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EFFECT OF PRESSURE AND DUCT GEOMETRY ON BLUFF-BODY FLAME STABILIZATION

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SUMMARY

Blowoff velocities and recirculation-zone lengths of propane-air flames stabilized by cylindrical flameholders were measured as a function of pressure (0.25 to 0.8 atm), cylinder diameter (3/8 to 1.0 in.), fuel-air ratio, and tunnel geometry (3 by 3 and 1 by 3 in.) for Reynolds numbers ranging from 0.64×10^4 to 17.3×10^4.

Blowoff velocity for stoichiometric mixtures varied with pressure to the 1.4 power in the 3- by 3-inch tunnel, and to the 2.1 power in the 1- by 3-inch tunnel. Blowoff velocity varied directly with flameholder diameter. Blowoff velocity for any particular flameholder was about 40 percent higher in the 3- by 3-inch tunnel than in the 1- by 3-inch tunnel. Recirculation-zone lengths for a given flameholder and tunnel geometry were a function of gas velocity rather than Reynolds number, to a first approximation. The length increased with velocity at low velocities, and became approximately independent of velocity at high velocities. At high gas velocities, the length was about 40 percent greater in the 3- by 3-inch tunnel than in the 1- by 3-inch tunnel. Critical times (ratio of recirculation-zone length to blowoff velocity) were calculated from the experimental results. The critical times were independent of flameholder diameter in the 1- by 3-inch tunnel but decreased with increasing flameholder diameter in the 3- by 3-inch tunnel. Pressure dependence of critical times was larger in the 1- by 3-inch tunnel than in the 3- by 3-inch tunnel. Arguments are advanced to show that these differences were the result of heat losses from the recirculation zone to the flameholder and tunnel walls.

It is concluded that the variation of blowoff velocity with flameholder size and tunnel geometry is the result of changes in the recirculation-zone length. The variation of the blowoff velocity with pressure is the result of variation of the critical time with pressure. Thus it appears that the separation of the flameholding process into two independent steps, characterized by the critical time and recirculation-zone length, is a useful means of explaining the effects of tunnel geometry and pressure on blowoff velocity. This method has previously shown its value in explaining the effects of fuel-air ratio, temperature, and flameholder size and shape on blowoff velocity.

INTRODUCTION

The stabilization of flames by bluff bodies is vital to the operation of such propulsion systems as ramjets and afterburners. Consequently, improvement of bluff-body flame stabilization can result in improved performance of these systems. A basic approach for attaining improved stability is to gain a thorough understanding of the mechanism of flame stabilization and then to use this knowledge to attack the problem along logical lines.

A sketch of a flame stabilized by a bluff body is shown in figure 1. It is generally conceded that the recirculation zone, the region of reverse flow behind the flameholder, is the essential feature of bluff-body flame stabilization. However, there is little agreement as to the details of the process, as evidenced by the number of flameholding models that have been proposed (refs. 1 to 5). Of all these analytical models, the critical-contact-time concept, mentioned by Spalding (ref. 4) and considerably developed by Zukoski and Marble (ref. 5), seems to explain the most data in the simplest way. This model of flame stabilization supposes that blowoff velocity is controlled by two independent factors, the recirculation length l and the critical time t_{cr}. The recirculation-zone length depends on aerodynamic factors such as gas velocity and flameholder size and shape. The critical time depends on physicochemical factors such as fuel concentration and temperature. The separation of the flameholding process into two independent parts is an extremely valuable concept, since it affords simple explanations of complex phenomena. Consequently, Zukoski's model of the flameholding process has been used as a guide for experimentation and as a means to explain the results.

This research was conducted first to confirm and then to extend the critical-time concept of bluff-body flame stabilization. For the former purpose, blowoff velocities and recirculation-zone lengths were measured for cylinders of various diameters and for different fuel concentrations. For the latter purpose, two additional factors were varied - pressure and tunnel geometry. Both these factors are known to affect blowoff velocity. There are several previous studies of the effect of pressure on blowoff velocity (refs. 1 and 6 to 8) but only limited data on the effect of tunnel geometry, although it is known that tunnel geometry strongly affects blowoff velocity (ref. 9).

SYMBOLS

A	area
C	constant
c_p	specific heat at constant pressure
d	flameholder diameter
h	flameholder length
k	thermal conductivity
l	recirculation-zone length
m	mass flow
Nu	Nusselt number
n,r,s	exponents
P	pressure
q	heat flux
Re	Reynolds number
T	temperature
t_{cr}	critical contact time
U	gas velocity
ρ	gas density
φ	equivalence ratio

Subscripts:

bo	blowoff
g	gas
w	wall

APPARATUS

A schematic diagram of the combustion tunnel is shown in figure 2. The 30-inch stainless-steel test section was constructed in such a way that its dimensions could be changed from 3 by 3 inches to 1 by 3 inches by changing the nozzle upstream of the test section from one having exit dimensions of 3 by 3 inches to one with dimensions of 1 by 3 inches. Inch-thick quartz windows were set in the test-section sides to permit viewing of the flame.

Flameholders used were water-cooled brass cylinders, ranging in diameter from 3/8 to 1 inch. They were located 10 inches upstream of the tunnel exit and 12 inches upstream of the water sprays that quenched the flame. A spark from a thin wire to the tunnel wall upstream of the flameholder was used for ignition. The thin wire remained in place throughout all the tests.

Pressure in the test section was measured about 2 inches upstream of the flameholder and was controlled by positioning the exhaust valve. Fuel (commercial propane; 95 percent propane, 5 percent other hydrocarbon) and air at 80° F were metered through critical-flow orifices. Critical-flow orifices are ideally suited for combustion studies at reduced pressure, since the mass flow through them is independent of test-section pressure.

Several layers of wire screen were placed between the entrance to the test section and the nozzle exit. The screens damped out longitudinal pressure oscillations in the tunnel when there was a pressure drop of 1 to 2 inches of mercury across them. Without the screens, stable combustion was not possible because of these oscillations.

An electrically operated probe was used to measure the recirculation-zone length.

PROCEDURE

The flame was ignited and blown off as follows: After the air was turned on, the pressure in the test section was adjusted to a value found by experience to give easy ignition. The ignition spark was then turned on, and fuel was admitted gradually to the stream by means of a manually controlled throttle valve. When ignition occurred, the throttle valve was opened wide.

After a steady flame was established, it was blown off by decreasing the pressure in the test section. As the pressure decreased, the flame became less vigorous because of the reduced pressure and also because of the increased velocity in the test section, since mass flow in the system is independent of test-section pressure. Eventually, a pressure was reached at which the flame was blown off. This pressure was recorded as the blowoff pressure corresponding to the mass flow and fuel-air ratio prevailing in the test section.

In nearly all cases, the mass flow was chosen to give a Reynolds number based on flameholder diameter of at least 10^4. This ensured (ref. 5) that the boundary layer on the flameholder was turbulent, thus avoiding or minimizing preferential diffusion effects found when the boundary layer is laminar.

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In order to obtain different mixture ratios at a given mass flow, the airflow was held constant while the fuel flow was changed. The slight change in Reynolds number resulting was neglected, and an average value was used. Usually two runs were made for a given mass flow or Reynolds number. Since it was nearly impossible to reset the flow to exactly its original value, the Reynolds numbers for supposedly duplicate runs often differed slightly. When using such sets of data, an average Reynolds number was assumed to apply to a mean line through the two sets of data.

Recirculation-zone lengths were measured by moving upstream a water-cooled probe inserted in the burned gases. When the ceramic-coated tip of the probe reached the recirculation zone, yellow-glowing gases resulting from vaporization of sodium compounds in the ceramic were swept upstream. This technique is similar in principle to that used in reference 5. The coating on the probe tip lasted only about an hour, but this was sufficient to make a number of measurements. Because it was necessary to water-cool the probe (otherwise the heat caused its rapid destruction), rich and lean flames were not hot enough to vaporize enough sodium to make a satisfactory measurement. Consequently, most of the lengths reported are for mixtures near stoichiometric.

RESULTS

Blowoff Velocities

The results of the blowoff measurements for the two tunnels are shown in figure 3, where blowoff pressure is plotted against fuel concentration expressed as equivalence ratio for four flameholder diameters. Curves are given for several different mass flows (expressed in terms of a Reynolds number referred to cylinder diameter).

Effect of pressure on blowoff velocity. - The experimental data were cross-plotted at constant cylinder diameter and equivalence ratio to obtain blowoff velocity as a function of pressure. Plots of blowoff velocity against pressure for stoichiometric mixtures are shown in figures 4(a) and (b) for the 3- by 3-inch and 1- by 3-inch test sections, respectively.

All velocities reported have been corrected for tunnel blockage by the flameholder (i.e., they are the velocities of the gas passing by the flameholder).

The figures show that, in general, the blowoff velocity varies directly with pressure raised to a power s, where s is between 1.2 and 2.5. However, in some of the results from the 1- by 3-inch tunnel, the rate of change of blowoff velocity with pressure becomes less at Reynolds numbers above 10^5, so that the log-log plot of blowoff velocity against pressure becomes curved at high velocities and pressures. For conditions corresponding to the curved portion of this plot, combustion was rough and noisy and the flames were not very steady. The calculations of Tsien (ref. 10) show that the velocity of the unburned gas between the flame and wall will become slightly supersonic somewhere downstream when the initial Mach number of the unburned gases exceeds a critical value (about 0.15 for a stoichiometric mixture). This point may move upstream at high Reynolds number; and, when the shock associated with this point touches the recirculation zone, serious effects on stability can be expected. Unpublished work of Zukoski has shown that the shock shortens the recirculation zone and reduces stability as observed in the 1- by 3-inch tunnel.

The exponent s that describes the pressure dependence of blowoff velocity was calculated neglecting the curved portions of the lines. The least squared values obtained for various sizes of flameholders are shown in figure 4. Based on the limited data available, the effect of flameholder size on the pressure exponent appears negligible. However, there does appear to be a definite effect of tunnel geometry on the exponent; the average values of s were 1.4 in the 3- by 3-inch tunnel and 2.1 in the 1- by 3-inch tunnel. The pressure exponents found here are larger than those previously observed. For example, DeZubay, using disk flameholders (ref. 1), and Ruegg and Klug, using cylinder flameholders (ref. 8), have both observed an exponent very near unity for hydrocarbon flames. These differences will be discussed later.

Effect of flameholder size on blowoff velocity. - The experimental data were cross-plotted at constant pressure and equivalence ratio to obtain blowoff velocity as a function of cylinder diameter. The results are plotted in figure 5. The data points from the 3- by 3-inch tunnel fall on straight lines, but those from the 1- by 3-inch tunnel (for which only three data points are available at each pressure) do not. At pressures above 0.60 atmosphere this may be the result of rough burning. For other conditions, it seems likely that this is a result of experimental error, since other investigators (refs. 1, 5, and 6) invariably observe that log-log plots of blowoff velocity against flameholder size are straight lines. Consequently, straight lines were sketched through the data from the 1- by 3-inch tunnel.

Exponents r describing the diameter dependence of blowoff velocity were calculated for the two duct geometries from the lines and are shown in figure 5. These exponents are close to unity with one exception, the exponent from the 1- by 3-inch tunnel at 0.70 atmosphere. This exception may be a result of rough burning, as mentioned previously. The observation that the blowoff velocity varies as about the first power of flameholder diameter is in agreement with other work (e.g., refs. 1 and 5). Reference 5 notes that this value of the diameter exponent is observed when the boundary layer of the flameholder is turbulent.

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Effect of tunnel geometry on blowoff velocity. - The experimental results were cross-plotted to obtain blowoff velocity at 0.5 atmosphere for a stoichiometric mixture and for a 1/2-inch flameholder in each of the two tunnels. The results were as follows: In the 3- by 3-inch tunnel the blowoff velocity was 222 feet per second, and in the 1- by 3-inch tunnel the blowoff velocity was 152 feet per second. These values may be compared with the blowoff velocity of 196 feet per second reported by reference 8 for a 1/2-inch flameholder in a 2- by 4-inch tunnel using a stoichiometric propane-air mixture. Note that the blowoff velocities for the two larger tunnels are in fair agreement and that these values are both larger than that for the 1- by 3-inch tunnel. Evidently, the geometric environment of the flameholder has a considerable effect on the blowoff velocity.

Thus, blowoff velocities measured by different workers cannot be compared unless the tunnel geometry is identical. The term "tunnel geometry" as used here also includes the distance from flameholder to duct exit. (This distance was constant for both tunnels in this research.) Barrere and Mestre (ref. 9) have shown this distance to have a large influence on blowoff velocity.

Reproducibility of blowoff data. - The general reproducibility of the data was thought to be of some interest, since many investigators note that reproducibility for blowoff data is poor. Figure 6 compares some data taken at different times. The scatter of the data is about ±10 percent, which is about what was expected from the small fluctuations continually present in the air supply and exhaust system.

Recirculation-Zone Lengths

Recirculation-zone lengths were measured in the 3- by 3-inch and 1- by 3-inch tunnels. In the course of the measurements, the flow patterns sketched in figure 1 were detected by the probe. The recirculating gases flow along the flameholder to the tunnel wall and then flow downstream along the tunnel wall. Since some of these cooled gases must reenter the recirculation zone, the flameholder and tunnel wall cool the recirculation zone. This has important effects on blowoff velocity, as discussed later.

Some typical results of the length measurements are shown in figure 7. This figure shows lengths for a 3/4-inch flameholder as a function of pressure for several equivalence ratios and mass-flow rates expressed as Reynolds number. The length is substantially independent of equivalence ratio φ, in agreement with previous results (ref. 5). The length appears to increase with flow rate and with decreasing pressure.

Since the stream velocity increases with both mass-flow rate and decreasing pressure (at constant mass-flow rate), recirculation-zone length was plotted against stream velocity (fig. 8). These figures show that the recirculation-zone length for a given flameholder is principally a function of gas velocity. The scatter of data points from a mean line averages about ±5 percent, which is similar to the scatter previously reported in reference 5.

At low gas velocities, the length increases with velocity. At some velocity, the length becomes independent of velocity. In general, this velocity is 50 feet per second greater in the 3- by 3-inch tunnel than in the 1- by 3-inch tunnel.

Recirculation-zone lengths for various flameholders in the two tunnels of this investigation and the 2- by 4-inch tunnel of reference 5 are compared in table I. The values given are mean values at high gas velocity where zone length is independent of gas velocity. The zone length in the 3- by 3-inch tunnel is about 40 percent greater than that in the 1- by 3-inch tunnel. (Note that the blowoff velocities for the 3- by 3-in. tunnel are also about 40 percent greater than those in the 1- by 3-in. tunnel.) The zone lengths in Zukoski's 2- by 4-inch tunnel are considerably larger than in the present tunnels. This difference may be due to the fact that the 2- by 4-inch tunnel of reference 5 was open to the atmosphere at the exit, while these tunnels exhaust into an 8-inch pipe connected to the vacuum system. On the other hand, examination of table I shows that the recirculation zone in both tunnels varies with the square root of flameholder diameter, in agreement with the results reported in reference 5 for a 2- by 4-inch tunnel.

As previously noted, the recirculation-zone-length measurements are subject to considerable scatter. This is caused by the following: (1) The downstream end of the recirculation zone is not sharp and distinct. (2) The apparent length depends somewhat on the quantity of vaporized material entering the recirculation zone; thus, a fresh ceramic tip on the probe yields a greater length than an old, nearly burned-out tip. (3) The sodium light dimmed as the pressure was lowered at constant Reynolds number, so that measurements became unreliable below about 0.5 atmosphere. This may have been caused by cooling of the recirculation zone as the pressure was reduced. Heat transfer from the recirculation zone is treated at greater length in the following section.

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DISCUSSION

Model of Flameholding Process

In Zukoski and Marble's flameholding model (ref. 5) considered here, the fresh gas from the free stream is continuously ignited by hot burned gases from the recirculation zone in the shear layer separating the recirculation zone from the fresh gas. The length of the shear layer is approximately equal to the length of the recirculation zone. The time t spent by the fresh gas in the shear layer, or mixing zone, is of the order l/U, where l is the recirculation-zone length and U is the velocity past the recirculation zone. If the fresh gas spends insufficient time in the shear layer, not enough gas is ignited to permit flame propagation and the entire flame blows off. The critical transit time t_{cr} required to maintain a flame must be $(l/U)_{bo}$. Thus, blowoff occurs whenever $l/U < t_{cr}$.

This flame-stabilization model indicates that blowoff velocity is controlled by two factors, l and t_{cr}. Zukoski observed that the recirculation-zone length depends on aerodynamic factors (such as gas velocity and flameholder size and shape) and t_{cr} depends on physicochemical factors (such as fuel concentration and temperature). The recirculation-zone length was measured in this research, and Zukoski's observations concerning it were confirmed. The critical time t_{cr} (ratio of recirculation-zone length to blowoff velocity) is discussed in the following section.

Critical Time

Blowoff velocities and their corresponding recirculation-zone lengths were used to calculate critical times. The results for stoichiometric mixtures are shown in figure 9. Figure 9(a) shows that, for the 3- by 3-inch tunnel, the critical time at any particular pressure is slightly dependent on flameholder diameter, the larger flameholders having the smaller critical times in most cases. The pressure dependence of t_{cr} varies in an irregular way from flameholder to flameholder. At least a part of the differences and irregularities observed are caused by the difficulty of getting precise recirculation-zone-length measurements in the 3- by 3-inch tunnel at high gas velocities. Figure 9(b) shows critical times as a function of pressure in the 1- by 3-inch tunnel. Here, the critical time is nearly independent of flameholder diameter, and the pressure dependence of critical time is almost independent of flameholder diameter.

Extrapolated average values at 1 atmosphere of the critical time in the two tunnels and Zukoski's average value of the critical time (for paint thinner, a mixture of 36 percent naphthenes, 58 percent paraffins, and 6 percent aromatics) are compared in the following table:

	Tunnel configuration		
	NACA 3X3"	NACA 1X3"	Ref. 5 2X4"
Critical time, t_{cr}, millisec	[a]0.35	[a]0.28	[b]0.29

[a]Extrapolated to 1 atm and averaged.

[b]Average value at 1 atm.

The three values are in fair agreement. This agreement of critical times for studies using two different hydrocarbon fuels indicates that the critical time is probably a combustion property akin to burning velocity (which differs little from hydrocarbon to hydrocarbon) and is probably not related to ignition delay (which usually differs greatly from hydrocarbon to hydrocarbon). More important, it indicates that differences in blowoff velocity from tunnel to tunnel for a given flameholder are caused primarily by changes in the recirculation-zone length.

The average pressure exponents for the critical time in the two tunnels are significantly different (-1.7 in the 1- by 3-in., -1.3 in the 3- by 3-in. tunnels). Such a difference is not expected from the critical-time model of flameholding. Since in most cases the pressure exponent for the critical time is the negative of the pressure exponent for the blowoff velocity, most blowoffs must occur at velocities corresponding to the flat portion of the plot of recirculation-zone length against velocity (fig. 8). If this is the case, DeZubay's exponent for the pressure dependence of blowoff velocity (0.95) of hydrocarbon flames probably corresponds to a pressure exponent for the critical time of about -0.9. This value is quite different from the value found herein.

Heat Losses from Recirculation Zone

As noted in the preceding section, several discrepancies are observed between the expected and actual behavior of the critical time. These are (1) the fact that the critical time seems to increase with flameholder size (especially notable in the 3- by 3-in. tunnel), and (2) the fact that the pressure exponents of the critical time (and therefore also of the blowoff velocity) differ in the two tunnels and also differ from previous results. In an attempt to explain these observations qualitatively, the following analysis of heat losses from the recirculation zone was made.

Heat loss from recirculation zone as function Reynolds number and tunnel geometry. - In the tunnel used herein, the ends of the recirculation zone are in contact with the water-cooled walls of the tunnel, as shown in figure 1. As a result, heat flows from the recirculation zone to the walls and to the water-cooled flameholder. This heat loss lowers the recirculation-zone temperature and causes it to be a less efficient ignition source (i.e., the value of the critical time is increased by cooling). A small change in recirculation-zone temperature can have a large effect on the critical time, as shown by Zukoski and Marble, who found an exponential dependence of time on temperature. If recirculation-zone temperature varies with pressure or tunnel geometry, the critical time will be affected.

It is assumed that the Reynolds number characterizing the flow in the recirculation zone is directly proportional to the approach-stream Reynolds number. Then the Nusselt number for heat transfer from the recirculation zone to the walls and flameholder can be expressed in terms of the Reynolds number as follows (ref. 11):

$$Nu \propto Re^n \tag{1}$$

Since the value of n for heat transfer in turbulent flow ranges from 0.6 (bluff body) to 0.8 (flat plate), n for this situation is probably less than 0.8.

The Nusselt number can be written as

$$Nu = \frac{qx}{(T_g - T_w)k} \tag{2}$$

where q is the heat flux to the flameholder and wall and x is a typical dimension (assumed here to be flameholder diameter d, to correspond with its usage in the Reynolds number).

The heat flux q can be written as

$$q = \frac{c_p \, \Delta T m}{A} \propto \frac{c_p \, \Delta T m}{(h + 2l)d} \tag{3}$$

where ΔT is the difference in temperature between gases entering and leaving the recirculation zone, m is the mass flow through the recirculation zone, and A is the wall and flameholder area effective in heat abstraction. This area is assumed to be proportional to the product of the flameholder diameter d and the sum of the flameholder length h and twice the recirculation-zone length l. These dimensions are illustrated in figure 1.

It is assumed that the mass flow through the recirculation zone m is proportional to the flameholder projected area hd and the mass-flow rate ρU past the flameholder. Thus,

$$m \propto \rho U h d \propto Re h \tag{4}$$

Combining equations (1) to (4) and assuming that ΔT is small enough that $T_g - T_w$ can be assumed constant,

$$\Delta T \propto Re^{n-1} \left(1 + \frac{2l}{h}\right) \tag{5}$$

Since $l = C\sqrt{d}$ (ref. 5), where C is a constant whose value depends on the tunnel geometry, this equation can be rewritten as

$$\Delta T \propto Re^{n-1} \left(1 + \frac{2C\sqrt{d}}{h}\right) \tag{6}$$

Effect of flameholder diameter on heat loss from recirculation zone. - At high Reynolds numbers ($>10^4$), the blowoff velocity is directly proportional to flameholder diameter. Then, the Reynolds number at blowoff varies as d^2. Equation (6) becomes

$$(\Delta T)_{bo} \propto d^{2(n-1)} \left(1 + \frac{2C\sqrt{d}}{h}\right) \tag{7}$$

It is likely that n is less than or equal to 0.75. In that case, $(\Delta T)_{bo}$ decreases with increasing flameholder diameter. This causes the critical time to decrease with increasing flameholder diameter. Substitution of numerical values into equation (7) shows that $(\Delta T)_{bo}$ is larger in the 3- by 3-inch tunnel than in the 1- by 3-inch tunnel for $n < 0.75$. Thus, a larger effect of flameholder diameter on the critical time might be expected in the larger tunnel.

Effect of pressure on heat losses from recirculation zone. - For a given flameholder diameter, the Reynolds number at blowoff varies as P^{1+s}, where s is the pressure exponent for the blowoff velocity. Substituting this in equation (6) gives

$$(\Delta T)_{bo} \propto P^{(s+1)(n-1)} \left(1 + \frac{2C\sqrt{d}}{h}\right) \tag{8}$$

Since n is less than unity, $(\Delta T)_{bo}$ will increase with decreasing pressure. Recalling that the critical time increases with ΔT, the net effect of the pressure dependence of $(\Delta T)_{bo}$ is to produce an abnormally large pressure dependence for the critical time. This effect may be expected to be largest in the 1- by 3-inch tunnel, in which h is smallest.

All these qualitative predictions are in accord with the experimental results. There does appear to be a tendency for the critical time to increase with flameholder diameter and for this effect to be greatest in the 3- by 3-inch tunnel. The pressure exponents for the critical time are larger in the present tunnels, where the flameholder is cooled and the recirculation zone is in contact with the wall, than in DeZubay's tunnel, where the flameholder was not cooled and the recirculation zone did not touch the wall. In addition, the pressure dependence of t_{cr} is larger in the 1- by 3-inch tunnel than in the 3- by 3-inch tunnel (-1.7 against -1.3). This agrees with the conclusion that the cooling effect should be greater and the exponent larger for shorter flameholders (smaller h).

Experimental confirmation of analysis. - A limited test of the preceding discussion was made as follows: A 3-inch-long flameholder can be used in the 1- by 3-inch tunnel if it is placed on the long axis of the tunnel cross section. The critical time should have the same pressure dependence for this configuration as for the 3- by 3-inch tunnel, since h is the same in both cases. In order to test this, blowoff velocities were measured for a 1/2-inch flameholder placed on the long axis of the 1- by 3-inch tunnel. The results are shown in figure 10 along with data from the 3- by 3-inch and 1- by 3-inch (short flameholder) tunnels. Above about 0.6 to 0.7 atmosphere, combustion was very rough and unsteady. Evidently the small distance over which the flame must spread to reach the wall causes the early onset of supersonic flow near the recirculation zone. Thus, a line was drawn only through the data points in the region of smooth combustion. The slope of this line is essentially the same as that for the 3- by 3-inch tunnel, indicating that the critical time has the same pressure dependence in the two cases. This is evidence that cooling of the recirculation zone is a factor in determining the critical time and its pressure dependence.

SUMMARY OF RESULTS

Blowoff velocities and recirculation-zone lengths of propane-air flames stabilized by cylindrical flameholders were measured as a function of pressure, flameholder diameter, and tunnel geometry for a range of Reynolds numbers. The results were as follows:

1. Blowoff velocities for cylindrical flameholders in 3- by 3-inch and 1- by 3-inch tunnels have different pressure dependences but about the same diameter dependences. The value of the blowoff velocity for a given pressure and flameholder diameter is greater in the 3- by 3-inch than in the 1- by 3-inch tunnel.

2. Recirculation-zone lengths in the two tunnels are a function of gas velocity, increasing at low velocities and becoming constant at high velocities. Recirculation-zone lengths are larger in the 3- by 3-inch tunnel than in the 1- by 3-inch tunnel. The recirculation zone-length varies as about the square root of the flameholder diameter and is independent of fuel-air ratio to a good approximation.

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3. Critical times (ratios of recirculation-zone length to blowoff velocity) were independent of flameholder diameter in the 1- by 3-inch tunnel, but decreased slightly with increasing flameholder diameter in the 3- by 3-inch tunnel. The pressure dependence of the critical time was larger in the 1- by 3-inch tunnel than in the 3- by 3-inch tunnel. These discrepancies can be qualitatively explained as the result of cooling of the recirculation zone by the flameholder and tunnel walls. Average values of the critical time for the two tunnels at 1 atmosphere (extrapolated from low pressures) agreed reasonably well with one another and with a value reported previously for a different wind tunnel.

The results of this research support the view that the variation of blowoff velocity with flameholder size and tunnel geometry is largely the result of changes in the recirculation-zone length, and that the variation of blowoff velocity with pressure is principally the result of variation of the critical time with pressure.

Lewis Flight Propulsion Laboratory
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REFERENCES

1. DeZubay, E. A.: Characteristics of Disk-Controlled Flame Holders. Aero. Digest, vol. 61, no. 1, July 1950, pp. 54-56; 102-104.

2. Longwell, John P., Frost, Edward E., and Weiss, Malcom A.: Flame Stability in Bluff Body Recirculation Zones. Ind. and Eng. Chem., vol. 45, no. 8, Aug. 1953, pp. 1629-1633.

3. Lees, Lester: Fluid-Mechanical Aspects of Flame Stabilization. Jet Prop., vol. 24, no. 4, July-Aug. 1954, pp. 234-236.

4. Spalding, D. B.: Theoretical Aspects of Flame Stabilization. Aircraft Eng., vol. 25, no. 295, Sept. 1953, pp. 264-268; 276.

5. Zukoski, Edward E., and Marble, Frank E.: Experiments Concerning the Mechanism of Flame Blowoff from Bluff Bodies. Proc. Gas Dynamics Symposium (Aerothermochem.), Northwestern Univ., 1956, pp. 205-210.

6. Friedman, J., Bennet, W. J., and Zwick, E. B.: The Engineering Application of Combustion Research to Ramjet Engines. Fourth Symposium (International) on Combustion, The Williams & Wilkins Co., 1953, pp. 756-764. (Discussion by E. A. DeZubay, p. 764.)

7. Pigford, Thomas Harrington: Effect of Pressure on the Stabilization of Flames in Propane-Air Mixtures. Ph.D. Thesis, M.I.T., 1952.

8. Ruegg, F. W., and Klug, H. J.: Fourth Report of Progress on the Studies of Jet Engine Combustors. Rep. 4797, NBS, June 30, 1956.

9. Barrere, M., et Mestre, A.: Stabilisation des Flammes par des Obstacles. Selected Combustion Problems - Fundamentals and Aeronautical Applications, Butterworths Sci. Pub. (London), 1954, pp. 426-446.

10. Tsien, H. S.: Influence of a Flame Front on the Flow Field. Jour. Appl. Mech., vol. 18, no. 2, June 1951, pp. 188-194.

11. Spalding, D. B.: Some Fundamentals of Combustion. Academic Press, Inc., 1955, p. 49.

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TABLE I. - RECIRCULATION-ZONE LENGTHS FOR VARIOUS CYLINDER DIAMETERS IN DIFFERENT TUNNEL GEOMETRIES

Flameholder diameter, d, in.	Recirculation-zone length, l, in.		
	NACA 3X3"	NACA 1X3"	Ref. 5 2X4"
0.375	1.8	---	4.0
.50	2.4	1.7	4.6
.75	3.1	2.5	5.6
1.0	3.7	2.7	6.5

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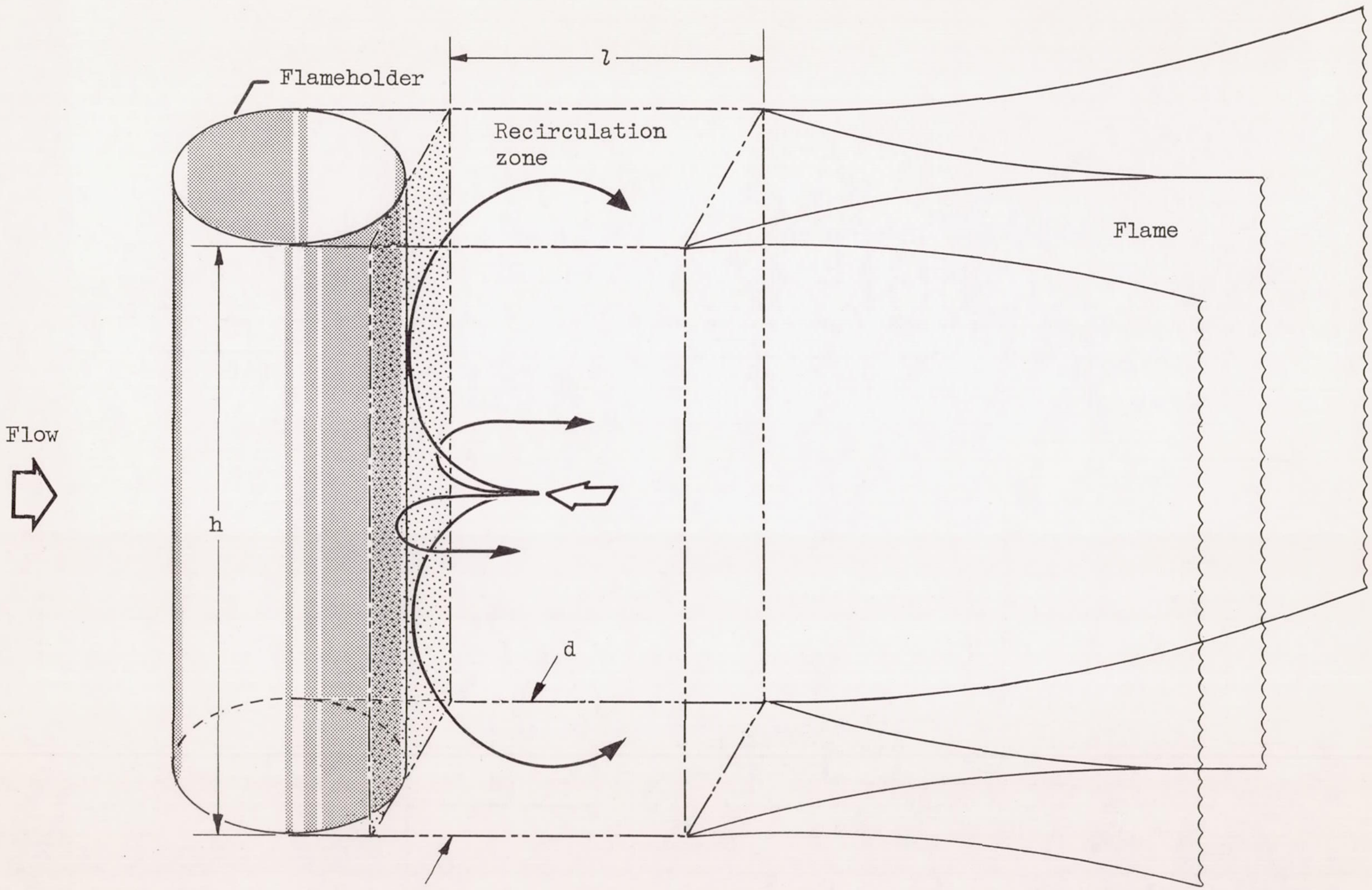
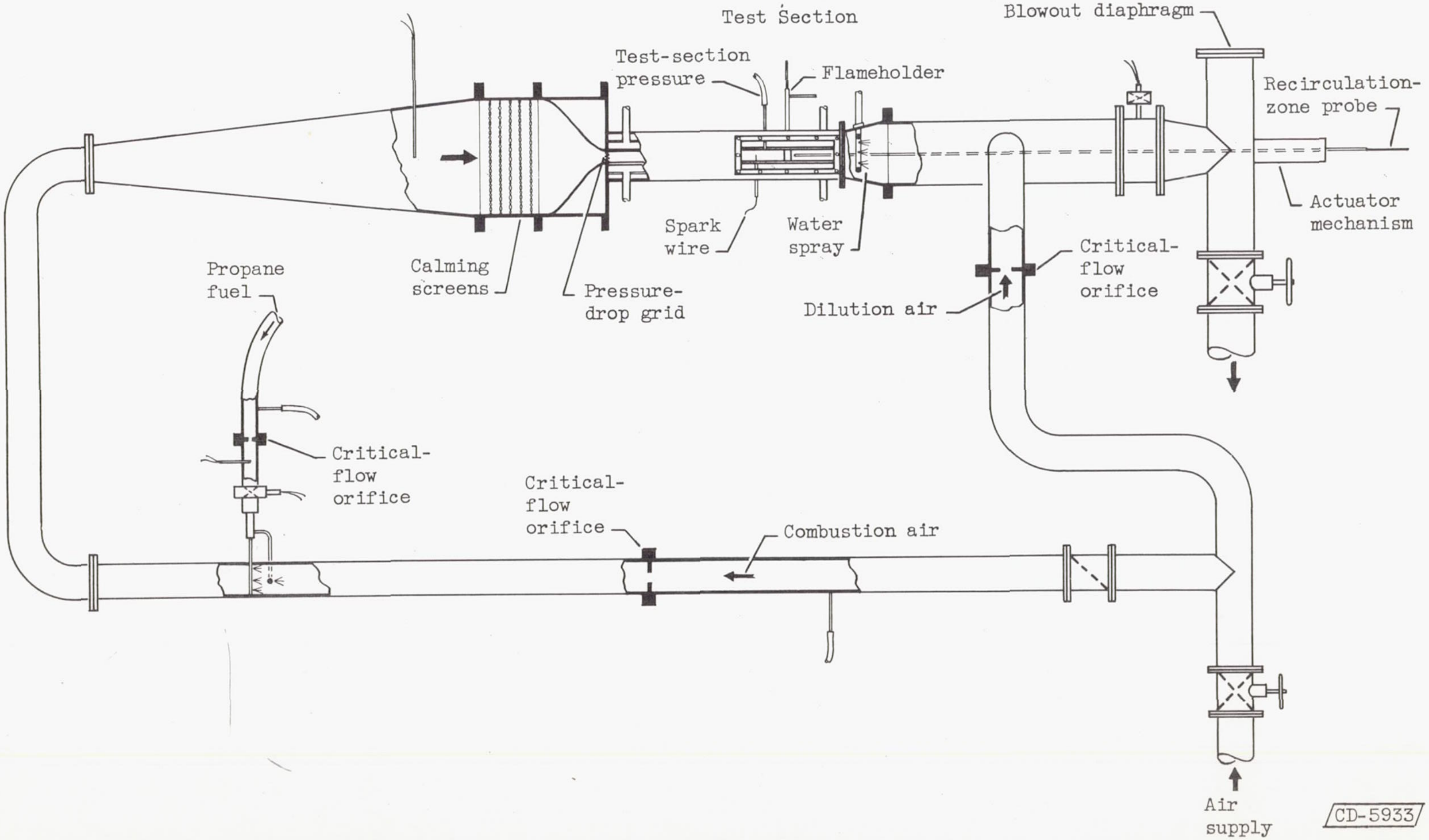
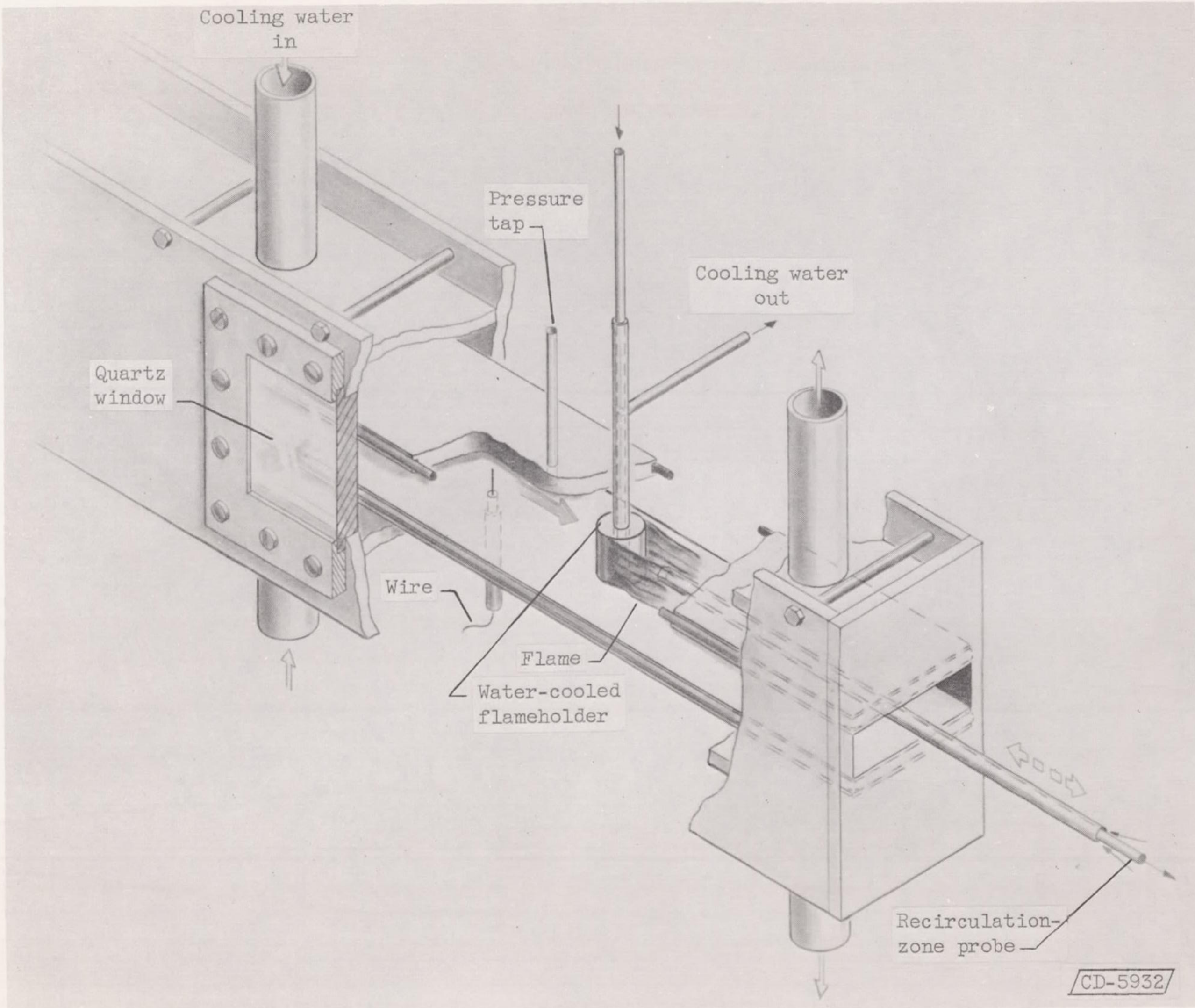


Figure 1. - Flame stabilized by a bluff body.



(a) Complete system.

Figure 2. - Low-pressure flame-stability apparatus.



(b) Test section, 1- by 3-inch tunnel.

Figure 2. - Concluded. Low-pressure flame-stability apparatus.

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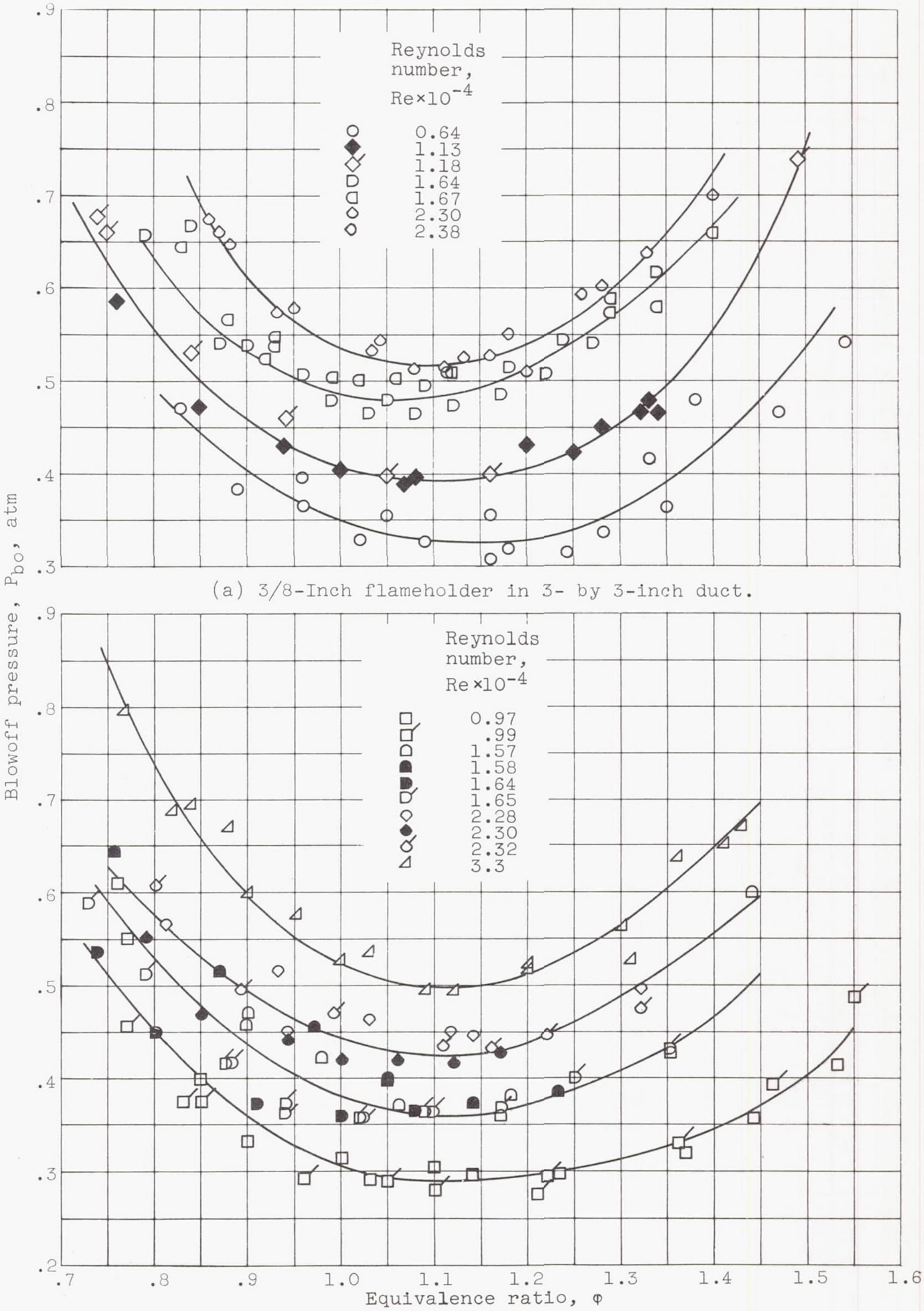

(b) 1/2-Inch flameholder in 3- by 3-inch duct.

Figure 3. - Variation of blowoff pressure with fuel concentration for different Reynolds numbers.

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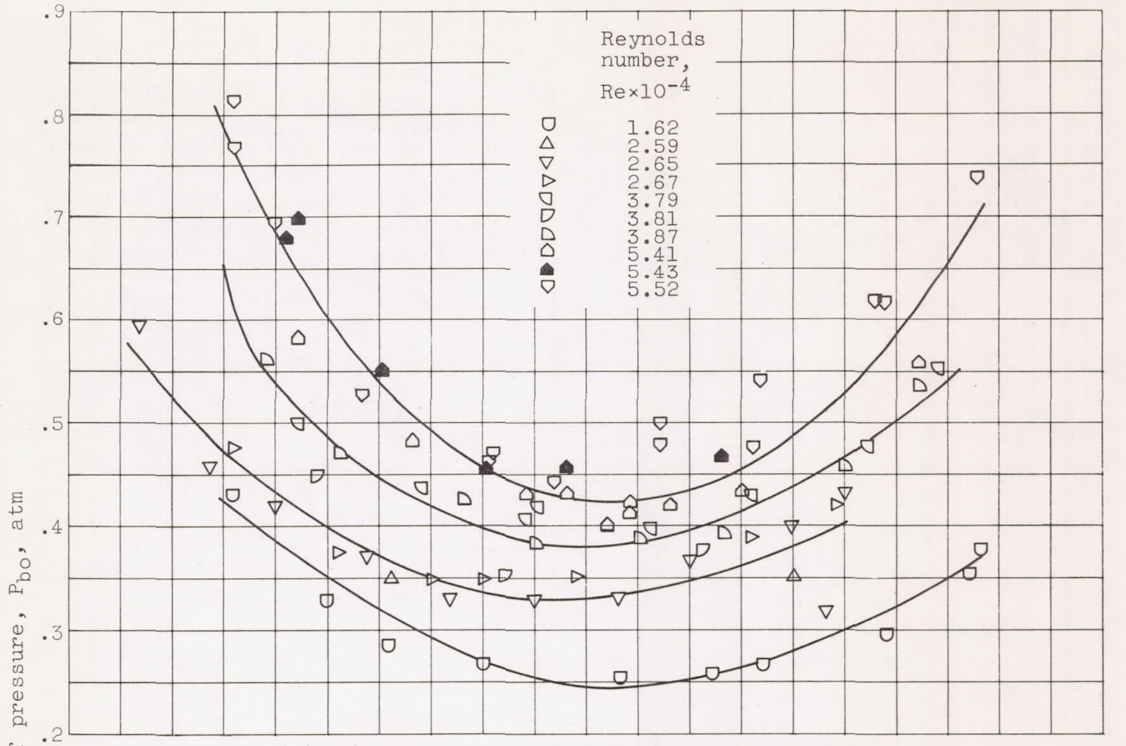
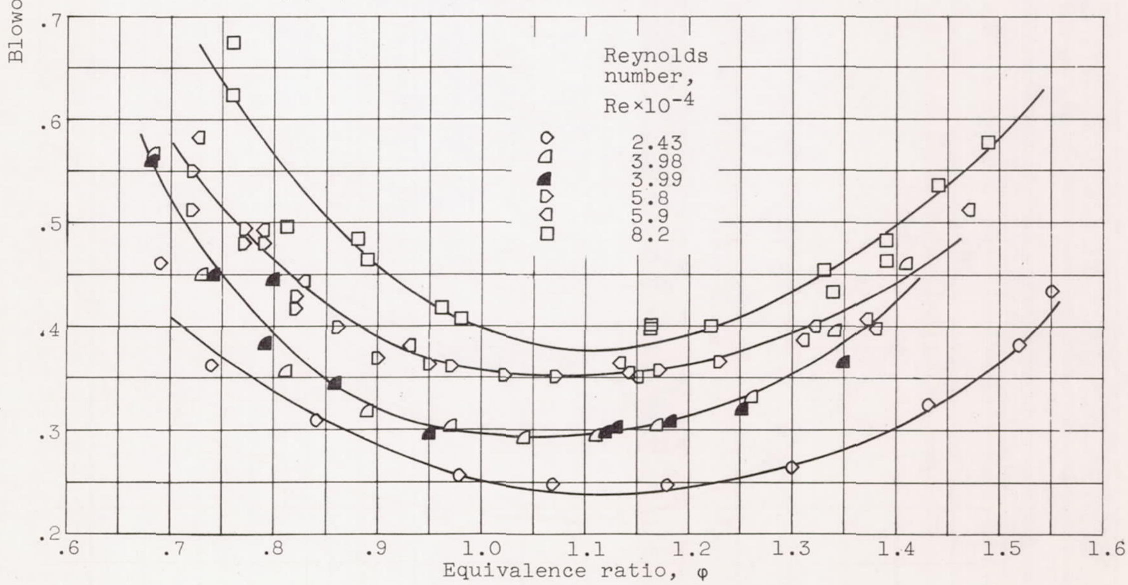
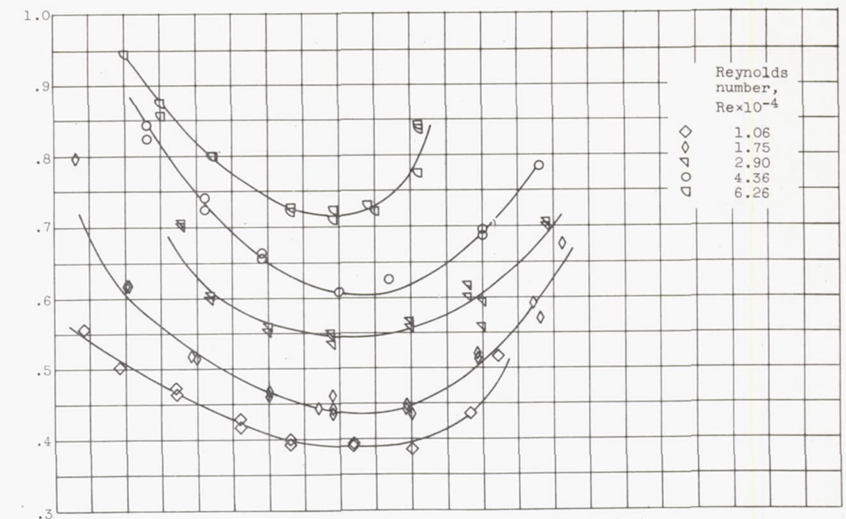


(c) 3/4-Inch flameholder in 3- by 3-inch duct.

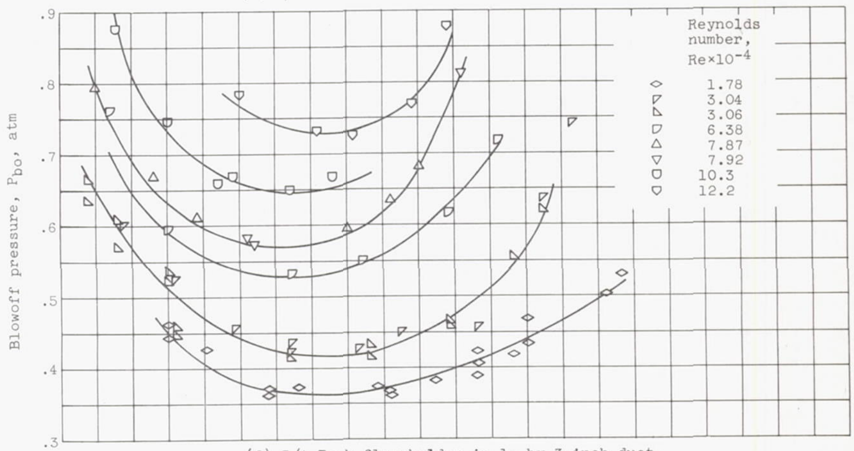


(d) 1-Inch flameholder in 3- by 3-inch duct.

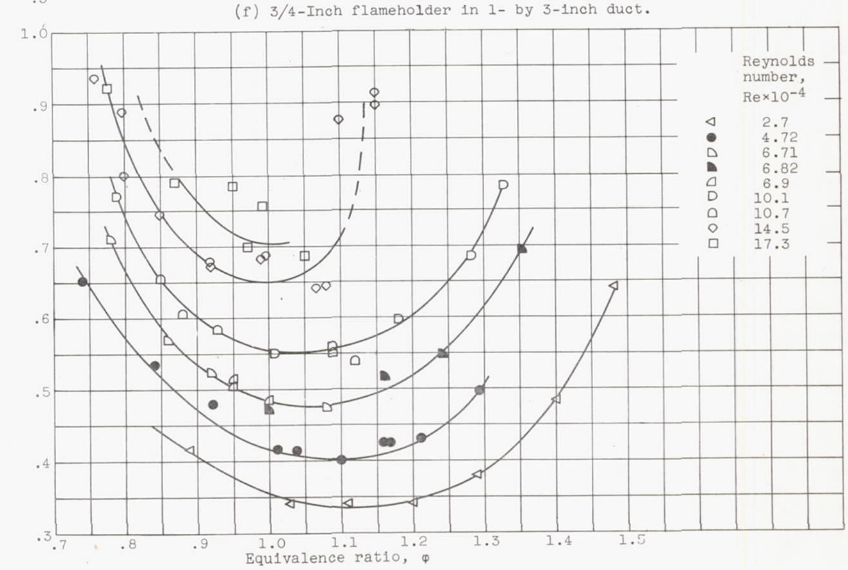
Figure 3. - Continued. Variation of blowoff pressure with fuel concentration for different Reynolds numbers.



(e) 1/2-Inch flameholder in 1- by 3-inch duct.



(f) 3/4-Inch flameholder in 1- by 3-inch duct.



(g) 1-Inch flameholder in 1- by 3-inch duct.

Figure 3. - Concluded. Variation of blowoff pressure with fuel concentration for different Reynolds numbers.

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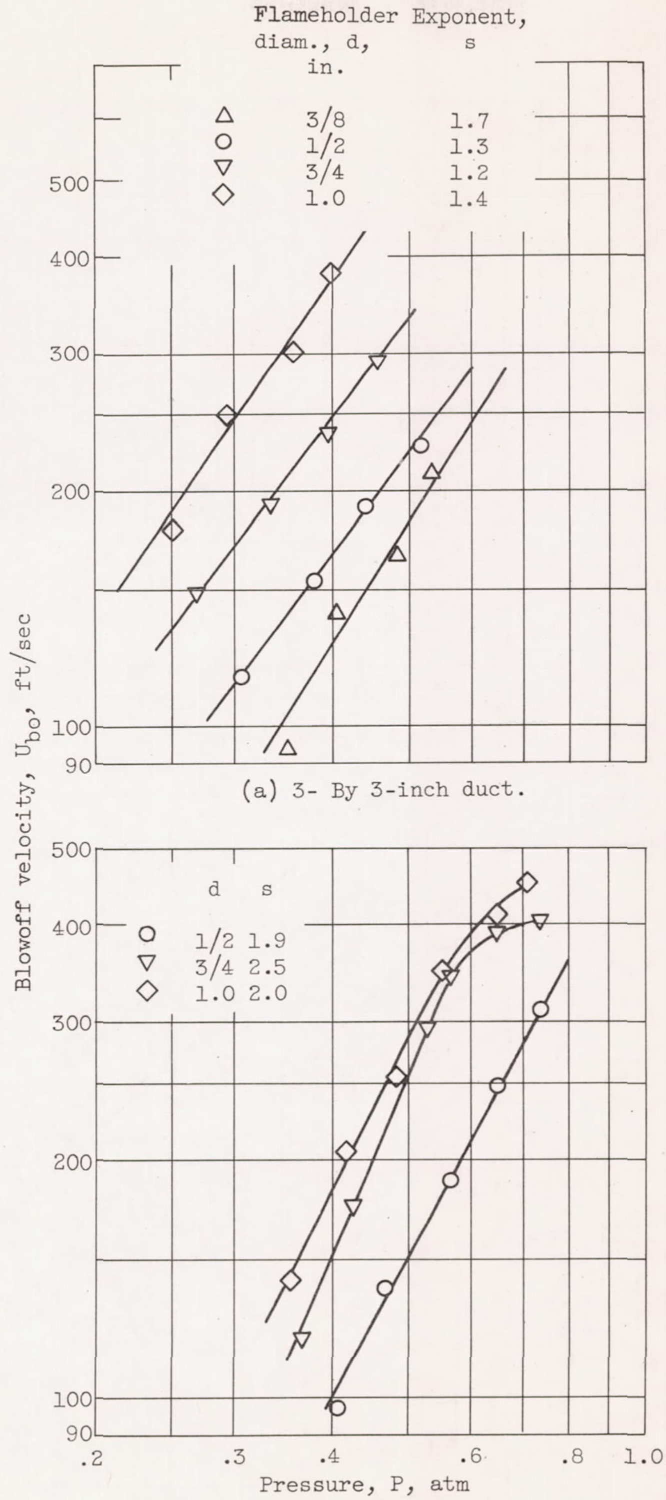
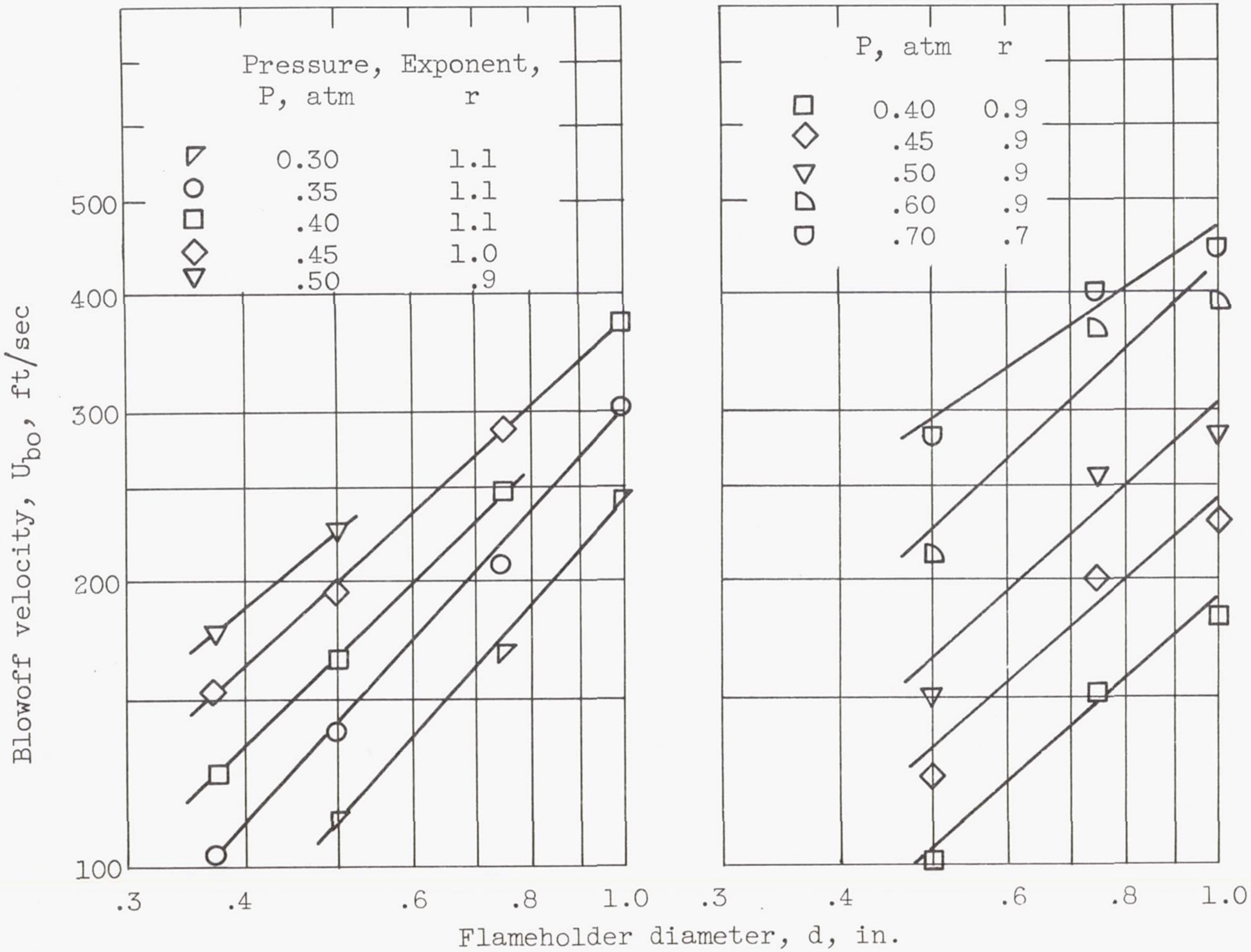


(b) 1- By 3-inch duct.

Figure 4. - Effect of pressure on blowoff velocity of stoichiometric mixtures.



(a) 3- By 3-inch duct. (b) 1- By 3-inch duct.

Figure 5. - Effect of flameholder diameter on blowoff velocity of stoichiometric mixtures.

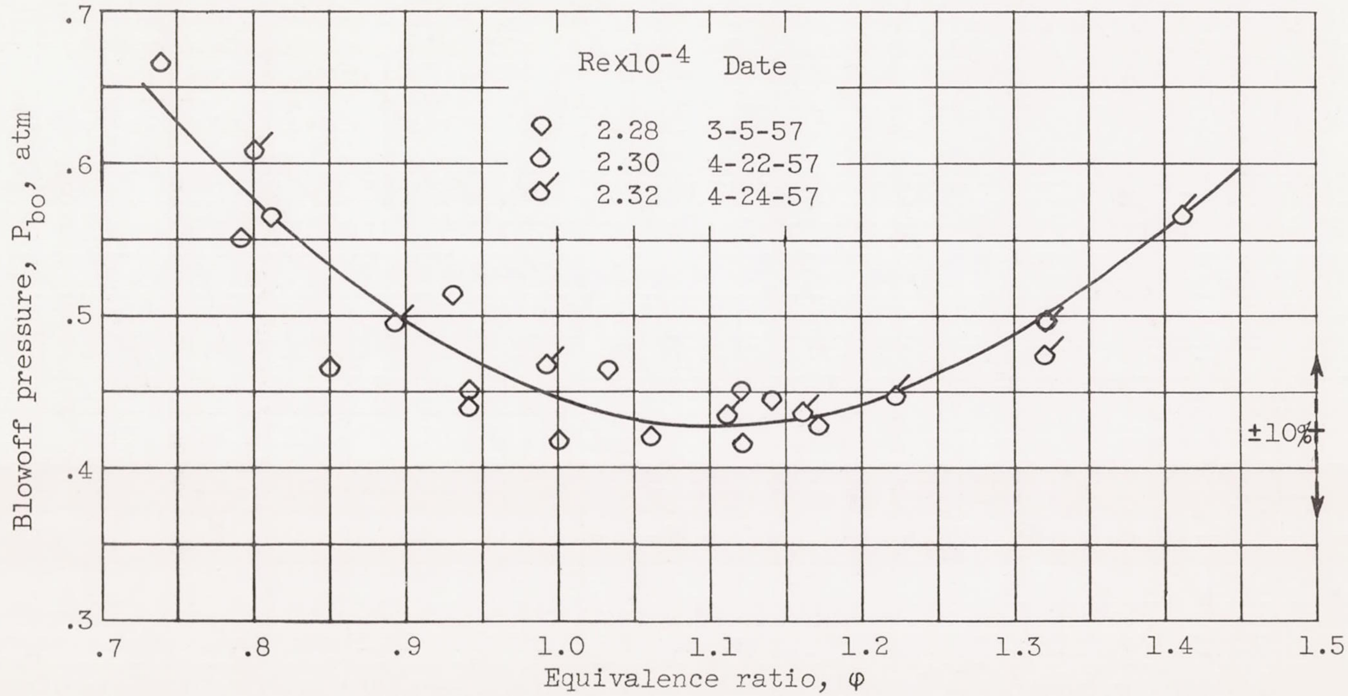


Figure 6. - Reproducibility of data. Blowoff pressures in 3- by 3-inch duct for 1/2-inch flameholder.

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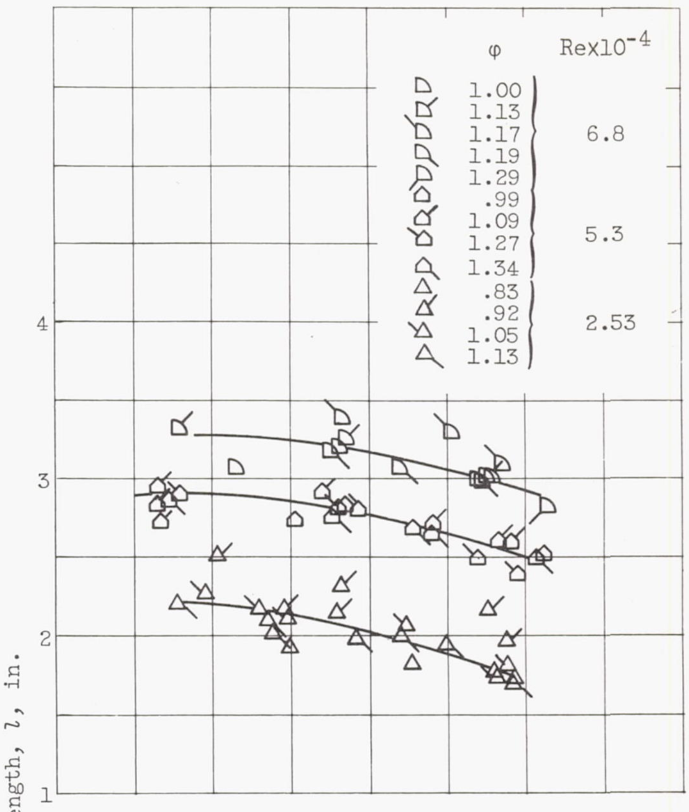
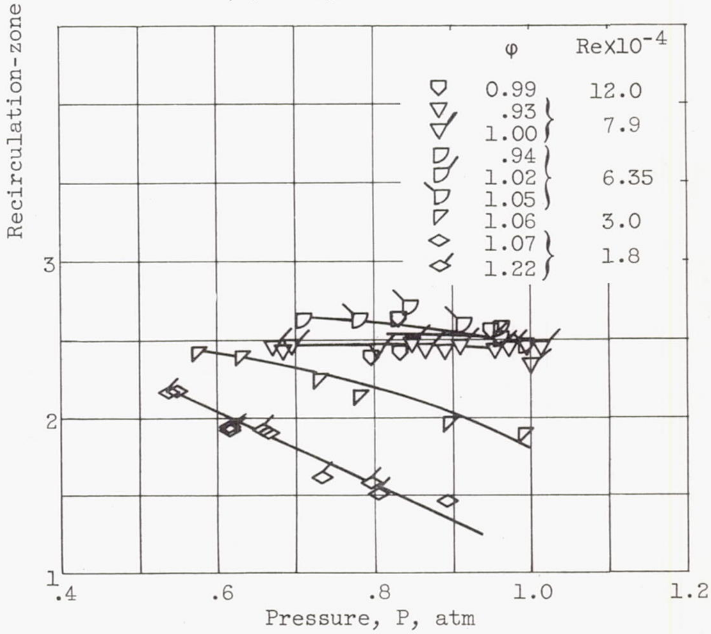
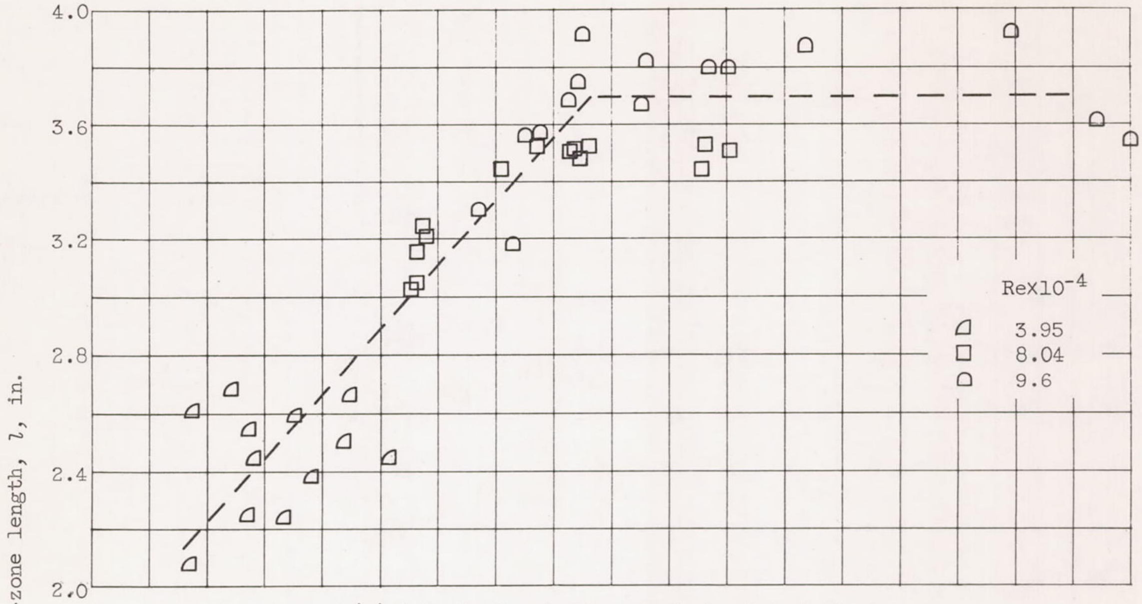


(a) 3- By 3-inch duct.

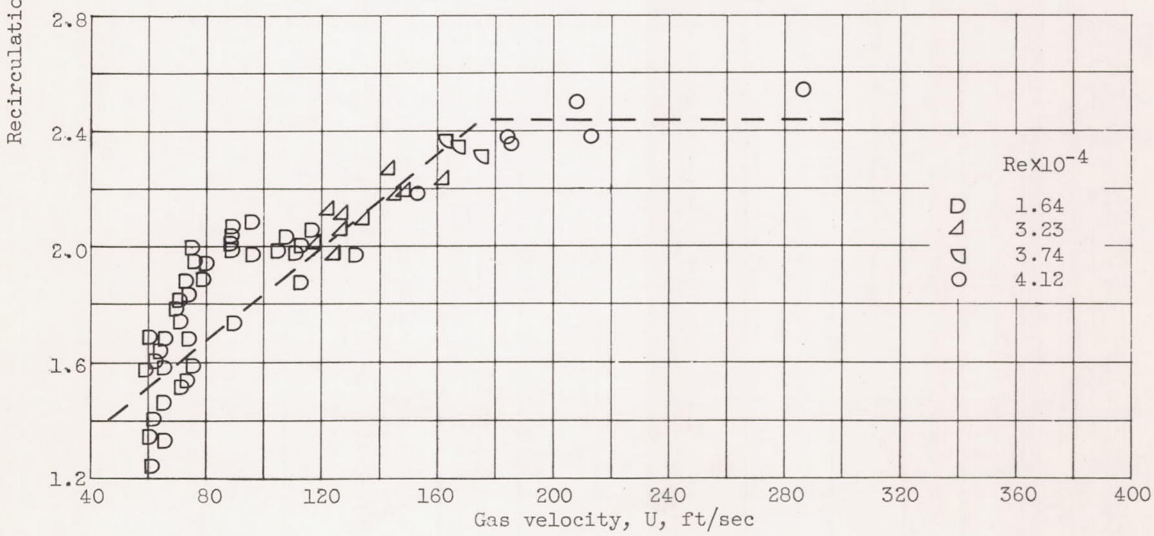


(b) 1- By 3-inch duct.

Figure 7. - Typical plots of recirculation-zone lengths against pressure for various mass flows. Flameholder diameter, 3/4 inch.



(a) 1-Inch flameholder in 3- by 3-inch duct.



(b) 1/2-Inch flameholder in 3- by 3-inch duct.

Figure 8. - Recirculation-zone length as function of gas velocity.

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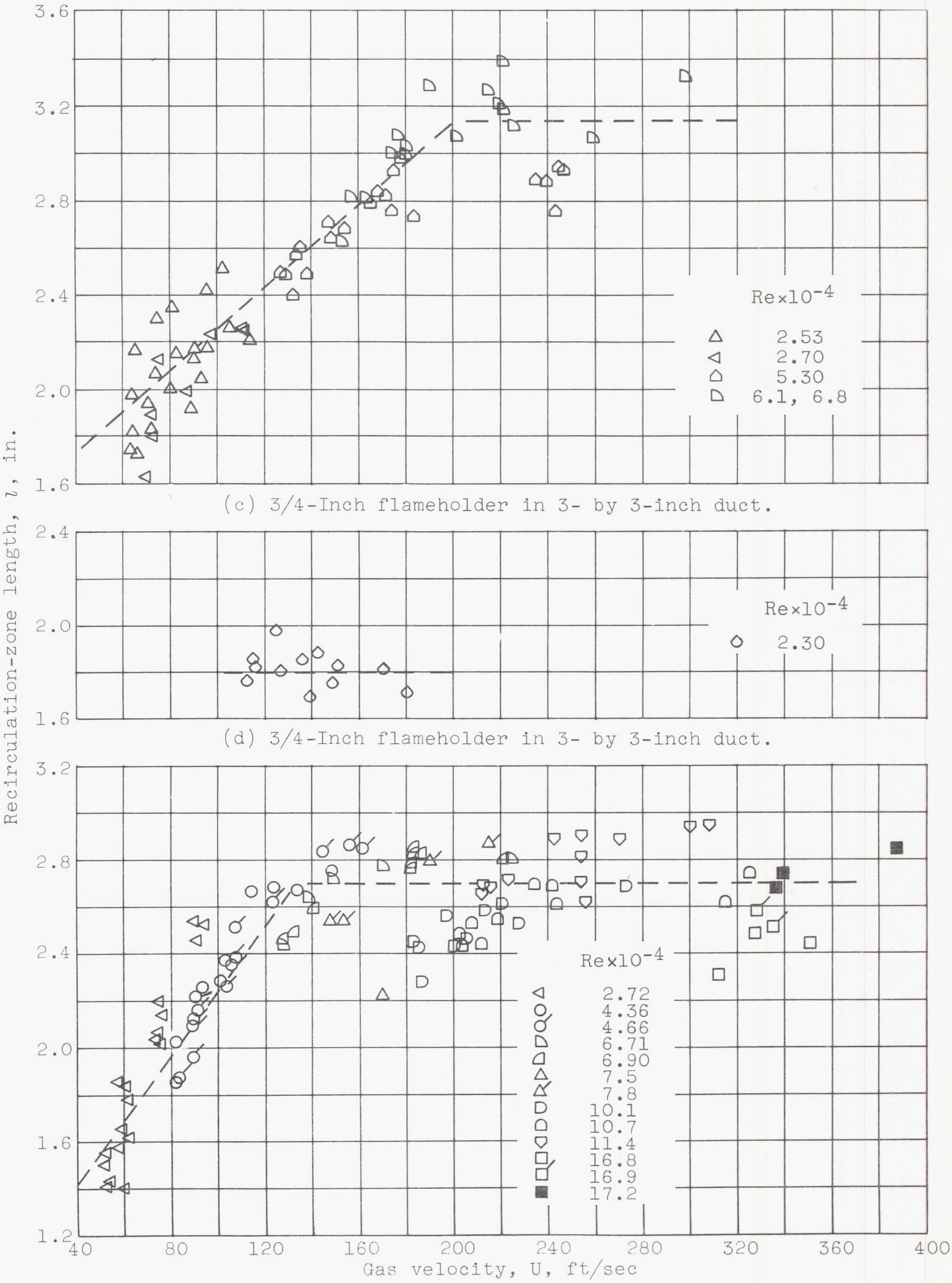
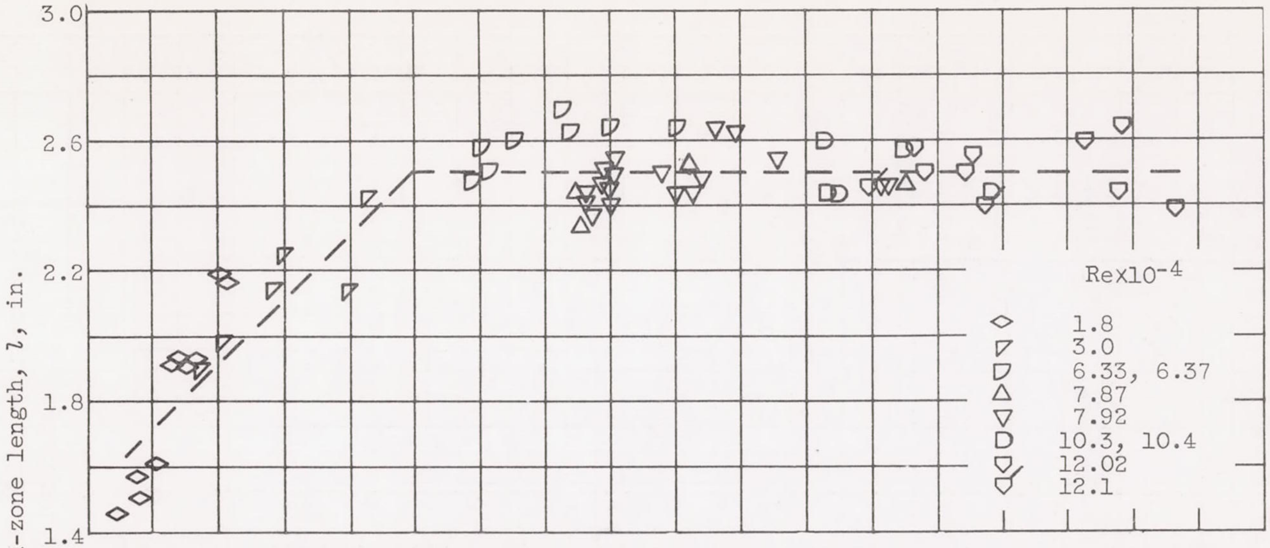


(c) 3/4-Inch flameholder in 3- by 3-inch duct.

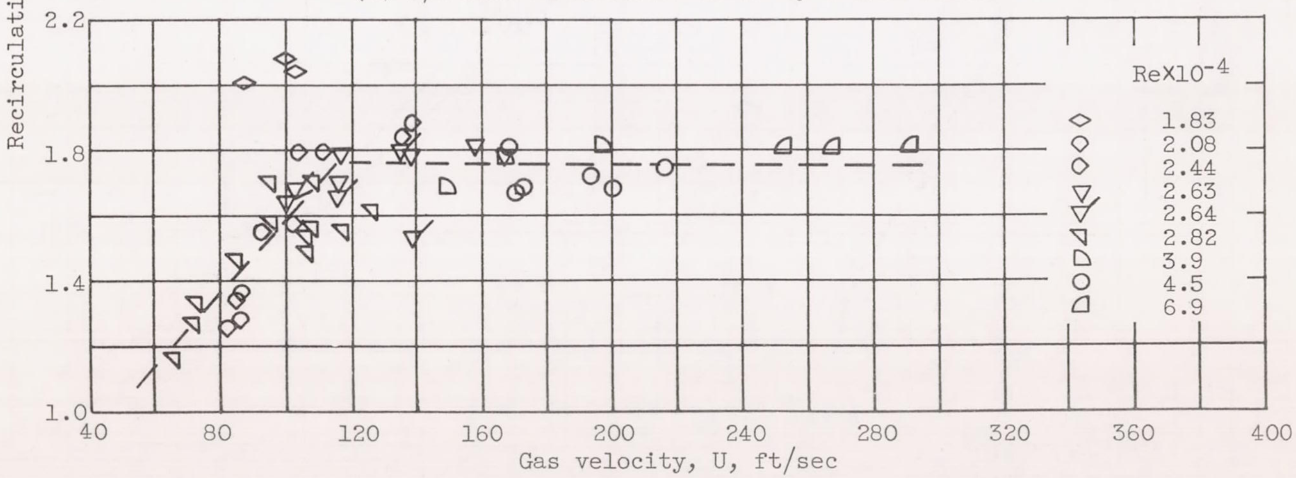
(d) 3/4-Inch flameholder in 3- by 3-inch duct.

(e) 1-Inch flameholder in 1- by 3-inch duct.

Figure 8. - Continued. Recirculation-zone length as function of gas velocity.

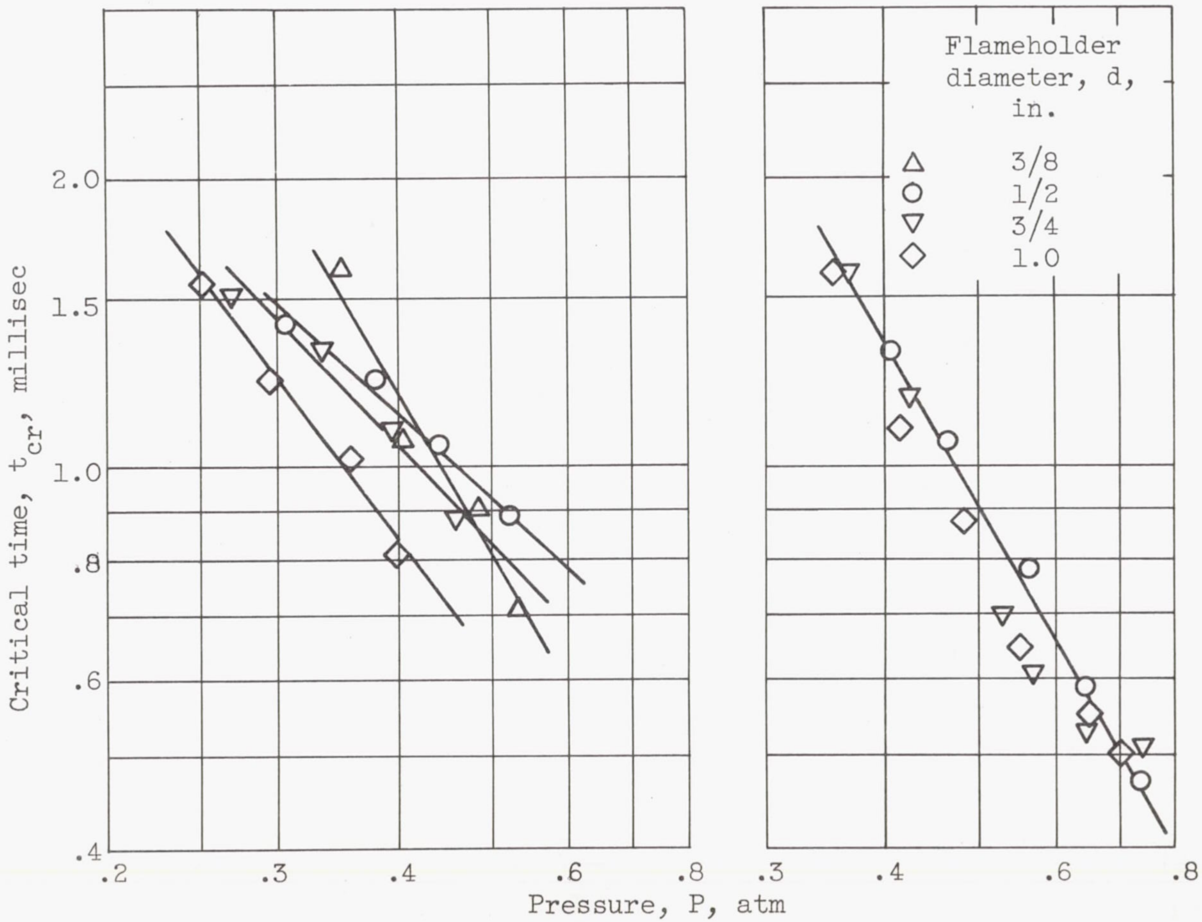


(f) 3/4-Inch flameholder in 1- by 3-inch duct.



(g) 1/2-Inch flameholder in 1- by 3-inch duct.

Figure 8. - Concluded. Recirculation-zone length as function of gas velocity.



(a) 3- By 3-inch duct.

(b) 1- By 3-inch duct.

Figure 9. - Critical time as a function of pressure for various flame-holder diameters.

4866

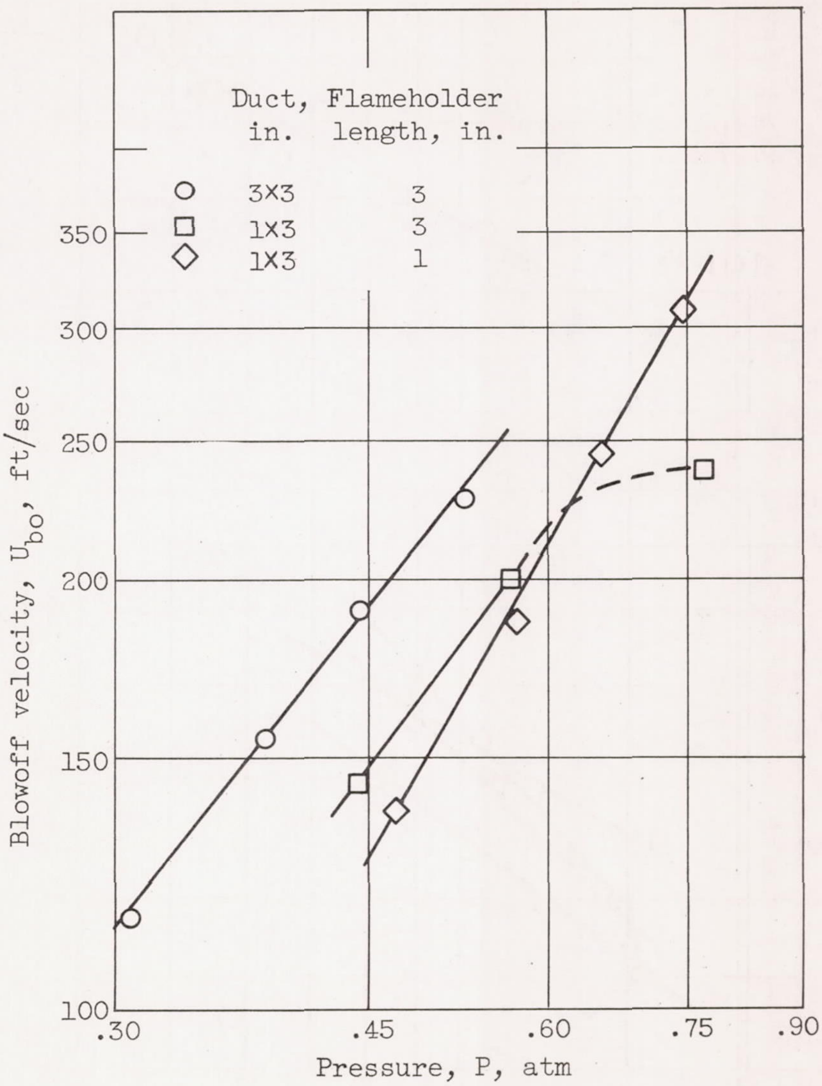


Figure 10. - Pressure dependence of blowoff velocity for a 1/2-inch flameholder in three different tunnel geometries.

NACA - Langley Field, Va.