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LEAN COMBUSTION LIMITS OF A CONFINED PREMIXED-PREVAPORIZED PROPANE JET

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16. Abstract

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ABSTRACT

Lean blowout limits are reported for a premixed-prevaporized propane jet issuing into a cylindrical combustor. A single hole in a flat plate was used as a flameholder. Flameholders with various hole diameters were used. Jet velocities were varied from 3 to 290 meters per second. The combustor cross-sectional area was changed by using different quartz liners of 12.7 and 22.2 millimeters diameters. As a result the combustor Reynolds number varied from 1000 to 9000. Stability was achieved at laminar as well as turbulent conditions. Three zones of flame stability were observed. The blowout equivalence ratio varied with step size and the combustor and jet Reynolds numbers. The combustor inlet mixture temperature was 395 K, and the combustor pressure was 1 atmosphere.

INTRODUCTION

An experimental investigation was conducted to determine the effects of jet velocity and confinement on lean premixed-prevaporized propane/air blowout limits.

Oxides of nitrogen, NO_x, have been found to be an important major pollutant of both subsonic and supersonic aircraft cruising at high altitudes. The National Academy of Sciences and the Climatic Impact

Assessment Program suggested the cruise NO_x emissions be reduced by ten- to twenty-fold from current levels (refs. 1 and 2).

Recent studies have shown lean premixed-prevaporized (LPP) combustion to be an effective means of reducing NO_x formation in gas turbines (ref. 3). One of the major problems of LPP combustion is stabilizing the flame near lean blowout. It has been suggested that a fundamental investigation of the influence of reference velocity and confinement on lean blowout limits be made (ref. 4).

Perforated plates are candidate flameholders for LPP combustors. Since it is both difficult and expensive to test all of the hole diameter and flameholder step combinations, a small combustor having a single hole perforated plate flameholder was designed to provide quick screening of combinations of flameholder hole size and percent blockage. Blowout data for three small can combustors of multihole design are reported in Ref. 5. The hole pattern and size of the recirculation zone were found to influence blowout. However, the effect of blockage and turbulence on stability was not clarified. The single hole perforated plate flameholder should provide baseline data on stabilizing LPP flames.

EQUIPMENT AND PROCEDURE

The combustor consisted of a single hole flameholder within a quartz liner. Propane was used as the fuel because of the similarity between its blowout characteristics and those of jet fuel (refs. 6 and 7). Propane is quite safe from an autoignition standpoint (ref. 8) and it vaporizes at room temperature so that it can be premixed easily.

A photograph of the combustor and associated parts is shown in Fig. 1. The propane and air were mixed in a tee located 1 meter upstream of the inlet. Further mixing occurred in the mixing chamber. The mixing chamber was 52 millimeters in diameter by 40 millimeters long, see Fig. 2. A 20-millimeter thick layer of ceramic fibre packing was placed upstream of the flameholder between a wire mesh holder and the flameholder plate to prevent flashback and to distribute the flow uniformly across the flameholder hole.

Five flameholder plates and two quartz liners were used in the experiment. The holes in the flameholder plates were 3.2, 6.3, 12.7, 19.1, and 22.2 millimeters in diameter. The plates were 3.2 millimeters thick. The flameholder plates were bolted between flanges so that they could be changed easily. The quartz liners were 164 millimeters long with inside diameters of 12.7 and 22.2 millimeters. The quartz liners were centered inside the 52 millimeter diameter stainless steel body with centering rings. Quartz insulation was packed between the liner and outer tube to keep heat loss to a minimum. Combustion was initiated by a spark plug ignitor placed outside of the combustion chamber. The hot combustion gases were exhausted to the atmosphere through a water-cooled pipe.

The flow schematic of the air and propane as well as the instrumentation stations is shown in Fig. 3. The system was operated from a remotely located control room where test conditions were set using digital voltmeter displays. Electrical inputs were supplied to an IBM 360/67 computer for data recording and on-line data analysis. The airflow was metered through a subsonic, 2.54-millimeter diameter, calibrated orifice.

The propane was passed through a steam heat exchanger and the flow rate measured with a 0.3-millimeter diameter orifice calibrated for both subsonic and sonic flow. The propane lines downstream of the heat exchanger were steam traced which heated the inlet mixture to 395 K. Static and differential pressures were measured by transducers and temperatures measured by Chromel-Alumel thermocouples.

Combustion was initiated by opening a remotely controlled bypass valve which allowed some of the fuel-air mixture to bypass the flameholder through a spark ignition system. The burning gases from the spark ignitor were injected into the combustor through a 6-millimeter hole in the liner. This ignition system prevented any object from projecting into the jet stream to act as a flameholder. After the thermocouple probe showed burning in the combustor, the bypass valve was closed.

The procedure, after the combustor was ignited, was to set a fuel flow and continue to increase airflow until blowout occurred. Airflow was increased slowly so that the liner would cool and not provide hot spots as sources of stability. The output of the thermocouple probe was viewed on a strip chart recorder and when a rapid drop in temperature occurred, this was taken as the blowout point. Data was taken as the airflow was increased and stability plots made. Only the data points just before blowout are included in this report for reasons of figure clarity.

One series of tests were made with the outer stainless steel body and quartz insulation removed. This was done to observe the zones of flame stability inside the quartz liner.

The combustor and the associated valves and transducers were assembled on a cart for ease of removal from the test cell. The assembled apparatus is shown in Fig. 4.

TEST CONDITIONS

Airflow was varied from 1 to 2.3 grams per second. Inlet mixture temperature was 395 K ± 5. Liner reference velocity defined as the airflow rate divided by the product of the inlet air density and the liner cross-sectional area varied from 1 to 16 meters per second. Since the combustor was vented, combustion took place at 1 atmosphere.

Table I is a list of configurations tested which include five configurations with the 22.2-millimeter liner and two configurations with the 12.7-millimeter liner. The percent blockage was based on the area of the liner minus the hole area ratioed to the area of the liner.

RESULTS AND DISCUSSION

The stability of combustion was determined for a confined premixed-prevaporized propane jet. Lean limit stability was obtained as a function of combustor Reynolds number. Three zones of stability were recognized from analysis of the data and confirmed by visual observation of the flame. The three zones are shown schematically in Fig. 5. The region where the flame stabilized depended upon the Reynolds numbers of the liner and the jet and upon the step size of the flameholder. The Reynolds numbers were computed from the diameter of the liner and jet and the fluid properties at the inlet mixture temperature and pressure.

At low jet velocities the flame is stabilized within the jet, called zone 1. A very dim flame cone was seen to form in the center of the combustor with flame cells burning around the base of the cone. The appearance of the cone depended on the Reynolds number of the jet. For Reynolds numbers below 2100, the cone was well defined and sharp. For Reynolds numbers above 2100, the cone thickened into a flame brush. As the jet velocity was increased, the flame was stabilized by the recirculation zone lip, zone 2. However, for the small recirculation zone steps (i.e., large hole diameters), the step size was not large enough to stabilize the flame. In this case the flame became lifted and zone 3 combustion existed. The flame was stabilized at the wall downstream of the step and the flame appeared as an inverted cone.

The stability data for the 22.2-millimeter liner is shown in Fig. 6(a-e). The equivalence ratio is defined as the fuel flow rate divided by the stoichiometric fuel flow rate required to completely consume all of the oxygen in the air. The flame is stable at equivalence ratios above the blowout curve shown in the figure. For the 22.2-millimeter hole flameholder (fig. 6(a)) no step exists and only zone 1 or zone 3 flames exist. At low Reynolds numbers, zone 1 would exist and as the equivalence ratio was decreased blowout would occur. Flashback into the mixing chamber was prevented by the ceramic fibre packing. At higher Reynolds numbers the flame would be stabilized at zone 3. The exact point of transition from zone 1 to zone 3 burning was not determined.

For jet hole sizes larger than 6.3 millimeters (figs. 6(a) to (c)) the stability plots show a maximum occurring between a Reynolds number of 2000 to 3200. To the left of the maximum, laminar burning is taking place. The increase in blowout equivalence ratio, until a Reynolds number of 2000 to 3200 is reached, is caused by the increasing inability of the laminar flame front to propagate through the mixture at higher mass flows. Higher equivalence ratios are required to obtain higher laminar burning speeds. For example, at 395 K between equivalence ratios of 0.60 and 0.66 laminar burning speed increases from 0.22 to 0.29 meters per second, respectively (ref. 9).

When the mass flow rate was increased so that the Reynolds number was greater than 3200, the combustion became turbulent. Since turbulent flame propagation speeds are greater than laminar flame speeds, the blowout equivalence ratios again decrease.

A composite figure for the 22.2-millimeter liner is shown in Fig. 6(f). The 3.2- and 6.3-millimeter flameholders never formed laminar burning flows because the high turbulence level of the inlet jet was not dissipated. For these two flameholders the zone 1 flames were observed to be very turbulent and intense, even at low liner Reynolds numbers.

The stability curves for the flameholders cross each other at a Reynolds number of about 2000, indicating that the step size below this Reynolds number is not effective in stabilizing combustion. For the large step sizes the residence time in the recirculation zone is large in comparison to the chemical reaction time; and wall quenching is important. When the flow rate into the recirculation zone balances the wall quench, zone 2 stability exists. The flow rate into the recirculation zone increases with increasing velocity and turbulent mixing. A point is reached where the heat release rate is greater than the wall quench rate and combustion is maintained in zone 2. It appears that the size of the recirculation zone controls the minimum equivalence ratio. However, as the step size is increasing, the hole diameter is becoming smaller and for a given liner Reynolds number the jet Reynolds number increases with decreasing hole size. For the large step sizes, stability improves with turbulence. The different cases all approach each other near a Reynolds number equal to 6000 as shown in Fig. 6(f).

Figure 6(f) also shows an interesting difference between the 19.1- and 22.2-millimeter test cases in the 1000 to 3000 Reynolds number range. The lean blowout equivalence ratio for the 22.2-millimeter case is unexpectedly less than the 19.1-millimeter case. The difference is quite large considering the small step involved. The small decrease in flow area for the 19.1-millimeter case increases the velocity with a net decrease in stability more than the step increases stability. The disturbance in the flow causes the unburnt mixture to quench the laminar flame which is basically wall stabilized.

Test results for the 12.7-millimeter liner, shown in Fig. 7(a) to (c) indicate a reverse trend in stability versus liner Reynolds number. As the liner Reynolds number increased the stability deteriorated (i.e., the lean blowout equivalence ratio increased). This reversal was attributed to the stability mechanism changing from wall quench limiting to chemical kinetic limiting. The relative recirculation zone sizes for the two liners at a given hole size are shown schematically in Fig. 8. The recirculation zone size was decreased by a factor of about 5 which decreased the residence time within the recirculation zone to values equivalent to the chemical kinetic reaction time. As the jet velocity was increased, the equivalence ratio had to be increased to compensate for the decreased residence time available.

The decreased recirculation zone size characteristic of the 12.7-millimeter liner when compared to the 22.2-millimeter liner coupled with higher liner velocities was thought to be the cause for the increase in minimum blowout equivalence ratio for a given jet hole size. This result is depicted in Fig. 9.

SUMMARY OF RESULTS

Lean stability limits were mapped for a confined propane jet in a cylindrical combustor. Three zones of flame stability were observed depending on the liner and jet Reynolds number and the combustor geometry. At low Reynolds number the combustor was jet stabilized. As the Reynolds number was increased the combustor became either recirculation zone stabilized, or for small recirculation zone step sizes, the combustor was wall stabilized.

The factors affecting stability seem to be the Reynolds numbers of the liner and inlet jet and the flameholder step size. For laminar burning as the jet velocity was increased the combustor equivalence ratio had to be increased to maintain flame stability. After transition to turbulent flow the flame speed increased and the blowout equivalence ratio improved by becoming leaner.

At a fixed liner Reynolds number, corresponding to a fixed mass throughput rate, as the flameholder step size increases the jet Reynolds number increases. For the 22.2-millimeter liner, the stability limit usually improved as the flameholder step size was increased. For the 12.7-millimeter liner, the reverse was true, the stability deteriorated as the flameholder step size was increased. This reversal was attributed to the mechanism for stability changing from wall quench limiting to residence time limiting.

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TABLE I

Combustor liner diameter, mm	Flameholder hole size, mm	Flameholder blockage, mm	Liner wall thickness, mm
22.2	3.2	97.9	1.8
	6.3	91.8	
	12.7	67.3	
	19.1	26.5	
	22.2	0	
12.7	3.2	93.7	1.3
	6.3	75.0	

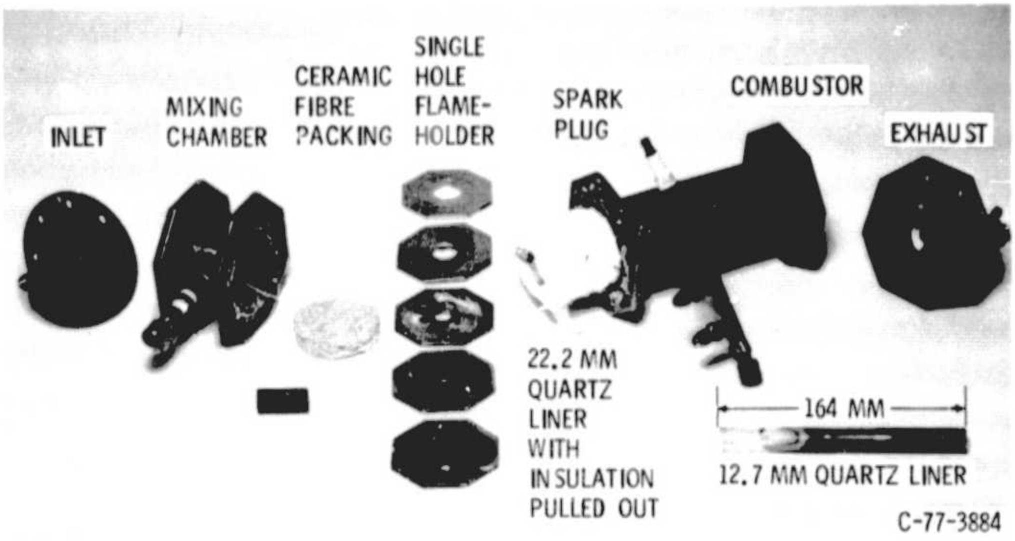


Figure 1. - Photograph of unassembled combustor.

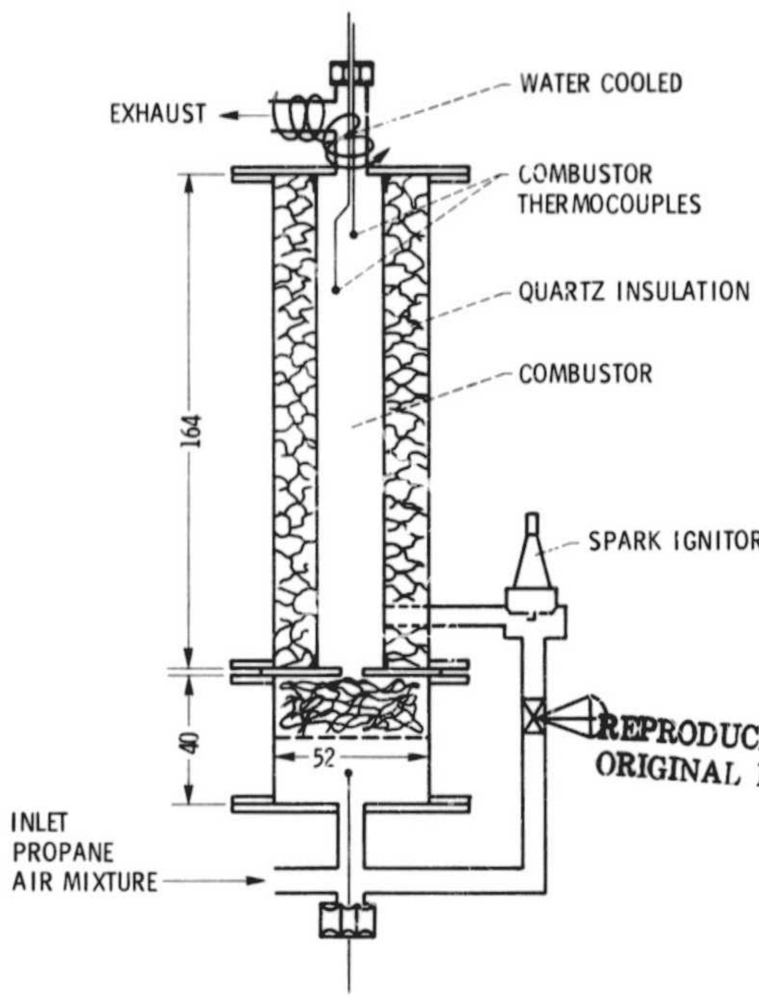


Figure 2. - Schematic of combustor dimensions in millimeters.

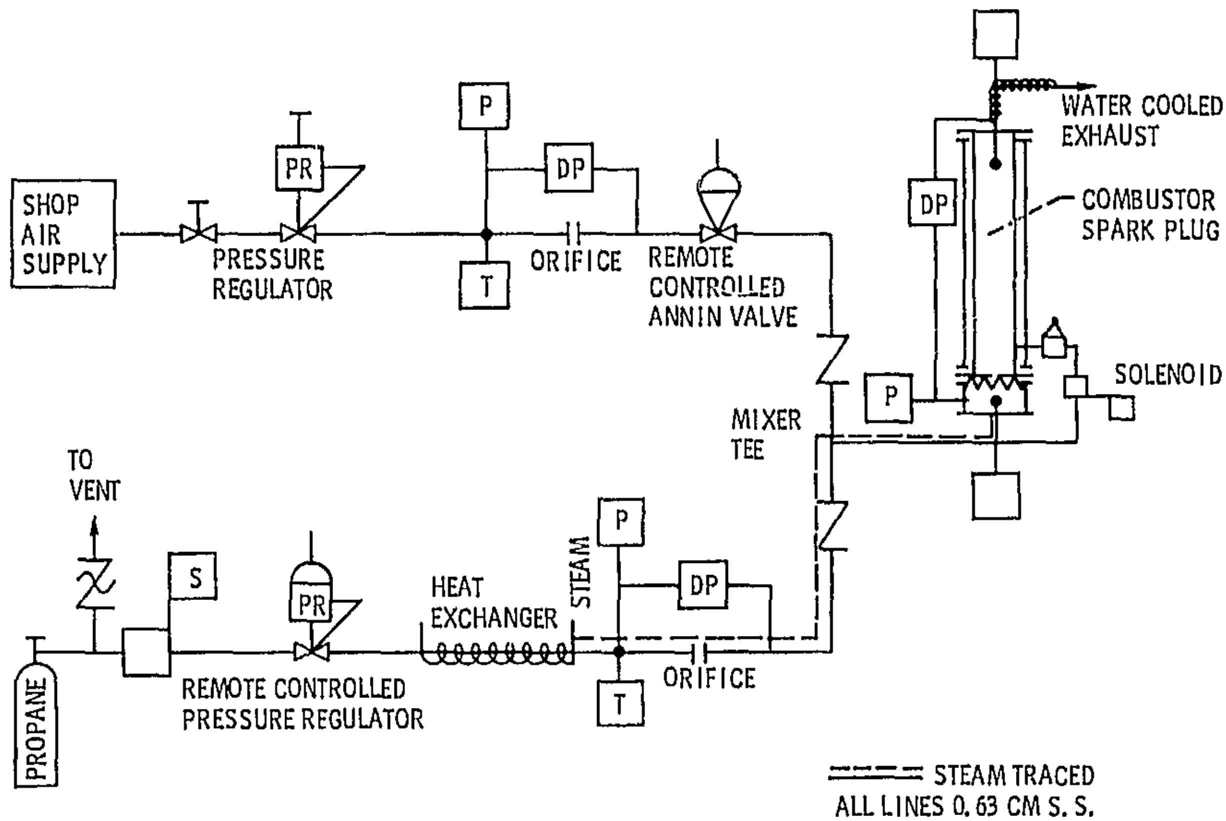


Figure 3. - Flow schematic of air and propane showing instrumentation.

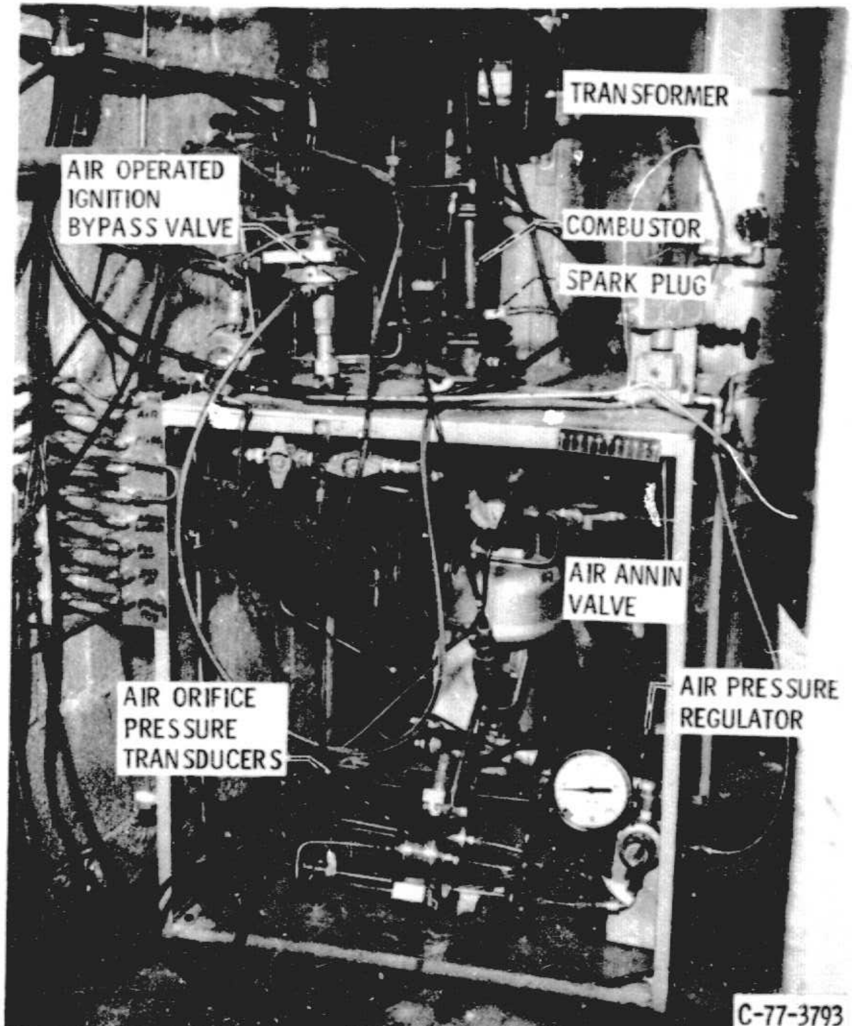


Figure 4. - Assembled combustor on cart.

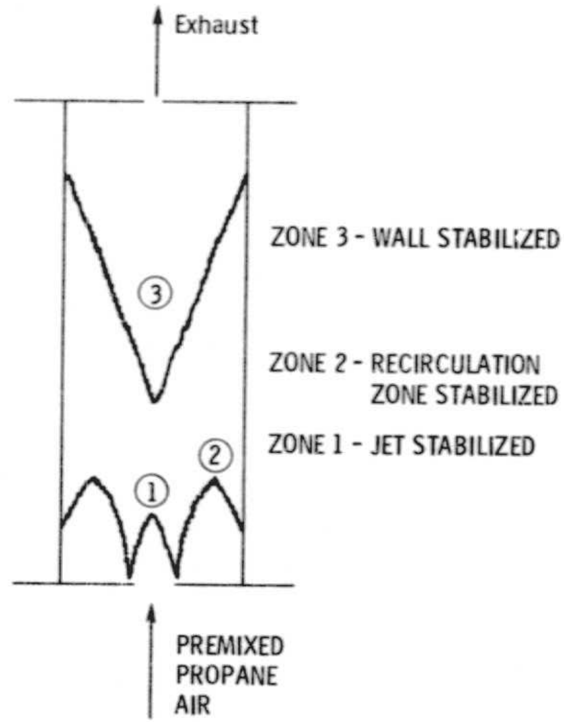
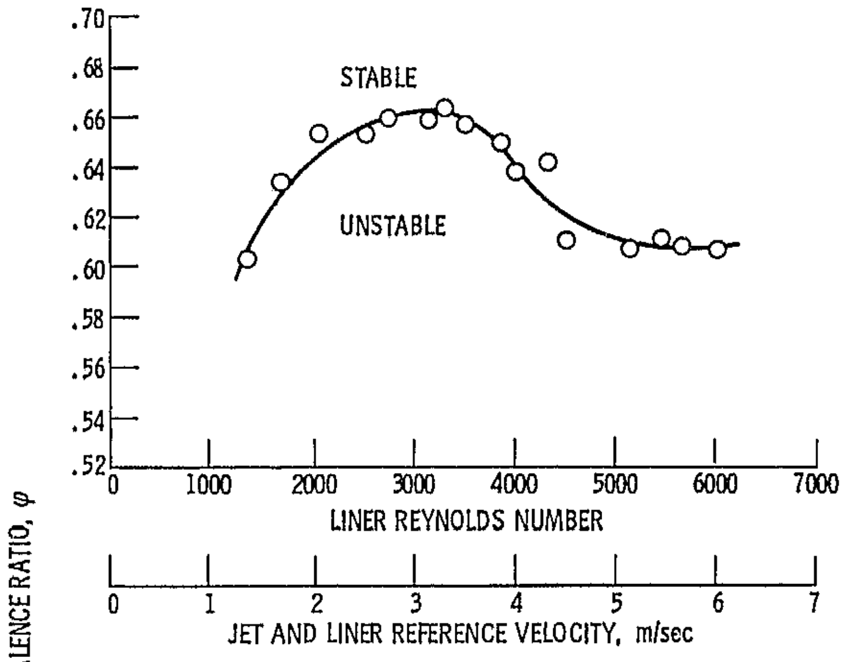
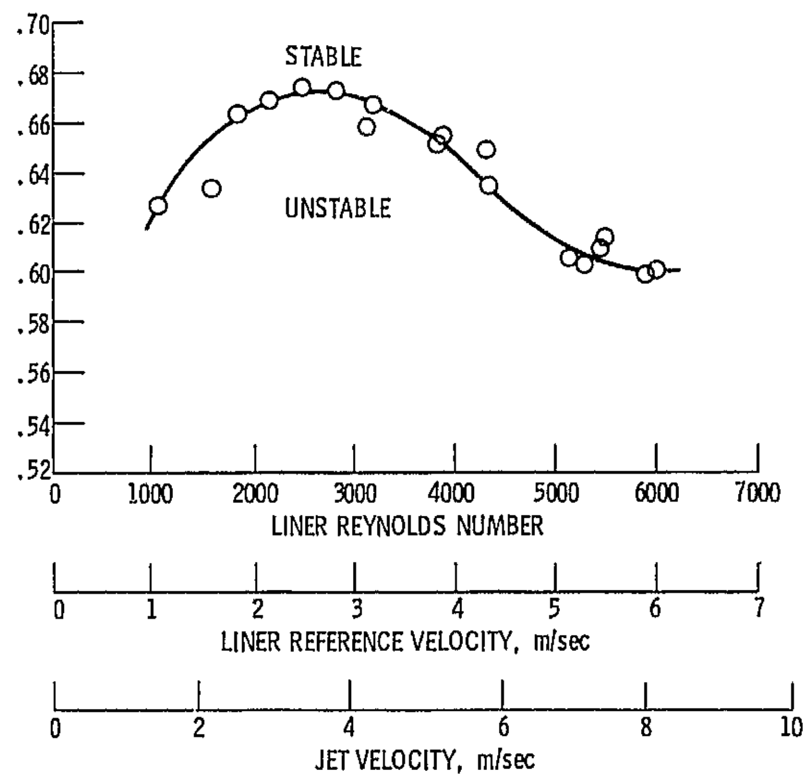


Figure 5. - Zones of combustion stability.

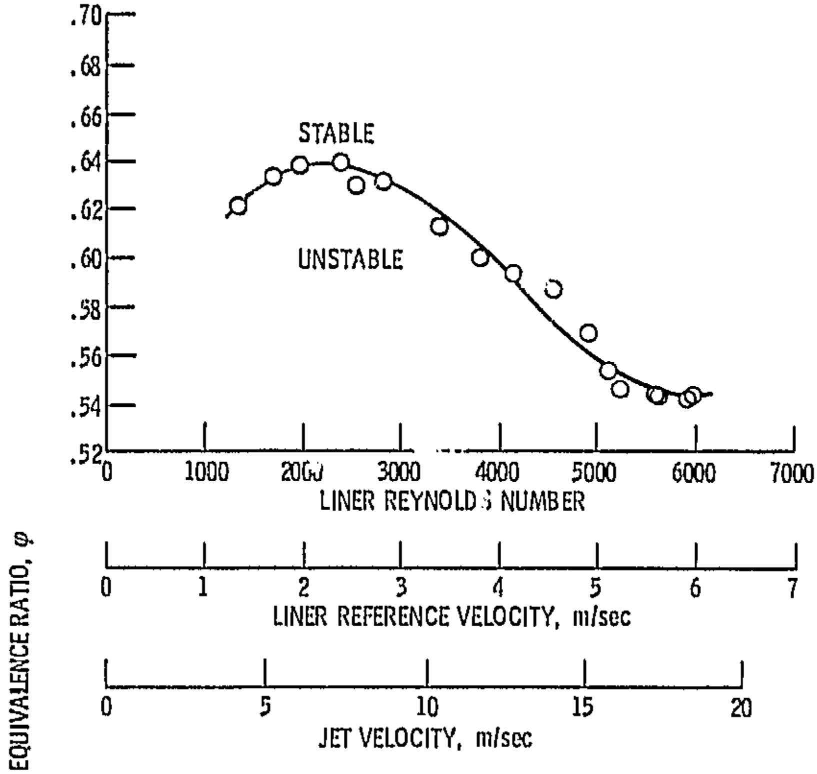


(a) STABILITY MAP OF 22.2 mm FLAMEHOLDER WITHIN 22.2 mm LINER.

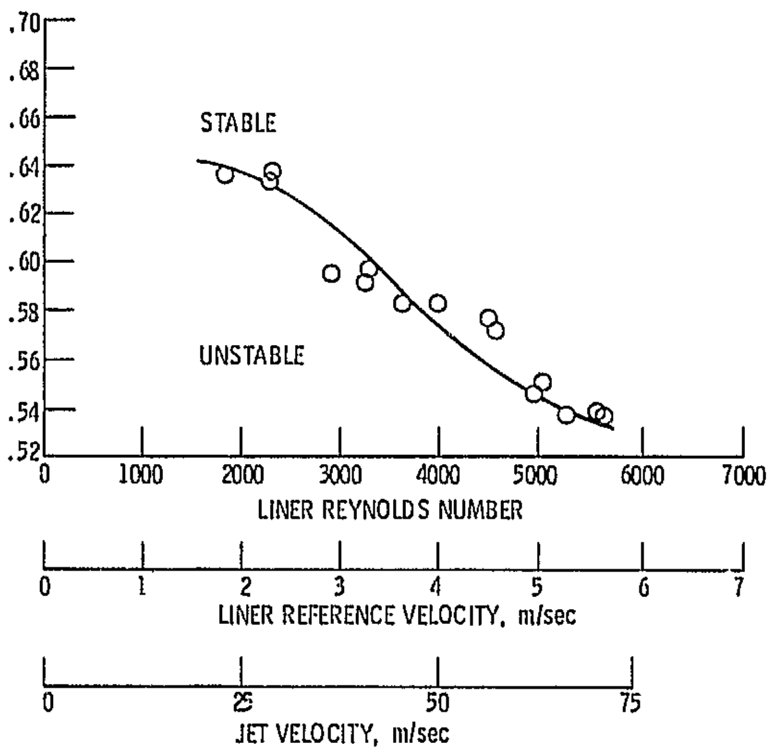


(b) STABILITY MAP FOR 19.1 mm HOLE FLAMEHOLDER IN 22.2 mm LINER.

Figure 6.

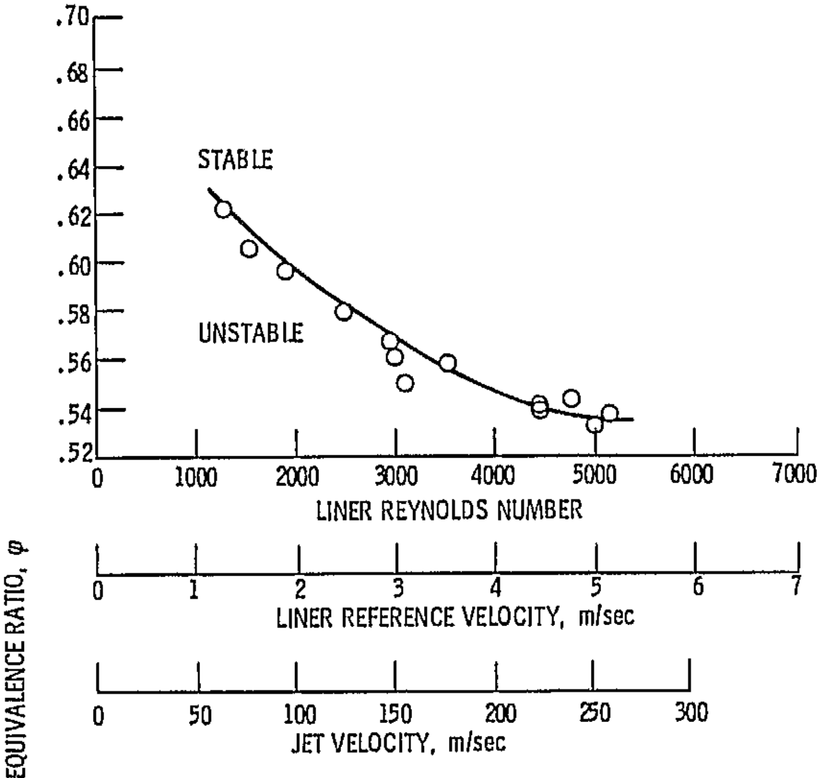


(c) STABILITY MAP FOR 12.7 mm HOLE FLAMEHOLDER IN 22.2 mm LINER.

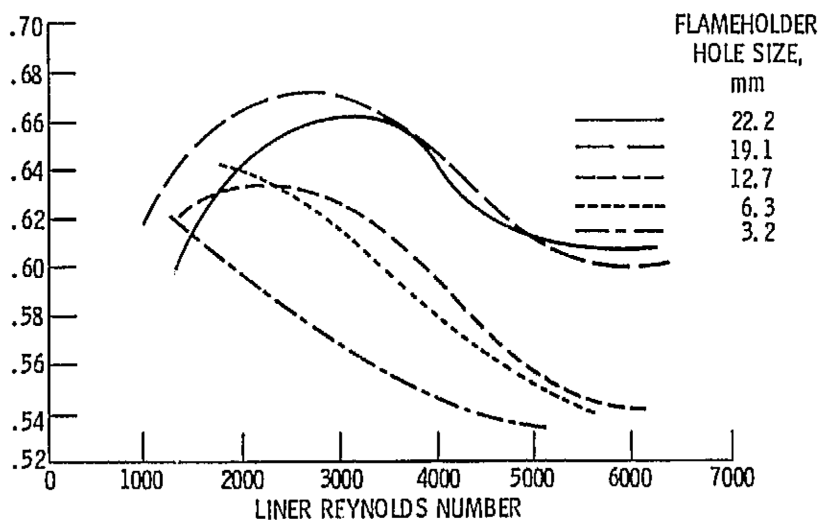


(d) STABILITY MAP FOR 6.3 mm HOLE FLAMEHOLDER IN 22.2 mm LINER.

Figure 6. - Continued.

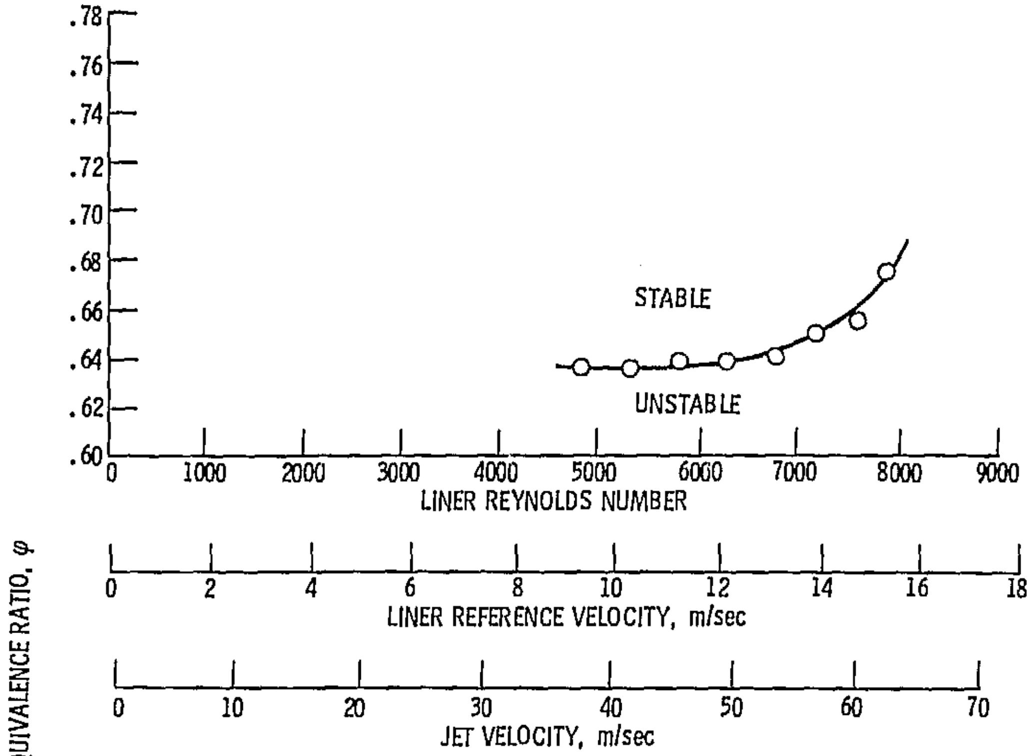


(e) STABILITY MAP FOR 3.2 mm HOLE FLAMEHOLDER IN 22.2 mm LINER.

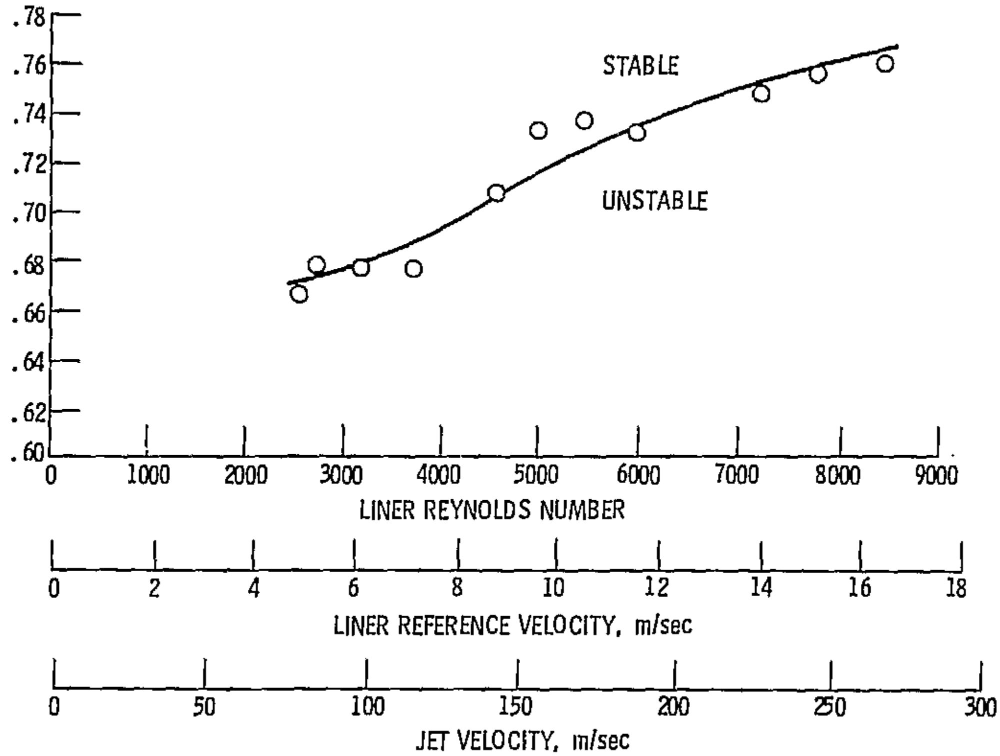


(f) STABILITY MAPS FOR 22.2 mm LINER.

Figure 6. - Concluded.

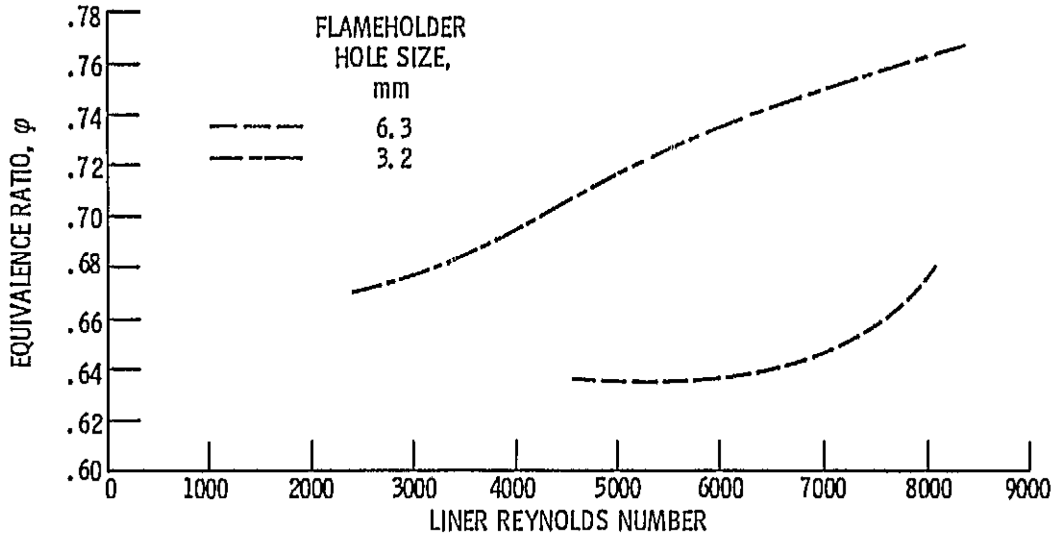


(a) STABILITY MAP FOR 6.3 mm HOLE FLAMEHOLDER IN 12.7 mm LINER.



(b) STABILITY MAP FOR 3.2 mm HOLE FLAMEHOLDER IN 12.7 mm LINER.

Figure 7.



(c) STABILITY MAPS FOR 12.7 mm LINER.

Figure 7. - Concluded.

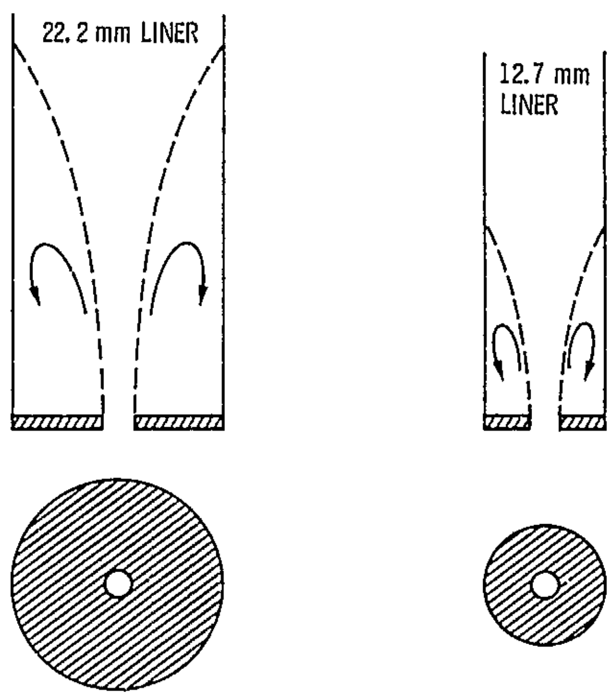


Figure 8. - Sketch of flameholder recirculation zone for 3.2 mm hole flameholder.

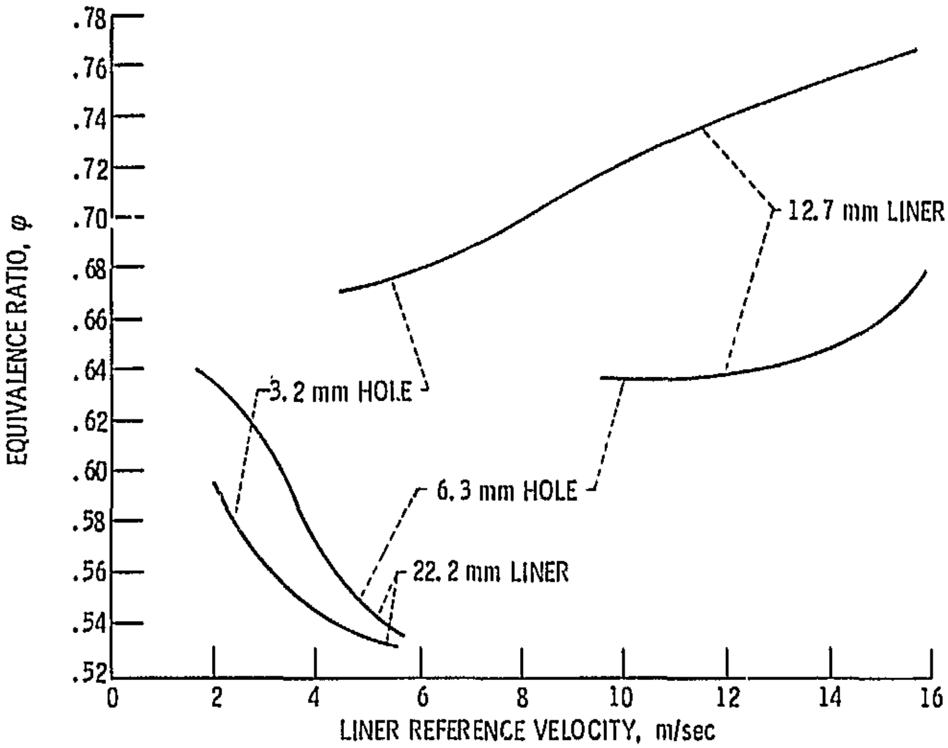


Figure 9. - Effect of flame confinement on stability.