like-on-like doublets forming intersecting sheets, fuel-oxidant-fuel triplets, and oxidant-fuel-oxidant triplets.

High performance, 95 percent or more of theoretical was attained with the doublet injectors by using a long combustor length (21 in. (53.3 cm)). The highest performance attained with the triplet injectors was 92 percent of theoretical. Furthermore, performance with most combustors using the triplet injectors reached a maximum at an intermediate length, and was not improved by increasing the length. A vaporization-limited model gave results which indicated that performance was controlled by the oxidant vaporization rate. The model also indicated that the triplet injectors produced abnormally large drops relative to the jet diameters, which suggested that interfacial hypergolic reactions interfered with impingement of the unlike propellants.

Combustion was most stable with the parallel sheet type injector and least stable with the oxidant-fuel-oxidant triplet type injector. In general, low-frequency instability (chugging) occurred with low flow rates. No high-frequency high-amplitude oscillations (screaming) were observed with the parallel sheet type injector. Spontaneous screaming was observed with the other three injectors. From these results, it is concluded that unlike impingement of hypergolic propellants may initiate high-frequency oscillations.

INTRODUCTION

It has been suggested (ref. 1) that a rocket combustor burning nitrogen tetroxide (N_2O_4) with hydrazine (N_2H_4) be used as a gas generator for simulating the high pressure high-temperature supersonic gas stream required for ground testing of large scale scram-jet combustors. When burned at an oxidant-to-fuel weight ratio (O/F) of about 3, the combustion products approximate air in which water vapor replaces part of the nitrogen. Operational engines exist which burn nitrogen tetroxide with fuels which are substituted hydrazine compounds, or mixtures of these compounds with hydrazine. The substituted hydrazine compounds are generally unsymmetrical dimethyl hydrazine $(CH_3)_2NNH_2$, or monomethyl hydrazine $(CH_3)N_2H_3$. These fuels are undesirable for use in the gas generator application because the combustion products contain carbon compounds. It was found, as reported in reference 1, that injectors which gave stable, high performance with nitrogen tetroxide and a mixture of 50-percent hydrazine and 50-percent unsymmetrical dimethyl hydrazine as the fuel, could not be used with pure hydrazine because high-frequency instability resulted. Baffles could be used, but they present severe cooling and operational problems.

Previous studies (refs. 2 to 4) have shown that interfacial reactions occur at the impingement point of hypergolic propellants, which disturb the injection and subsequent combustion processes. This suggests that the injector configuration may be an important stability controlling parameter in the combustion of hypergolic propellants such as nitrogen tetroxide with hydrazine.

The purpose of this study is to investigate the effects of several injector configurations using nitrogen tetroxide and hydrazine over a range of operating conditions on combustion stability and performance. The results of this study are applicable for either gas generator or rocket propulsion engines. The tests were conducted with small scale, uncooled combustors, using four different injectors. The thrust level ranged from about 100 to 300 pounds (445 to 1330 N), with a nominal O/F range of 2.5 to 3.5. Parameters varied were combustor length, contraction ratio, injector configuration, propellant flow rate, and chamber pressure.

APPARATUS AND PROCEDURE

Combustor

Chamber and nozzles. - Combustion chambers including the convergent portion of the nozzles, were 3 to 21 inches (7.62 to 53.3 cm) long, 2 inches (5.08 cm) in diameter, and had nominal contraction ratios of 1.5 and 3. Convergent nozzle lengths were 1 and

3 inches (2.54 and 7.62 cm). Characteristic length varied from about 7 to 70 inches (17.8 to 178 cm). Thrust, depending upon propellant flow rate and nozzle diameter, varied from about 100 to 300 pounds (445 to 1330 N). Chambers were uncooled stainless steel, and nozzles were water-cooled copper.

Injectors. - Four flat-faced aluminum alloy injectors of the following configurations were used:

Type A:

Eight oxidant-doublets and three fuel-doublets forming parallel sheets

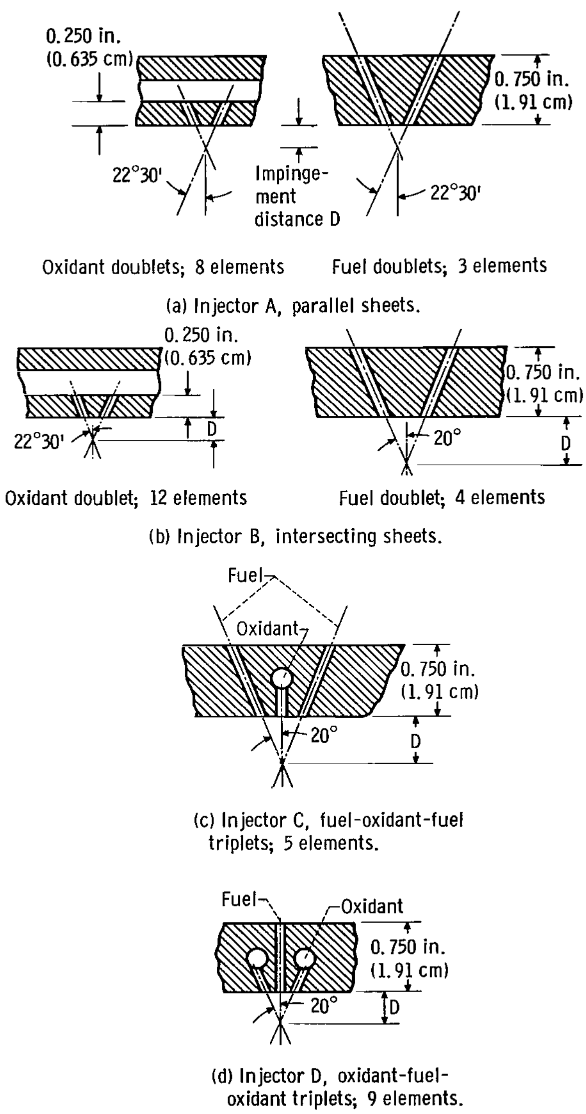


Figure 1. - Sections of injector elements.

Type B:

Twelve oxidant doublets and four fuel doublets, fuel sheets intersecting with oxidant sheets

Type C:

Five element fuel-oxidant-fuel triplets

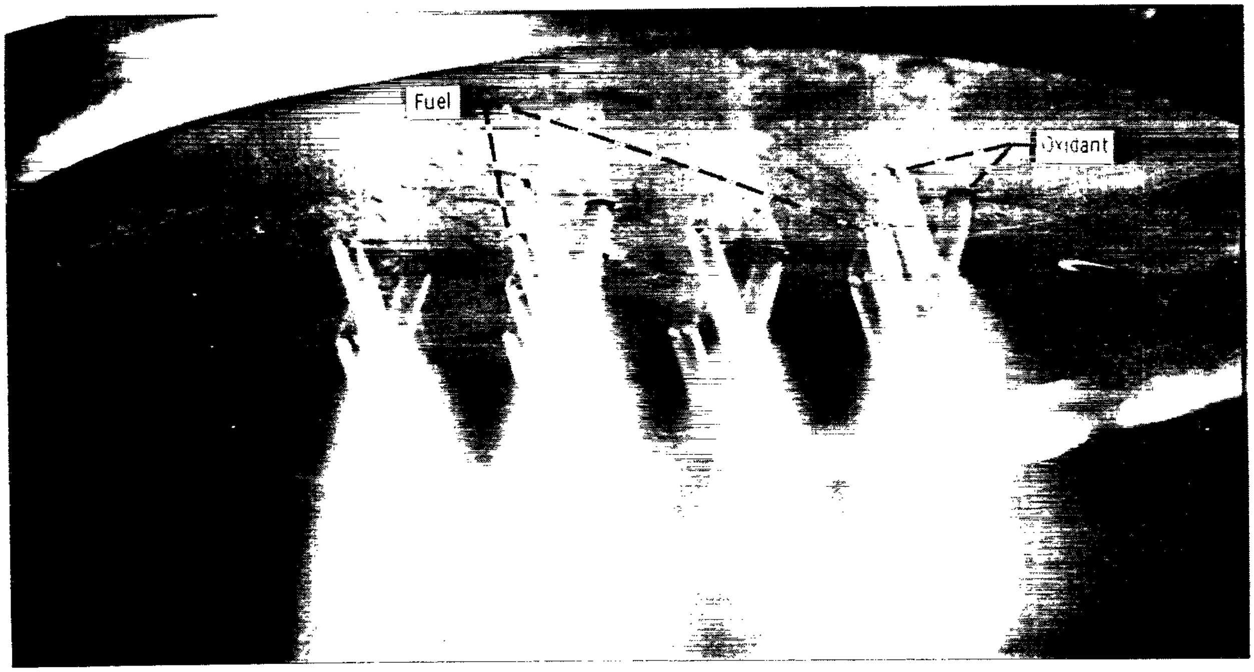
Type D:

Nine element oxidant-fuel-oxidant triplets

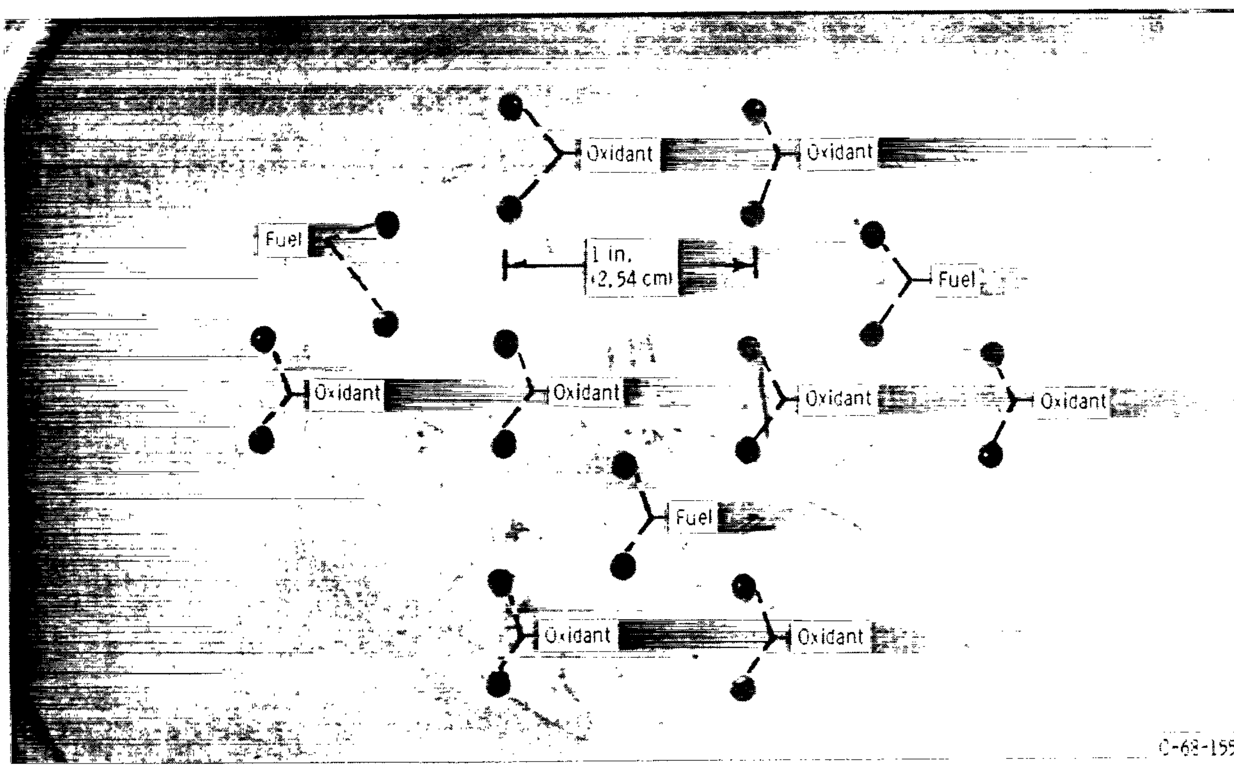
Cross-sectional details of the injection elements are shown in figure 1. Oxidant injector holes are fed by 0.25-inch (0.635-cm) diameter holes parallel to the injector face. Fuel holes are fed from a common cavity, 1.625-inch (4.12-cm) diameter, 0.25-inch (0.635-cm) deep, supplied by one 0.25-inch (0.635-cm) inside-diameter tube. Injectors B and C were run with two hole sizes. Injector hole diameters and impingement distances are given in table I. Photographs of the injector faces and water sprays are shown in figure 2.

TABLE I. - INJECTION ELEMENT DIMENSIONS

Injector	Oxidant				Fuel			
	Hole diameter		Impingement distance, D		Hole diameter		Impingement distance, D	
	in.	cm	in.	cm	in.	cm	in.	cm
A, like-on-like doublets forming parallel sheets	0.0520	0.1321	0.250	0.635	0.0520	0.1321	0.250	0.635
B-1, like-on-like doublets forming intersecting sheets	.0382	.9703	.250	.635	.0420	.1067	.560	1.42
B-2, like-on-like doublets forming intersecting sheets	.0430	.1092	.250	.635	.0472	.1199	.560	1.42
C-1, fuel-oxidant-fuel triplets	.0935	.2375	.560	1.42	.0420	.1067	.560	1.42
C-2, fuel-oxidant-fuel triplets	.1065	.2705	.560	1.42	.0472	.1199	.560	1.42
D, oxidant-fuel-oxidant triplets	.0430	.1092	.438	1.11	.0410	.1041	.438	1.11



(a) Injector A, parallel sheets; spray pattern.



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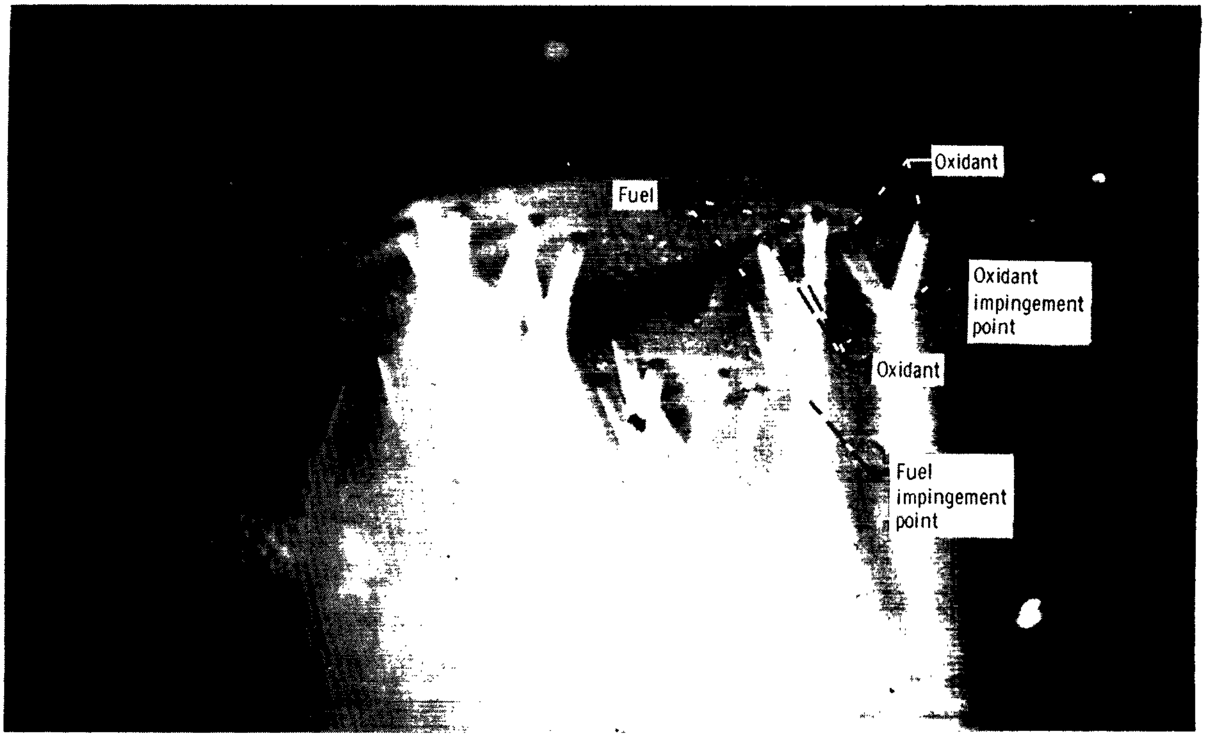
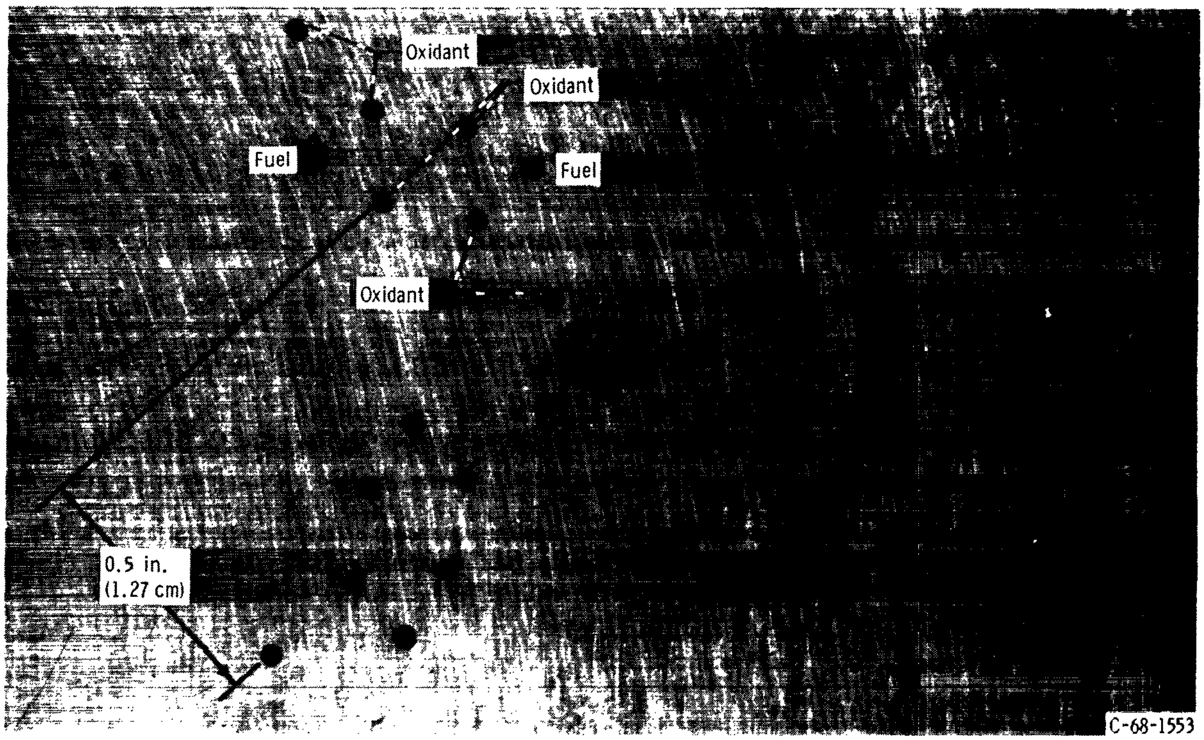
(b) Injector A, parallel sheets; face pattern.

Figure 2. - Injectors.

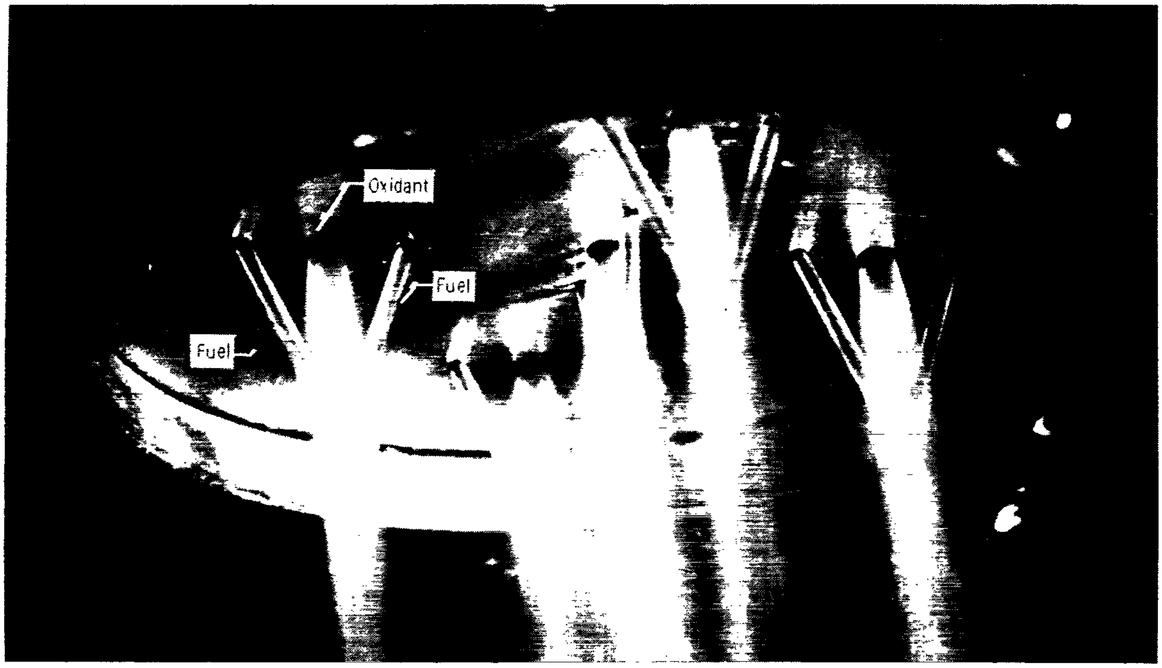


(c) Injector B, intersecting sheets; spray pattern.

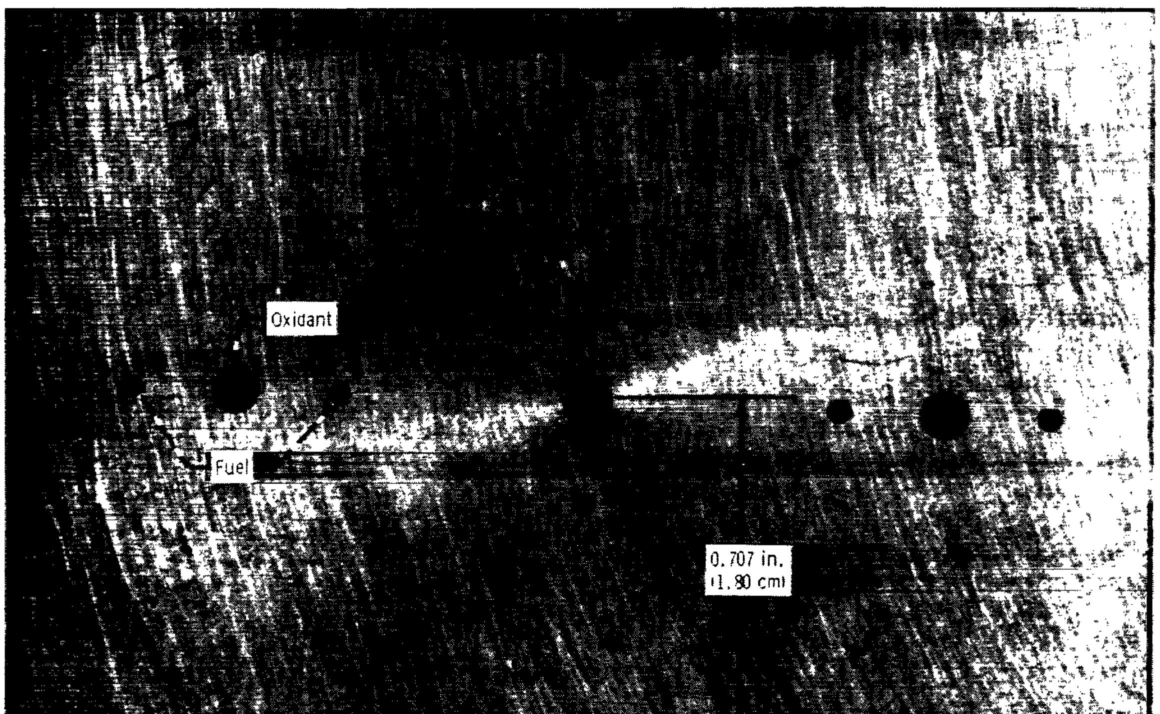


(d) Injector B, intersecting sheets; face pattern.

Figure 2. - Continued.

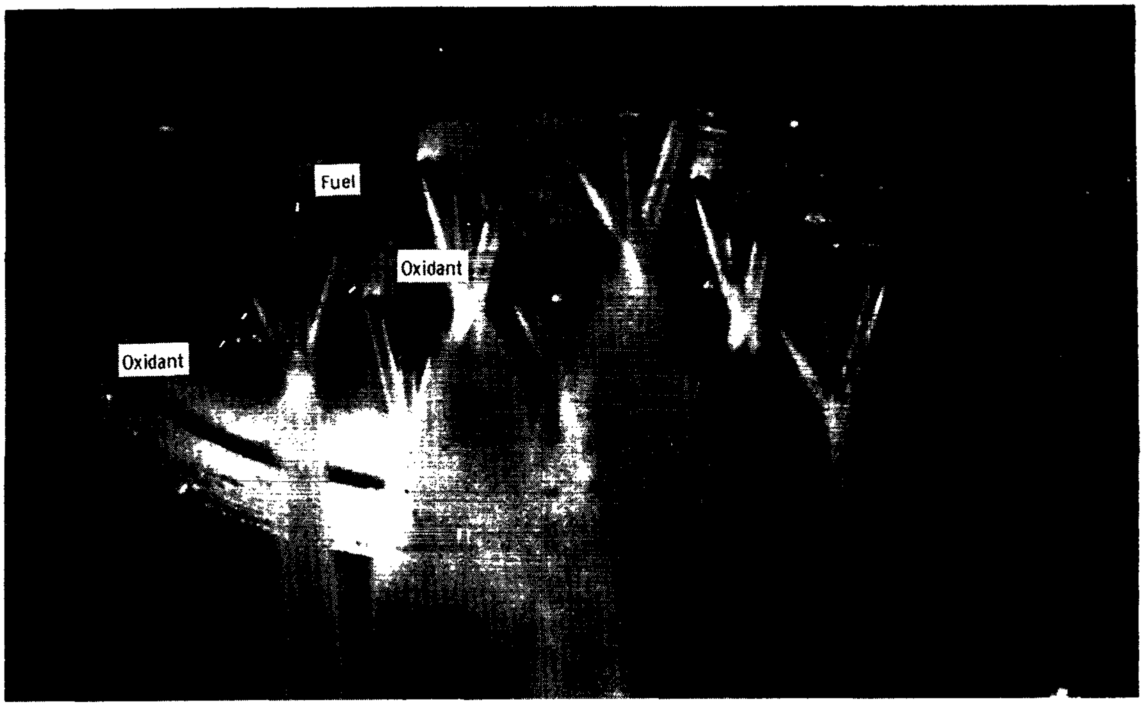


(e) Injector C, fuel-oxidant-fuel triplets; spray pattern.

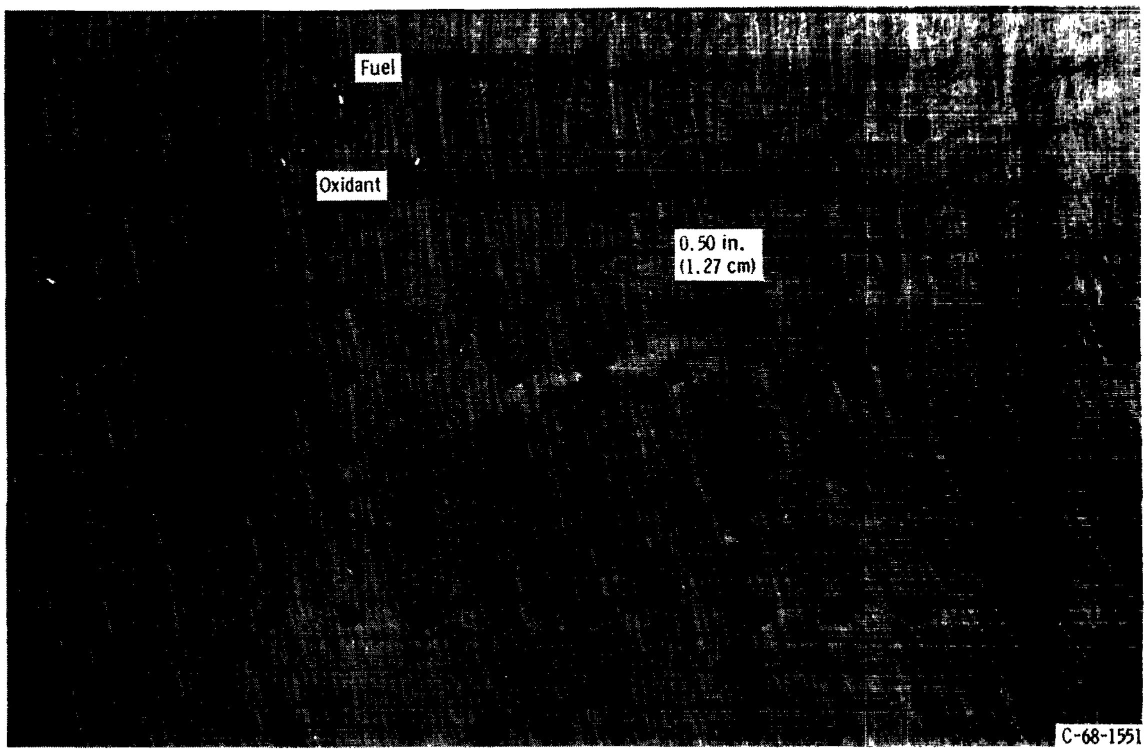


(f) Injector C, fuel-oxidant-fuel triplets; face pattern.

Figure 2. - Continued.



(g) Injector D, oxidant-fuel-oxidant triplet; spray pattern.



(h) Injector D, oxidant-fuel-oxidant triplet; face pattern.

Figure 2. - Concluded.

Instrumentation

Performance. - Performance, in terms of characteristic exhaust velocity efficiency, percent C*, was determined from measurements of chamber pressure, propellant flow rates, and nozzle diameter. Chamber pressure was measured with a strain gage type transducer located 1 inch (2.54 cm) downstream from the injector face. Propellant flow rates were measured with turbine type meters. Accuracy of C* determined in this way is about ±1 percent. Run lengths of about 2 seconds were sufficient to establish stable equilibrium flows.

High frequency. - A piezoelectric pressure transducer was used to detect the presence of high-frequency combustion instability. The signal from this transducer was tape recorded. A spectrum analyzer and oscilloscope were used to study the recorded signals.

Heat transfer. - Approximate heat transfer rates were determined by using the uncooled combustion chambers as calorimeters. The equilibrium chamber wall temperature which stabilized after the end of the run was measured with imbedded thermocouples. The chambers were insulated from the nozzle and injector. Heat losses to the surroundings from the chamber were neglected.

Operating Conditions

The variable operating conditions were propellant mass flow rate, combustor length, contraction ratio, and injector configuration. The O/F weight varied from 2.5 to 3.5. Propellant flow rate varied from about 1 to 2 pounds per second (0.454 to 0.908 kg/sec). At a contraction ratio of 1.5, chamber pressure varied from about 70 to 190 psia (4.82×10^5 to 1.31×10^6 N/m^2). At a contraction ratio of 3, chamber pressure ranged from 150 to 280 psia (1.03×10^6 to 1.93×10^6 N/m^2).

The range of injection velocities for the various injectors as a function of flow rate is shown in figure 3. A chamber pressure scale is also shown on the abscissa, assuming 100 percent C* performance and an O/F of 3.

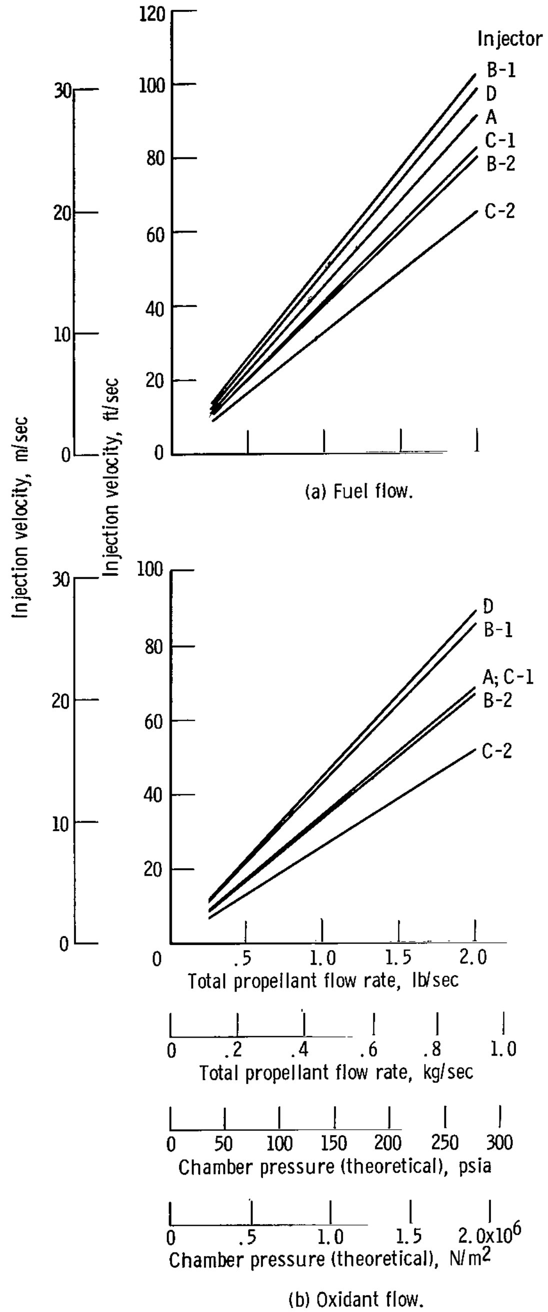


Figure 3. - Injection velocities. Oxidant-fuel ratio, 3; contraction ratio, 3; chamber diameter, 2 inches (5.08 cm).

RESULTS AND DISCUSSION

Performance

Experimental performance, expressed as percent theoretical C* is shown in figure 4 as a function of combustor length. With the exception of injector D and a contraction ratio of 1.5, for which there were almost no stable data obtained, only stable combustion data were used for evaluating performance. Performance was observed to decrease during screaming. Separate results for each injector and contraction ratio are given. Variation in propellant flow rate, chamber pressure, and O/F at each combustor length appeared to have little effect on performance. The range of C* performance due to these variations is indicated by the vertical lines.

The curves of figure 4 are faired through the arithmetic average of all runs at each combustor length. The data were corrected for momentum pressure loss. Several of the curves indicate a slight performance decrease at the longest lengths. This decrease could be attributed to heat transfer losses. Measurements of heat transfer to the combustor walls indicated a maximum performance loss of 2.5 percent C* at the longest lengths.

High performance, 95 percent or greater of theoretical, was attained with the doublet injectors by using a long combustor length. The curves of figure 4(a) to (e) suggest that performance with the doublet injectors might be further improved by using even longer lengths. In contrast, the highest performance attained with the triplet type injector was about 92 percent. Furthermore, with most combustors using the triplet injectors, performance leveled off at an intermediate length, rather than increasing with length. Variation of injector hole diameter had only a small effect on performance.

Comparison of Theoretical to Experimental Performance

Theoretical C* performance was calculated using the method of reference 4. The model assumes that performance is controlled by the propellant having the slowest vaporization rate. Theoretical performance is a function of contraction ratio, injection temperature, injection velocity, drop size, propellant molecular weight, and propellant enthalpy. Calculations were made for chamber pressure ranging from 100 to 300 psia (6.89×10^5 to 2.07×10^6 N/m^2) and corresponding injection velocities for the various injectors (fig. 4), an O/F of 3, and a contraction ratio of 3. A constant drop size, 0.003 inch (75 μm) was required for agreement with experimental results. The injection temperature was assumed to be 77° F (298 K).

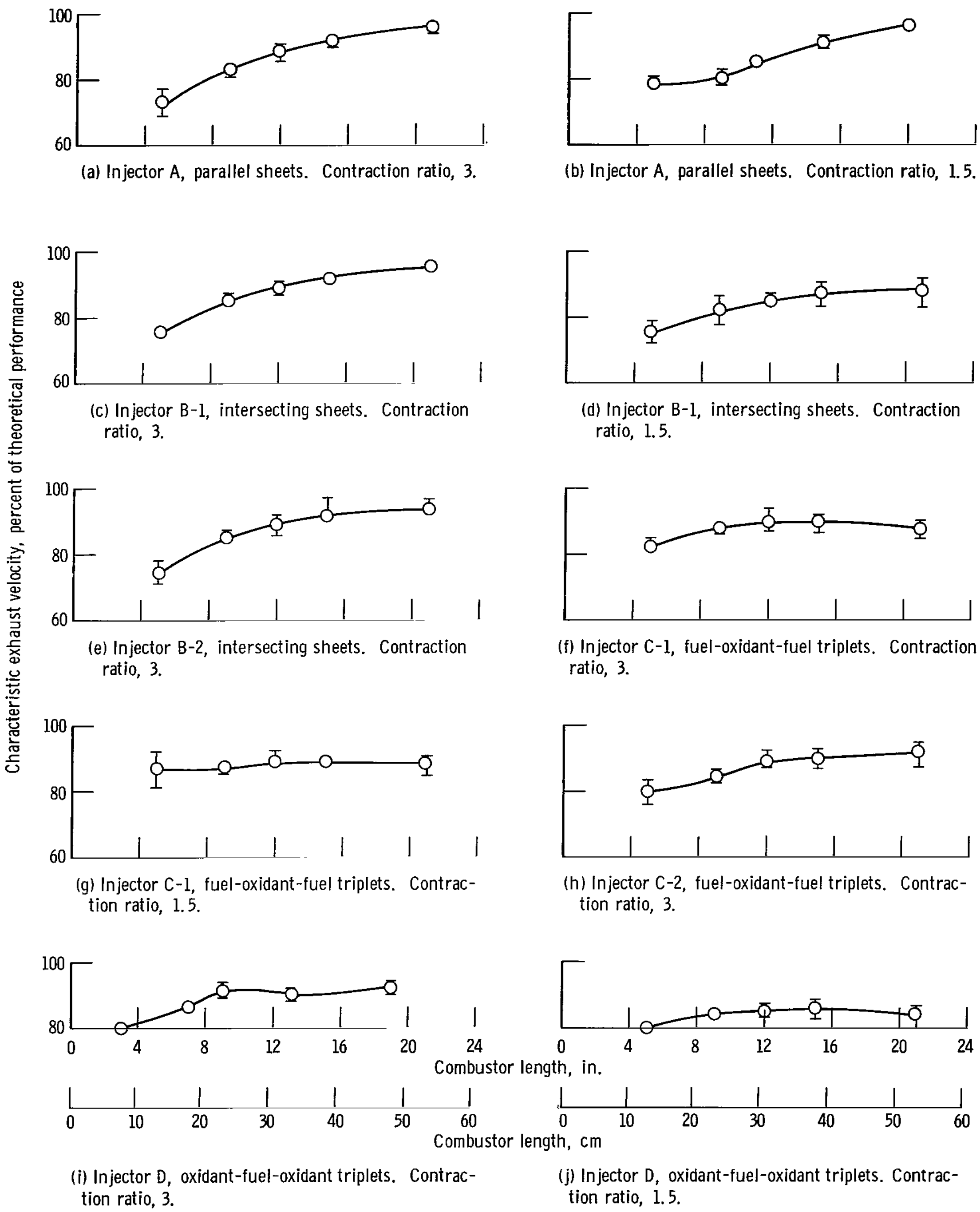


Figure 4. - Experimental performance characteristics.

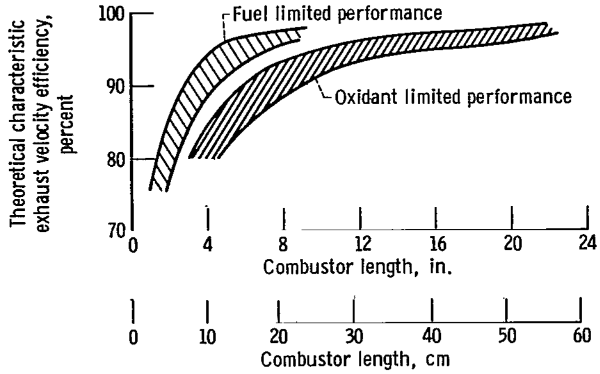


Figure 5. - Performance efficiency calculated with vaporization model. Oxident fuel ratio, 3; chamber pressure, 100 to 300 psia (0.69 to 2.07×10^6 N/m^2); contraction ratio, 3; total propellant flow rate, 1 to 2 pounds per second (0.454 to 0.908 kg/sec).

Theoretical C^* efficiency as a function of combustor length is shown in figure 5. Two bands are shown: one for fuel and one for oxidant vaporization limited performance. The effects of chamber pressure and injection velocity variation on performance is indicated by the band widths.

Predicted performance gradually increases with combustor length, and agreed best but was somewhat higher than experimental performance of injectors C and D. These results indicate that a relatively long combustor length is needed to achieve high performance. Results of the calculations indicated performance to be nearly independent of propellant flow rate, chamber pressure, and O/F variation, in agreement with most of the experimental results. Significantly, the calculations show oxidant vaporization to be performance limiting. This agrees with previous results (refs. 2 and 3). Decreasing the contraction ratio from 3 to 1.5 would slightly increase predicted performance.

Triplet injectors having hole diameters of those used here should produce drops considerably smaller than 0.003 inch (75 μm) (ref. 5). Higher performance would have been attained if the triplet injectors actually had produced smaller drops. The results of reference 4 indicate that the triplet injectors produced drop sizes corresponding more nearly to parallel jet injectors. This suggests that interfacial reactions disturbed unlike-jet impingement, causing them to deflect, and behave similar to doublet or parallel jets. The 0.003-inch (75-μm) drop size used for the doublet (like-on-like impinging jets) injectors agree with that predicted by reference 4 for the hole diameters of this study. This suggests normal jet behavior for the doublet injectors.

Instability Observations

Instability data for the high contraction ratio combustors are shown in figures 6 to 10. Performance efficiency is shown as a function of the ratio of oxidant injection pressure drop to chamber pressure. An additional abscissa scale also indicates approximate oxidant injection velocities. Each data point represents a single run.

High-amplitude, low-frequency instability (chugging) occurred with all injectors at oxidant injection pressure drop to chamber pressure ratios less than 25 to 30 percent. With injector A (parallel sheets) some chugging was observed at pressure drop ratios as high as 60 percent. In general, contraction ratio had little effect on chugging characteristics.

The only combustors completely free of high-frequency instability (screaming) were those using injector A (figs. 6 and 7). However, this injector with a combustor length of 12 inches (30.5 cm) produced some low-amplitude-pressure spiking. The amplitude of these spikes was 10 to 15 percent of mean chamber pressure. Spontaneous screaming was observed with injectors B, C, and D at oxidant pressure drop to chamber pressure ratios greater than about 30 percent.

Three types of high-frequency instabilities were observed: a continuous wave, short bursts of continuous waves or intermittent screaming, and isolated high-amplitude-pressure spikes. Continuous screaming generally occurred with the longest combustor lengths, and bursts of screaming or pressure spiking at shorter lengths. For some combustors, intermittent screaming or pressure spiking developed into continuous screaming with increasing flow rate and oxidant injection pressure drop ratios. The amplitude of these high-frequency disturbances was approximately 100 percent of mean chamber pressure.

The injectors which caused screaming ranked in order of decreasing stability are: B, C, and D. Screaming was continuous with injectors C and D at the longest length, but intermittent at shorter lengths. Several runs were completely free of screaming with injector B at high flow rates and lengths of 15 inches (38.1 cm) and 12 inches (30.5 cm) (fig. 8). Intermittent screaming or pressure spiking was always encountered with injector C in the unstable region of flow rates with combustor lengths of 15 inches (38.1 cm) or shorter. With injector D, however, continuous screaming occurred with nearly all combustor lengths at oxidant pressure drop ratios greater than 25 percent of chamber pressure (fig. 10). Furthermore, with injector D, regions of chugging and screaming overlapped, as evidenced by simultaneous occurrence of low and high frequencies.

Combustors with a contraction ratio of 1.5 were instrumented for high frequency and run with the injectors having the best and poorest stability characteristics A and D. Decreasing contraction ratio appeared to have little effect on stability characteristics. Screaming was absent with injector A (fig. 7), but severe with injector D.

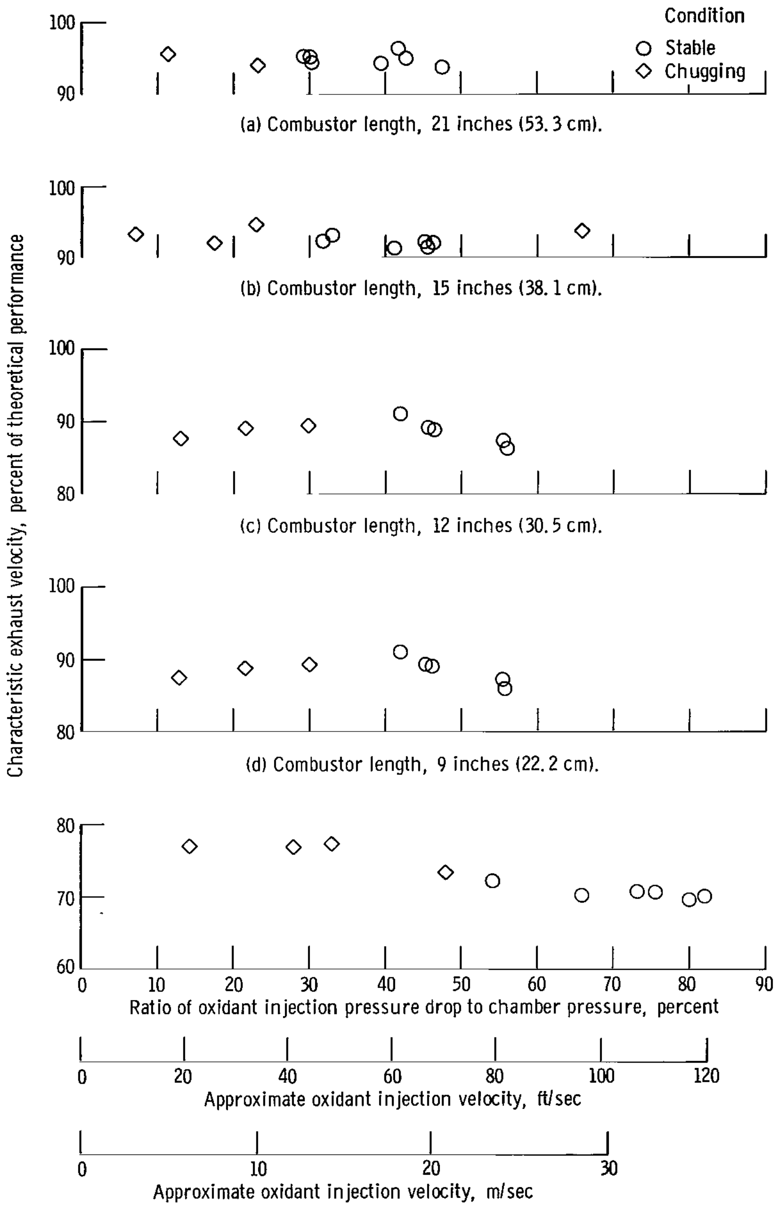


Figure 6. - Stability characteristics of injector A, parallel sheets. Contraction ratio, 3.

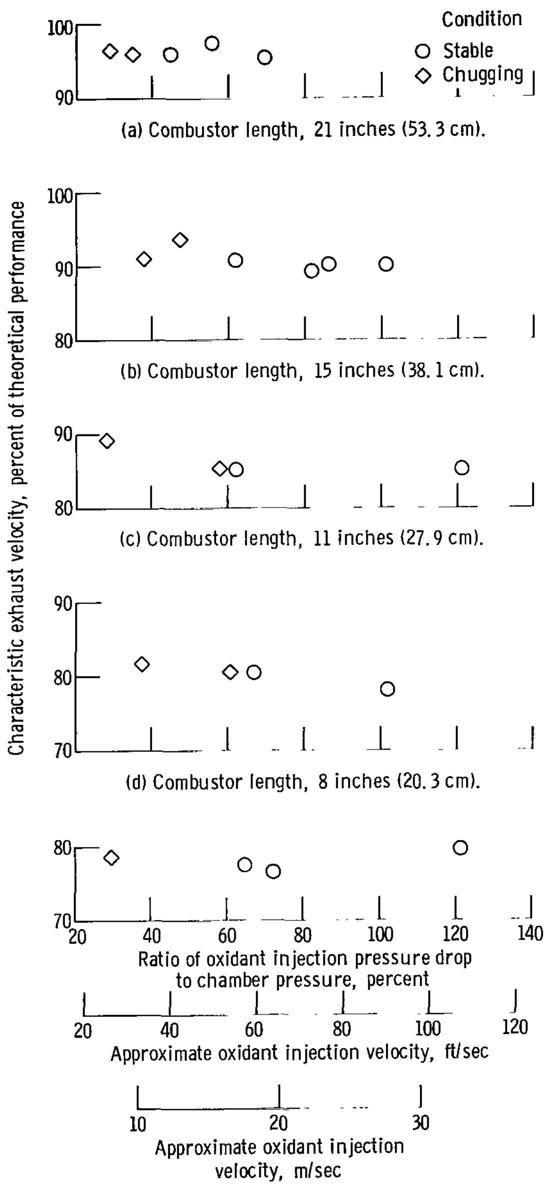


Figure 7. - Stability characteristics of injector A, parallel sheets. Contraction ratio, 1.5.

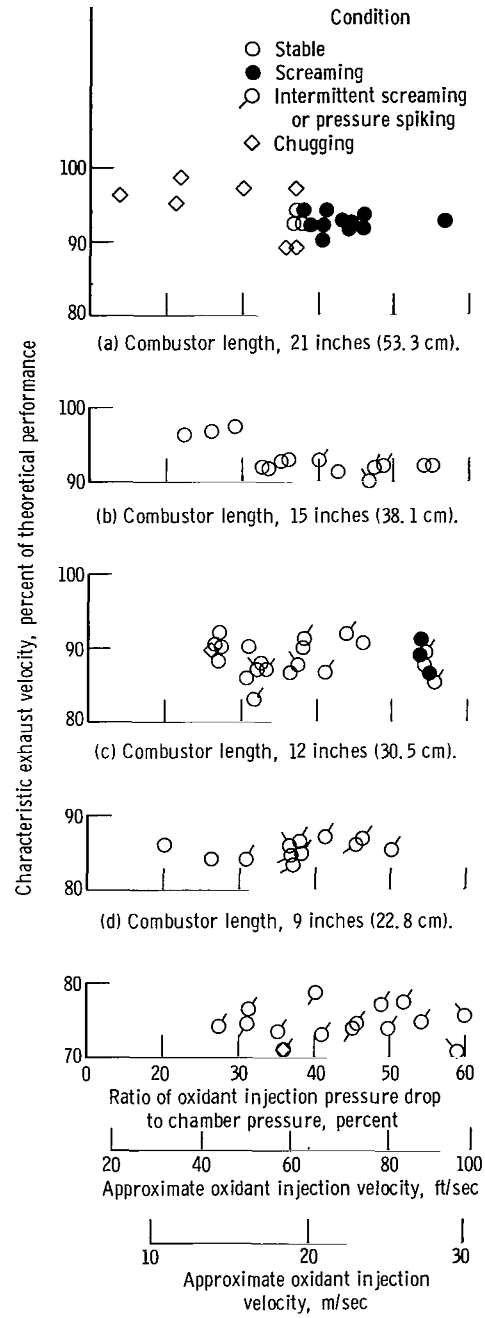


Figure 8. - Stability characteristics of injector B, intersecting sheets. Contraction ratio, 3.

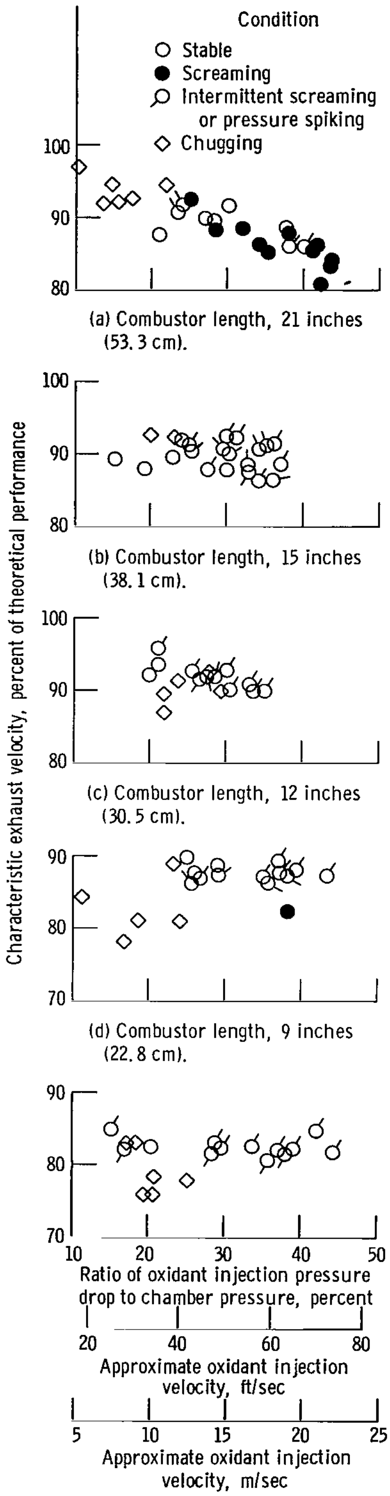


Figure 9. - Stability characteristics of injectors C-1 and C-2, fuel-oxidant-fuel triplets. Contraction ratio, 3.

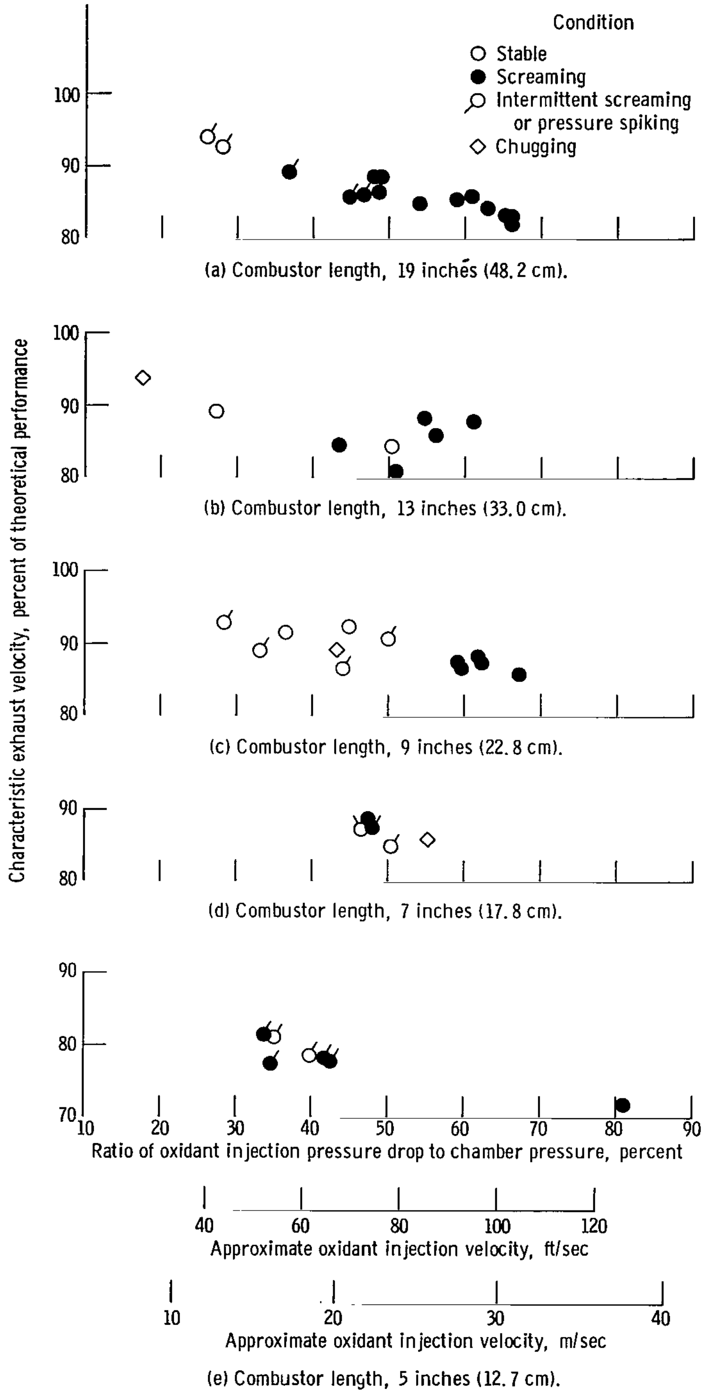


Figure 10. - Stability characteristics of injectors D-1 and D-2, oxidant-fuel-oxidant triplets. Contraction ratio, 3.

High-frequency instabilities were identified as the first longitudinal mode. Observed frequencies agreed with calculated fundamental frequencies based on combustor length and the speed of sound for equilibrium combustion products. The waveform was sawtooth. Spectrum analysis revealed presence of all higher harmonics with amplitude varying inversely with frequency. The pressure spikes were found to be of high frequency. Thus, these isolated pressure disturbances indicated a tendency of the combustor to scream rather than chug.

Burrows (ref. 2, and in more recent unpublished NASA data) observed an interfacial reaction at the impingement point of N_2O_4 and N_2H_4 jets. This reaction was found to cause the jets to momentarily repel each other, and divert them away from the impingement point. A similar periodic action may have caused the severe low-frequency oscillations observed at low flow rates for injectors C and D. Burrows also observed that the interfacial reactions caused very uneven distribution of oxidant and fuel droplets, which can lead to combustion instability.

The effects of interfacial reactions increase with increasing oxidant-fuel contact surface, and would be a maximum for unlike impingement of jets having nearly equal momentum. The injectors in order of increasing oxidant-fuel contact are: parallel sheets (a), intersecting sheets (B), fuel-oxidant-fuel triplets (C), and oxidant-fuel-oxidant triplets (D). The oxidant-to-fuel jet momentum ratios were about 5 and 1.4 for injectors C and D, respectively. It is significant then, that the injectors, ranked in order of decreasing stability, are A, B, C, and D.

These results suggest that unlike impingement of N_2O_4 with N_2H_4 is to be avoided for best stability characteristics. If unlike impingement is desired, the momentum ratio of the N_2O_4 to N_2H_4 jets should be far from unity. Furthermore, the results suggest that the center jet of each triplet element should be of higher momentum. Then, the local interfacial reactions might disrupt the outer edges of the atomization zone rather than all three jets of triplet element.

The interfacial reactions, by interfering with impingement can also explain why a large drop size was needed in the vaporization calculations to predict experimental performance for the triplet injectors.

CONCLUSIONS

Performance and stability characteristics were investigated for the propellant combination nitrogen tetroxide-hydrazine. The tests were conducted with small uncooled combustors. Four different injector configuration were used: like-on-like doublets producing parallel sheets of fuel and oxidant, like-on-like doublets forming intersecting sheets, fuel-oxidant-fuel triplets, and oxidant-fuel-oxidant triplets. The central oxidant stream of the fuel-oxidant-fuel injector had a high momentum relative to the fuel streams. The streams of the oxidant-fuel-oxidant triplets were of nearly equal momentum. Parameters varied were combustor length, contraction ratio, and propellant flow rate.

The following results were obtained:

1. With a contraction ratio of 3, high performance, 95 percent of theoretical, was achieved with like-on-like doublet injection at combustor lengths of 21 inches (53.3 cm). With triplet injectors, a maximum of 90 percent of theoretical performance was achieved at intermediate combustor lengths of 12 inches (30.5 cm). Combustor lengths longer than 12 inches (30.5 cm) were ineffective in producing higher performance with the triplet injectors. Performance was somewhat less dependent on combustor length with a contraction ratio of 1.5.

2. Low-frequency instability (chugging) was observed with all injectors when the injection pressure drop of oxidant flow was less than 25 to 30 percent of combustor chamber pressure.

3. The injectors in order of increasing spontaneous high-frequency, high-amplitude instability (screaming) were: like-on-like doublets forming parallel sheets (no screaming), like-on-like doublets forming intersecting sheets, fuel-oxidant-fuel triplets, and oxidant-fuel-oxidant triplets. This also corresponds to the order of increasing contact area of fuel with oxidant. This suggests that a probable initiating cause of screaming was poor distribution of propellants due to interfacial reactions at the impingement point of fuel and oxidant.

4. Based on the results of this study, it is concluded that best stability is obtained by using like-on-like impingement of hypergolic propellants to produce parallel sheets.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 26, 1968,
126-15-03-12-22.

REFERENCES

1. Metzler, Allen J.; and Lezberg, Erwin A.: A Hot Gas Generator for Large-Scale Supersonic Combustor Testing. Paper No. 68-647, AIAA, June 1968.

2. Burrows, Marshall C.: Mixing and Reaction Studies of Hydrazine and Nitrogen Tetroxide Using Photographic and Spectral Techniques. Paper No. 67-107, AIAA, Jan. 1967.

3. Beltran, M. R.; Breen, B. P.; and Gerstein, M.: Liquid Rocket Engine Combustion Instability Studies. Rep. SN-68-S1, Dynamic Science Corp., June 30, 1965. (Available from DDC as AD-474288.)

4. Kushida, Raymond; and Houseman, John: Criteria for Separation of Impinging Streams of Hypergolic Propellants. Paper No. WSCI 67-38, Combustion Institute, Western States Section, Oct. 1967.

5. Priem, Richard J.; and Heidmann, Marcus F.: Propellant Vaporization as a Design Criterion for Rocket-Engine Combustion Chambers. NASA TR R-67, 1960.

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