Influence of Laminar Flame Speed on the Blowoff Velocity of Bluff-Body-Stabilized Flames

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The water injection technique is used to determine the blowoff velocities of bluff-body-stabilized flames supplied with flowing combustible mixtures. The fuels employed include gaseous mixtures of methane, propane, and hydrogen with air. Additional tests are conducted using vaporized gasoline, kerosine (Jet A), and diesel oil (DF2). The apparatus normally comprises a flameholder in the form of a hollow cone which is mounted at the center of a circular pipe with its apex pointing upstream, but in some tests a rectangular working section is used in conjunction with two-dimensional, V-gutter flameholders. The results of the experiments generally confirm theoretical predictions in showing that peak blowoff velocity increases with increase in laminar flame speed.

Nomenclature

B_a = aerodynamic blockage of flameholder
C_s = flameholder shape factor
D_c = characteristic dimension (geometric) of flameholder
S_L = laminar flame speed
T = temperature
U = velocity
U_{BO} = blowoff velocity
α = thermal diffusivity

Subscript

0 = value just upstream of flameholder

Introduction

THE stabilization of a flame in the wake region created downstream of a bluff body immersed in a high-velocity gas stream is a phenomenon of practical as well as scientific interest. In certain types of combustors, for example, the afterburner of a turbojet engine, a bluff-body flameholder is deliberately inserted into the combustible gas stream in order to provide flame stabilization at flow velocities up to 200 m/s. Conversely, in other systems containing flowing combustible mixtures, every effort is made to avoid bluff-body stabilization by removing any discontinuity along the inner wall surface, or any projection into the moving stream that could create flow conditions conducive to the onset of flame stabilization upstream of the combustion zone. These practical considerations have prompted a large number of investigations into the factors that govern the stability limits of bluff-body-stabilized flames.[1-25] Based on the data contained in these studies several broad conclusions may be drawn. In general, the blowout velocity is raised and the stability limits are extended by 1) a reduction in mainstream velocity; 2) an increase in inlet temperature; 3) an increase in gas pressure; 4) a reduction in turbulence intensity; 5) any change in equivalence ratio toward unity; 6) an increase in flameholder size; 7) an increase in flameholder-base drag coefficient; and 8) a reduction in flameholder blockage (for a constant flameholder size).

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For liquid fuels, stability is further improved by 1) an increase in fuel volatility, and 2) finer atomization, i.e., reduction of mean drop size.

Theoretical studies have shown that the dominant fuel property affecting flame stability is the laminar burning velocity, or laminar flame speed.[16-19,24,25] However, few experimental data are available on the influence of burning velocity on flame stability. This is because in most of the reported studies the fuels employed were either propane, natural gas, or kerosine, all of which have roughly the same flame speed. In the past this narrow range of fuel types was quite adequate, especially for aircraft combustion systems, where stringent fuel specifications tended to perpetuate a basically kerosine-type fuel. However, the steps now being taken to ensure future supplies of fuels for gas turbines, in addition to various fuel-conservation measures, include the exploitation of alternative fuel sources and the acceptance of broader specifications for aviation fuels. The alternative fuels of major interest will be derived largely from oil shales, tar sands, heavy oils, and coal. For the longer term, methane and hydrogen are among the candidate fuels now being considered.

The present study is devoted mainly to assessing the influence of laminar flame speed on the blowoff limits of bluff-body-stabilized flames. Its objective is to determine the impact of broadening of fuel specifications to include wide variations in burning velocity on the stability limits of practical flameholding devices.

Experimental

The term stability is often employed to indicate the range of air/fuel ratios over which stable combustion can be achieved, but is also used as a measure of the maximum air velocity that the system can tolerate before flame extinction occurs. Both aspects are important in practical combustion systems. The burning range, in particular the weak extinction limit, is of great significance to all gas turbine combustors, and especially the lean, premix/prevaporize combustor concept which must, of necessity, operate very close to the weak extinction limit in order to reduce the rate of formation of nitric oxides successfully. At the same time the "tip" of the stability loop, corresponding to the peak blowoff velocity, is also important, since it represents the point of maximum heat release of the combustor. For most practical combustion systems it is always difficult, and usually impossible, to determine the peak blowoff velocity, due to the high cost of providing high air flow rates at the very low air pressures needed to achieve flame blowout. Fortunately, this problem can be readily surmounted by 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.[25-27]

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.

The apparatus employed is shown schematically in Fig. 1. Essentially, it comprises a supply of air at atmospheric pressure, a preheat combustion chamber, a working section containing the flameholder under test, and provision for injecting fuel and water in well-atomized form into the flowing gas upstream of the flameholder. Sufficient time and temperature are provided between the planes of injection of water and fuel and the flameholder to ensure that the water-fuel mixture is completely vaporized and thoroughly mixed 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 established in the recirculation zone downstream of the stabilizer. Water is then gradually admixed with the gas stream 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.

Some of the tests were conducted using a circular duct 0.152 m in diameter containing a flameholder in the form of a hollow cone which was mounted on three thin stays at the center of the duct with its apex pointing upstream. In other tests a 0.040-m-wide V-gutter was positioned horizontally at the center of a 0.15×0.2-m rectangular test section (as illustrated in Fig. 3). However, one series of tests was conducted with a flat plate fitted to the top of the test section at an angle of 30 deg. The length of this plate was chosen to create the same geometric blockage in the flow stream as the 60-deg V-gutter. The purpose of this arrangement was to produce a single-vortex flow pattern in the flameholder wake instead of the usual double-vortex formation.

The experimental program covered the following ranges: velocity: 60-140 m/s; temperature: 373-565 K; and effective pressure: 4.2-35 kPa; as measured in the gases just upstream of the flameholder.

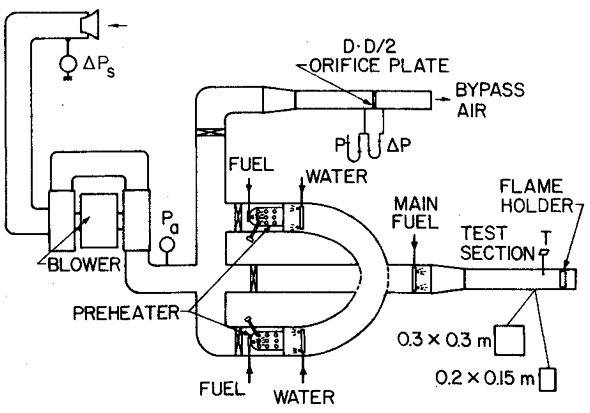

Fig. 1 Schematic diagram of test rig.

The experimental data obtained are shown plotted in Figs. 2-6.

Theoretical Aspects

Many theoretical studies have been conducted on the mechanisms of bluff-body flame stabilization, and several models have been proposed to acccount for the various experimental observations on flame blowoff. The relative merits of the earlier models have been discussed by Longwell,[13] Penner and Williams,[8] Zukoski and Marble,[12] and Herbert.[9] Rao and Lefebvre[25] reviewed these and other models and showed that essentially they must all yield the same general conclusions in regard to the influences of pressure, temperature, and flameholder size and geometry on blowoff velocity. Thus it was found that blowoff velocity can be expressed as[24,25]:

$$U_{BO} = C_s (D_c S_L^2 / \alpha_0) \tag{1}$$

where C_s is a "shape factor." Appropriate values of C_s for flameholders located in a freestream have been reported by Ballal and Lefebvre.[24]

For a flameholder in a duct, Eq. (1) becomes

$$U_{BO} = C_s (1 - B_a)(D_c S_L^2 / \alpha_0) \tag{2}$$

Similar relationships to Eqs. (1) and (2), indicating the same dependence of blowout velocity on laminar flame speed and flameholder dimensions, have been proposed by Putnam and Jensen,[16] Spalding,[17] Loblich,[18] and Radhakrishnan et al.[19]

Results

The stability loops obtained using Jet A, gasoline, and diesel oil are shown in Figs. 2 and 3. These fuels were chosen to cover the range of fuel types likely to be encountered in aircraft jet engines in the foreseeable future. It is clear from the figures that the stability loops are virtually the same for all three fuels, which tends to suggest a common value of laminar flame speed. This is not surprising, since most complex hydrocarbon fuels ar largely pyrolyzed to methane, other one- or two-carbon atom hydrocarbons, and hydrogen, before entering the flame reaction zone. Hence the gas composition entering the flame zone is substantially independent of the original fuel.

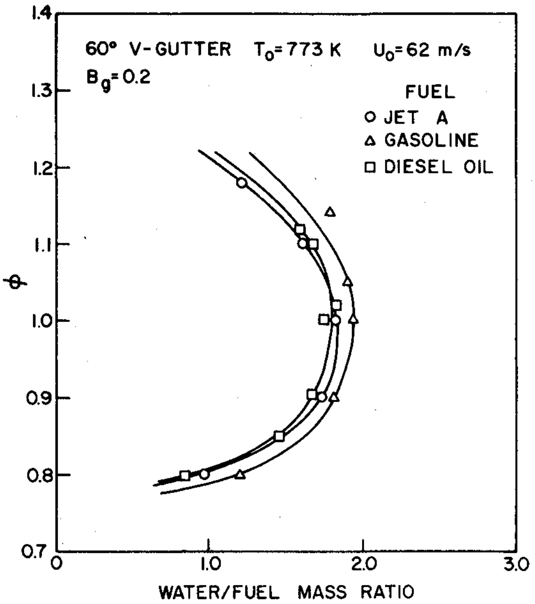

Fig. 2 Stability loops for a 60-deg V-gutter: $D_c = 0.04$ m, test section 0.15×0.2 m.

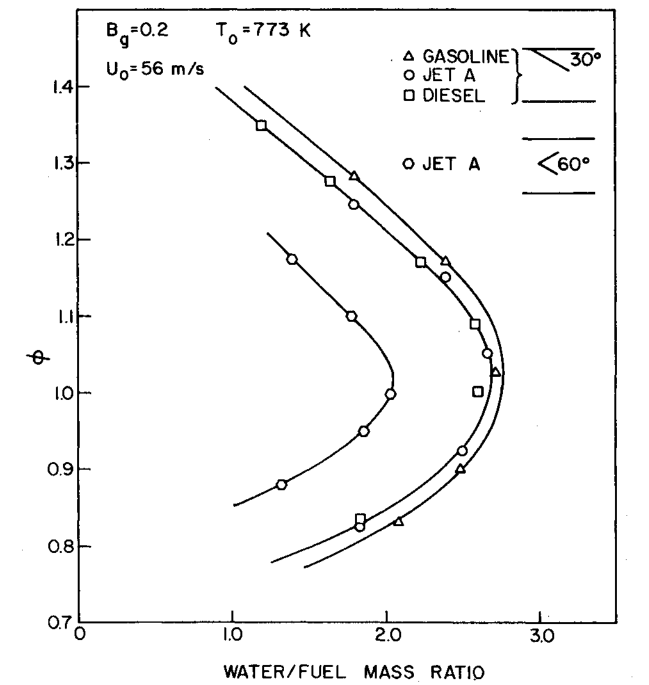

Fig. 3 Graphs illustrating the effect of fuel type and flameholder configuration on flame stability.

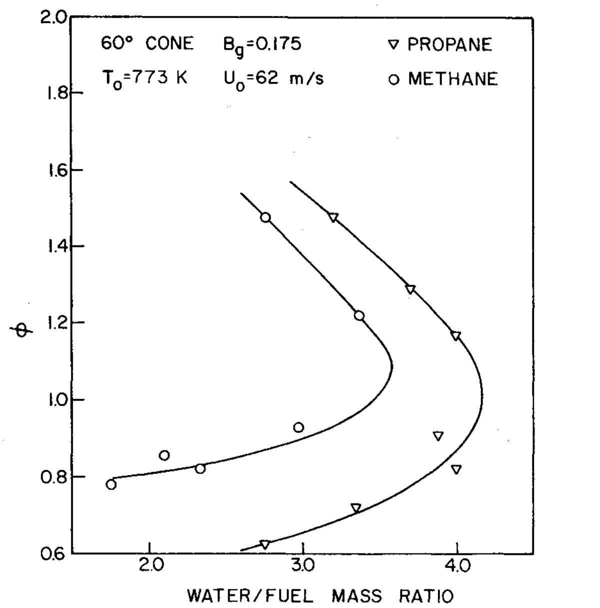

Fig. 5 Comparison of stability loops for mixtures of propane and methane with air.

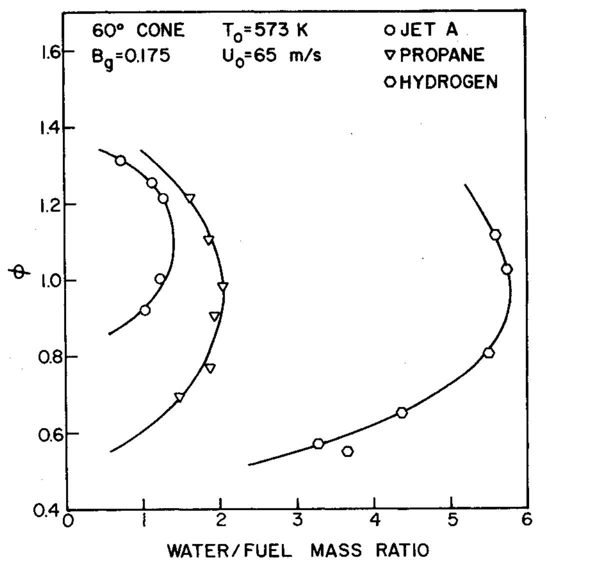

Fig. 4 Stability loops for a 60-deg cone: D_c = 0.064 m, test section 0.153 m diameter.

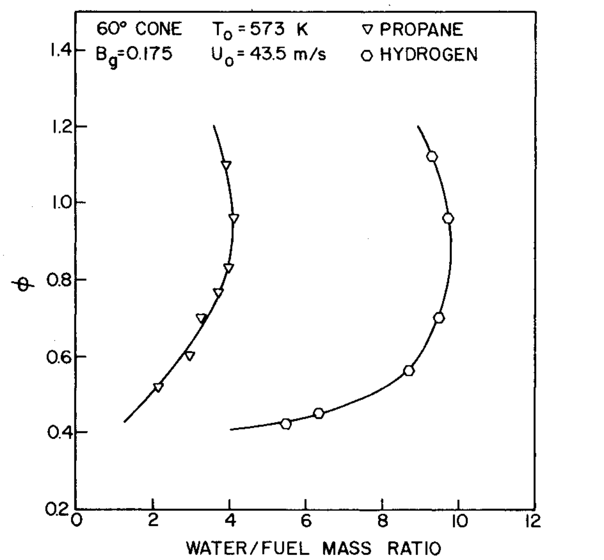

Fig. 6 Comparison of stability loops for mixtures of propane and hydrogen with air.

The slight deviations in stability peformance between the three liquid fuels are attributed to differences in their latent and sensible heat requirements, which cause the final mixture temperature for gasoline to be higher than that of Jet A which, in turn, is higher than that of diesel oil. These variations in initial mixture temperature produce small differences in burning velocity between the three fuels, as indicated, for example, in the following expression for propane-air mixtures due to Dugger and Heimel[28]:

$$S_L = 0.129 + 3.42 \times 10^{-6} T_0^2 \text{ m/s} \tag{3}$$

Figure 3 also illustrates the superior stability of the single-vortex system over the conventional double-vortex system for the same values of shape factor and blockage, due to the longer residence time provided by the single-vortex flow pattern.

The strong influence of burning velocity on flame stability is clearly evident in Figs. 4-6, which contain stability loops obtained with three gaseous fuels; namely, methane, propane, and hydrogen. Typical reported values of S_L for stoichiometric mixtures with air of these three fuels are 0.35, 0.43, and 3.10 m/s, respectively, which fully explains the observed differences in maximum blowoff velocity, as illustrated in Figs. 4-6.

Conclusions

The results of measurements carried out for both gaseous and liquid fuels on the flameholding characteristics of bluff-body-stabilized flames show that peak blowoff velocity increases with increase in laminar flame speed. Commercial gas turbine fuels in the range from Jet A to diesel oil (DF2) exhibit very similar flameholding characteristics since their laminar flame speeds are virtually the same.

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