The Relationship Between Flame Stability and Drag of Bluff-Body Flameholders

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The main purpose of this investigation is to establish a relationship between the blowoff velocity of a bluff-body flameholder and its drag coefficient. To this end, numerous measurements of blowoff velocity and drag coefficient are carried out on various forms of two-dimensional flameholders. They include conventional V-gutters of the type widely employed in turbojet afterburners, and "single-sided" flameholders that are characterized by a single-vortex flow pattern in their wake region. The test program covers wide ranges of effective pressure ratio obtained using the water injection technique, and it also includes variations in velocity, flameholder size, and flameholder blockage. The results confirm previous findings in regard to the strong influence of drag coefficient on blowoff velocity. They also provide a satisfactory explanation for the previously reported superior flameholding properties of single-vortex systems over double-vortex systems.

Nomenclature

B_a	= aerodynamic blockage of flameholder
B_g	= geometric blockage of flameholder
C_D	= drag coefficient for zero blockage
C_{D_b}	= base drag coefficient
D	= gutter width
P_e	= effective pressure
U_{BO}	= peak blowoff velocity
U_0	= approach stream velocity
ΔP	= pressure loss across flameholder
θ	= included angle of gutter
ϕ	= equivalence ratio

Introduction

IN the design of afterburner systems, steps must be taken to ensure that combustion can be initiated and sustained over a wide range of flight conditions. Effective flameholding must be maintained in highly turbulent gas streams flowing at velocities that exceed by two orders of magnitude the normal flame speeds of the fuel/air mixtures employed. Furthermore, the flame must stay lit during the various abnormal conditions that are sometimes encountered in flight. A notable example is the attainment of lightoff at high altitude with nozzle open, a situation which creates within the jet pipe a combination of very low pressure and exceptionally high velocity, both of which are detrimental to flame stability.

In addition to their numerous practical applications, bluff-body flameholders have also been widely used in experimental studies on flame stability. In fact, the great preponderance of available data on flame stability was obtained with bluff-body flameholders, usually in the form of discs, rods, cones, or V-gutters.

The stabilizing performance of a bluff-body flameholder may be described either in terms of the range of equivalence ratios over which stable combustion can be achieved, or by the maximum flow velocity that the system can tolerate before flame extinction occurs. Both aspects are important in practical combustion systems. Another important property of a flameholder is its aerodynamic drag. In general, any increase in the drag of a flameholder, whether it be caused by increase in size or change in geometry, will usually enlarge the volume of the wake region and thereby improve flame stability. However, drag or, more specifically, the pressure loss associated with drag has an adverse effect on the overall performance of engines fitted with afterburners. Thus, from a design viewpoint, a highly desirable form of flameholder is one having a high stability/drag ratio.

Because the flameholding properties of a bluff body and its aerodynamic drag are both related to the size and shape of the wake region, it has long been recognized that a physically more meaningful description of flame stability could be obtained by incorporating flameholder drag into the correlating parameter for blowoff velocity. The first steps toward establishing a relationship between blowoff velocity and drag coefficient are described by Barrère and Mestre in their paper published in 1954.[1] Using various types and shapes of flameholder, all of the same projected width, they obtained stability loops which showed that the characteristic dimension of a bluff body should be not its geometric width, but rather the maximum width of the wake created behind it. Mestre[2] later showed that the stability loops obtained with a number of differently shaped flameholders could, in fact, be made to coincide by the introduction of a drag coefficient term into the correlating parameter for blowoff velocity. According to Mestre, we have

$$U_{BO} \alpha C_D \tag{1}$$

As Mestre's experiments were all conducted on bluff bodies having short forebody shapes (i.e., negligible skin friction) the above correlation should really be in terms of C_{D_b}, the base drag coefficient.

Later analysis of Mestre's results, as well as the results of other workers, led Herbert[3] to suggest a relationship between blowoff velocity and drag coefficient of the form

$$U_{BO} \alpha C_D^m \tag{2}$$

where $m = 0.5$ for three-dimensional bodies, and $m = 1.0$ for two-dimensional bodies.

More recent analysis of the early data by Mestre[2] and Kutzko,[4] led Putnam and Razgaitis[5] to the conclusion that the effect of flameholder shape for axially symmetric flameholders can be eliminated by using the hot drag of the flameholder and the blowoff velocity as correlating factors. For the high

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Reynolds numbers of most practical interest, they obtained a simple overall correlation of air/fuel ratio at blowoff with $U_{BO}/C_D^{0.5}$.

The main incentive for the present work was to determine a relationship between blowoff velocity and drag coefficient for the sizes and shapes of flameholders employed in aircraft propulsion systems. Another objective was to investigate further the aerodynamic and flameholding properties of single-sided flameholders, i.e., flameholders that are characterized by a single-vortex flow pattern in their wake region. Previous work by Rao and Lefebvre[6] had indicated that this type of flameholder exhibits higher blowoff velocities than conventional V-gutters of the same basic shape, size, and blockage. Thus, the single-sided flameholder would appear to have considerable potential for practical applications provided, of course, its superior stability performance is not matched by a correspondingly high drag coefficient.

The experimental test program described below utilized both combustion and wind tunnel facilities. The first phase of the work included combustion rig tests to obtain stability loops for all the flameholders of interest. These same flameholders or plexiglass replicas were then inserted into a wind tunnel having the same size and geometry as the combustion test section, in order to measure the corresponding values of drag coefficient. The results of the two sets of experiments were then compared and analyzed with a view to establishing a relationship between stability performance and flameholder drag coefficient.

Flame Stabilization

Due to apparatus limitations, in particular the difficulty and high cost of providing high air flow rates at low (subatmospheric) pressures, most of the previous work on bluff-body flame stabilization has utilized fan air. This is essentially at atmospheric pressure, so that where the flameholders tested have been of a practical size, the results have usually been confined to very weak or very rich mixtures. This is a serious impediment to the analysis of stability loops and blowoff data because, when blowoff velocity is plotted against equivalence ratio, θ, the slope of the line representing θ vs U_{BO} is usually so small that slight errors in the measurement or determination of θ produce disproportionately large errors in U_{BO}. It is precisely this problem that renders the analysis of Mestre's data, as well as those of many other workers, so difficult.

When tests have been carried out in the range of equivalence ratios where the blowoff velocity is least sensitive to variations in equivalence ratio, i.e., near stoichiometric (see Figs. 1-3), either velocities have been very high or dimensions very small. In either event, extrapolation to practical velocities or practical dimensions has been a somewhat dubious process. It is difficult to extrapolate dimensions because any such extrapolation must also take into account effects arising from a change in "blockage." It is equally difficult to extrapolate velocities because at high velocities compressibility effects can change the flow pattern in and around the combustion zone.

In the present study, this problem is surmounted using the well-established "water injection technique," in which low pressures are simulated by injecting water or steam into the fuel-air mixture flowing into the combustion zone. This approach allows complete stability loops to be drawn for large flameholders at simulated pressures down to one-twentieth of an atmosphere.

The main advantage of the water injection technique is that it allows the combustion performance of large-scale combustion systems to be fully evaluated while operating within their normal range of velocities and fuel/air ratios. Air is supplied at normal atmospheric pressure, usually from a fan, and lower pressures are simulated by introducing water into the combustion zone. The success of the method relies on the inability of the reaction zone to detect the difference between a reduction in gas pressure and a reduction in reaction temperature which, in this instance, is accomplished by the addition of water.[7]

The apparatus employed comprises a supply of air at atmospheric pressure, a preheat combustion chamber, a working section containing the flameholder under test, and a provision for injecting kerosene and water in well-atomized form into the flowing gas upstream of the flameholder. Sufficient time and temperature is provided between the planes of injection of water and fuel and the flameholder to ensure that both liquids are fully prevaporized and premixed upstream of the reaction zone.

The test procedure is quite simple. The velocity and temperature of the gas flowing over the stabilizer are adjusted to the desired values; the fuel is turned on, and a flame is established in the recirculation zone downstream of the stabilizer. Water is then gradually admixed with the fuel in increasing amounts until extinction occurs. This process is repeated at a sufficient number of fuel flow rates for a complete stability loop to be drawn.

Curves of this type provide a useful means for comparing the basic stability of various designs of flameholder. The only assumption involved is a reasonable one, namely that the flameholder requiring the largest amount of water to cause flame extinction has the best stability. The value of the technique is greatly enhanced by the relationship which has been derived from global reaction rate considerations between the amount of water added and the equivalent reduction in pressure.[6-8] For example, it is found that injecting a quantity

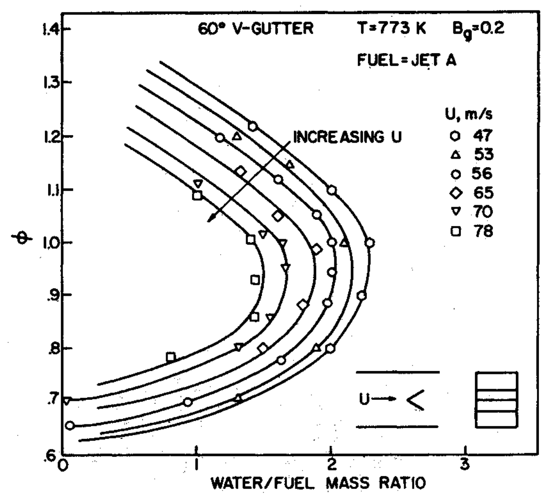

Fig. 1 Graphs illustrating the effects of flow velocity on stability for conventional V-gutters.

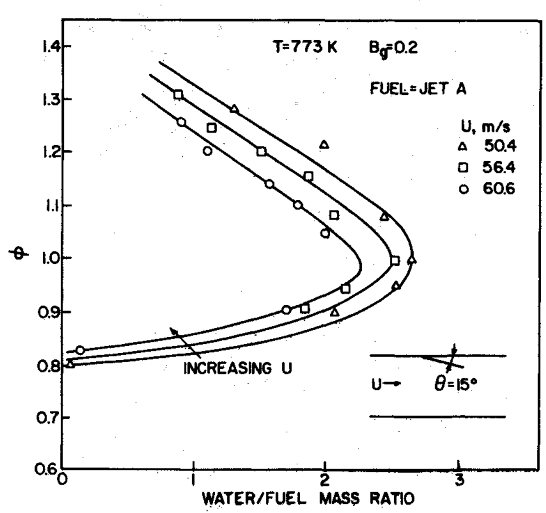

Fig. 2 Graphs illustrating the effects of flow velocity on stability for a single-sided flameholder.

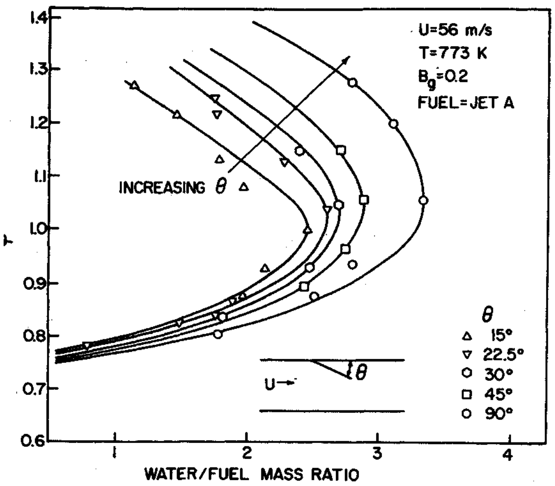

Fig. 3 Graphs illustrating the effects of gutter included angle on stability.

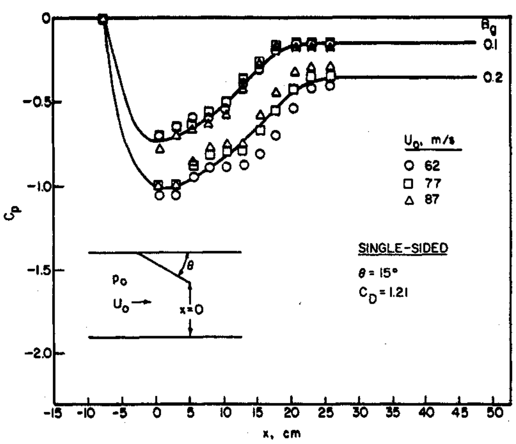

Fig. 4 Values of pressure loss coefficient for a single-sided 15 deg flameholder.

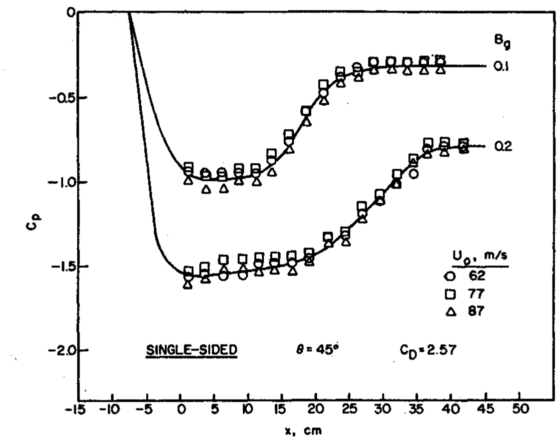

Fig. 5 Values of pressure loss coefficient for a single-sided 45 deg flameholder.

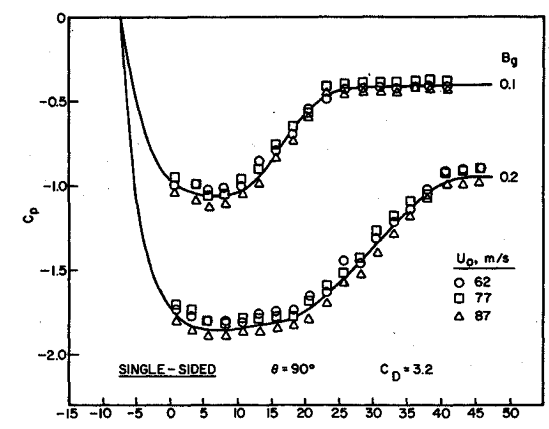

Fig. 6 Values of pressure loss coefficient for a single-sided 90 deg flameholder.

of water equal to the fuel flow rate into the combustion zone is equivalent to halving the gas pressure.

The tests were carried out in a 0.15 × 0.2 m rectangular test section using kerosene fuel (Jet A). The temperature of the air issuing from the preheat combustion chamber was maintained constant at 773 K. In some experiments, as illustrated in Fig. 1, the flameholder was mounted horizontally at the center of the test section with its apex pointing upstream. In other tests (see Fig. 2 for example) a flat plate was fitted to the top of the test section to produce a single-vortex flow pattern in its wake instead of the usual double-vortex formation.

It is well known that an increase in stream velocity affects stability adversely by reducing the time available for combustion. This is illustrated in Fig. 1, which shows five stability loops obtained with a 60-deg V-gutter for a geometric blockage ratio B_g of 0.2. Similar results were obtained with a single-sided flameholder, as illustrated in Fig. 2. The influence of flameholder shape on flame blowoff is demonstrated in Fig. 3. The five stability loops drawn in this figure represent five single-sided gutters, all having the same geometric blockage, but different included angles (15, 22.5, 30, 45 and 90 deg). For these gutters an increase in included angle increases the size of the recirculation zone and, thereby, extends the residence time of the reactants in the combustion zone. The beneficial effect on stability due to increase in included angle is very apparent in Fig. 3.

In Figs. 1-3, attention is focused on the peaks of the stability loops which are easy to identify and always occur at or near the stoichiometric fuel/air ratio. For all stability loops, the effective pressure ratio P_e is obtained from the water/fuel mass ratio corresponding to the peak blowoff velocity, using the method described in Refs. 6-8.

Drag Coefficient

The total drag produced by a gutter immersed in a ducted airstream is made up of several components. One of these is the additional skin friction drag created at the duct walls due to the increase in flow velocity past the trailing edge of the gutter. Another is the skin friction drag of the gutter itself. This can also influence the base drag since the higher the friction drag, the thicker the boundary layer over the trailing edge. The measurements of drag described below include both these friction losses; but, for the geometries selected, they are small in comparison with the gutter base drag. In any case, it is the base drag which governs the general size, shape, turbulence characteristics, and entrainment properties of the wake region; and thus, it is the base drag which is of prime importance to flame stability.

Values of C_D were obtained by mounting the gutters in turn into a plexiglass duct of rectangular cross section (0.15 × 0.2 m) supplied with air at room temperature and pressure. Static pressure tappings, located at intervals of 2.5 cm along the centerline of the duct roof, were connected to a bank of manometer tubes to give the axial distribution of static pressure in the flow region adjacent to the gutter. Figures 4-6, which relate to the 15, 45, and 90 deg gutters, respectively, are typical of the results obtained. Similar results for a 60-deg V-gutter are shown in Fig. 7. For each gutter, the pressure loss was calculated by subtracting the average of three readings taken well downstream of the gutter from the average of three

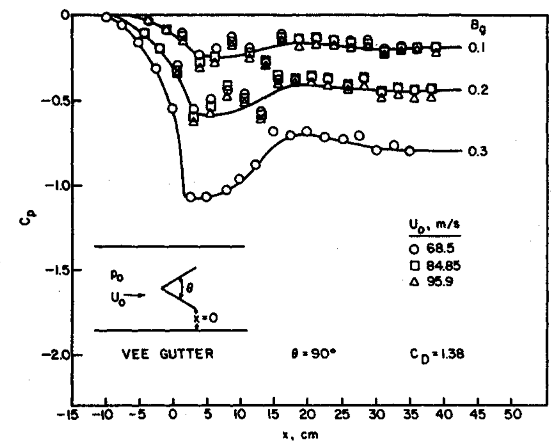

Fig. 7 Values of pressure loss coefficient for a 90-deg V-gutter.

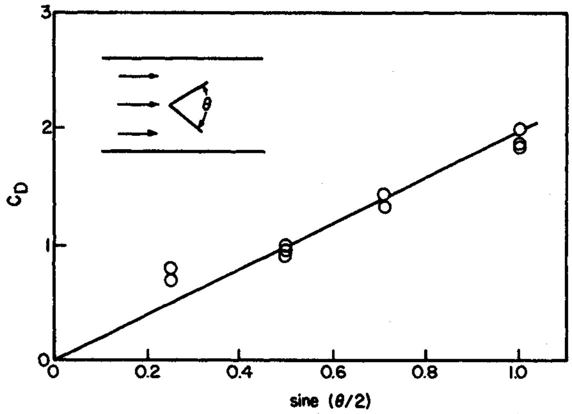

Fig. 8 Drag coefficient as function of included angle for V-gutters.

readings taken just upstream of the gutter. The pressure loss coefficient C_p is then obtained as

$$C_p = \Delta P / 0.5 \rho U_0^2 \tag{3}$$

where ΔP is the pressure loss across the flameholder and U_0 the approach stream velocity. The gutter drag coefficient C_D is then given by

$$C_D = C_p (1 - B_g)^2 / B_g \tag{4}$$

Insertion of this value of C_D, along with the corresponding value of B_g, into the following equation[9] yields B_a

$$\left[\frac{1}{(1-B_a)^2} - 1\right] = 3.7\ C_D \left[\frac{B_g}{(1-B_g)^2}\right] \tag{5}$$

The results of the measurements of drag coefficient are summarized in Figs. 8 and 9. For conventional V-gutters, it is found that drag coefficient is described with good accuracy by the relationship.

$$C_D = 2\sin(\theta/2) \tag{6}$$

where θ is the gutter included angle.

For single-sided gutters the corresponding expression is

$$C_D = 3.2 \sin\theta \tag{7}$$

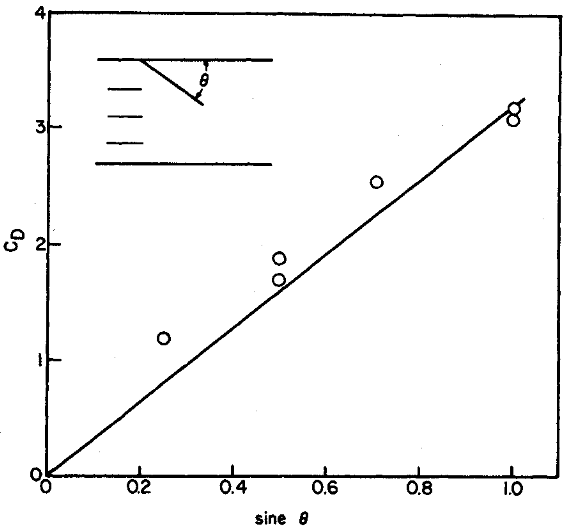

Fig. 9 Drag coefficient as function of included angle for single-sided gutters.

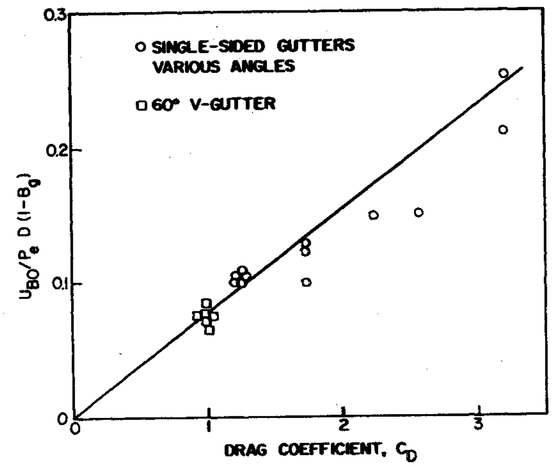

Fig. 10 Correlation of blowoff velocity with drag coefficient.

Discussion

An explanation for the higher blowoff velocities exhibited by single-sided flameholders may be obtained by inspection of Eqs. (6) and (7), which show that the drag coefficients of single-sided gutters are appreciably higher than those of conventional V-gutters. This higher drag coefficient must stem from a larger wake region which enhances flame stability by extending the residence time of the reactants within the combustion zone. For example, it might be expected that a 30 deg single-sided flameholder would have the same stability performance as a 60 deg V-gutter, provided their blockage is the same. The experimental data show that the single-sided configuration has superior flameholding properties, but its drag coefficient is correspondingly higher. Thus, the results of this investigation strongly emphasize the importance of base drag coefficient to bluff-body flame stabilization.

For all stability loops, the peak blowoff velocities, along with their corresponding values of gutter width, effective pressure, drag coefficient, and aerodynamic blockage, were used to plot the graph shown in Fig. 10 which conforms to the relationship

$$U_{BO}/[P_e D(1-B_g)] \alpha C_D \tag{8}$$

This result, showing that for two-dimensional gutters blowoff velocity is directly proportional to base drag coefficient, fully confirms the previous findings of Mestre.[2]

Conclusions

For the two-dimensional flameholders investigated, it is found that peak blowoff velocities are directly proportional to base drag coefficient. This result confirms the previous findings of Mestre. Also, the superior stability performance exhibited by single-sided flameholders in comparison with conventional V-gutters is accompanied by a corresponding increase in drag coefficient. Thus, from an overall performance viewpoint, single-vortex flameholders appear to offer no advantage over double-vortex systems.

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