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Authors

PECK, RE
SAMUELSEN, GS

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Generalized Stability Criteria for an Opposed-Jet Flameholder

R.E. Peck*

University of Kentucky, Lexington, Ky.

and

G.S. Samuelsen†

University of California, Irvine, Calif.

Nomenclature

A = air
 d = diameter
 E = activation energy
 f = function
 F = fuel
 $\dot{m}$ = mass flow rate
 R = gas constant
 T = temperature
 U = mean axial velocity
 x = axial distance
 Z = momentum ratio
 ρ = density
 τ = time
 ϕ = equivalence ratio
 ψ = stream function

Subscripts

ad = adiabatic
 c = critical
 cr = chemical reaction
 fm = fluid mechanic
 j = jet stream
 m = main stream
 o = inlet or initial
 p = penetration
 s = stoichiometric

Introduction

PREDICTIVE models that address flame stability, exhaust emissions, and heat release behavior are a useful tool for the design of continuous combustion devices. Although quantitative predictions of turbulent, backmixed combustion have been limited by uncertainties about the fundamental combustion processes, the recent advent of characteristic time modeling¹ has enabled reliable estimates of combustor performance to be made. The technique relies on the specification of the duration of relevant combustion processes. A comparison of controlling events has been shown to correlate blowoff limits² and emissions³ for bluff-body-stabilized combustors.

The present study explores the applicability of the modeling procedure for aerodynamic flameholders. The particular combustor configuration considered employs an opposed-jet flameholder⁴ as shown in Fig. 1. The flowfield consists of a turbulent pipe flow of premixed reactants confronted by a small ($\dot{m}_j/\dot{m}_m \ll 1$) jet injected at a high velocity along the centerline and in a direction opposite to the main stream. A highly turbulent recirculation zone that anchors the flame is generated along the periphery of the jet. The size and shape of

the recirculation zone can be varied by altering the relative velocity of the main and jet streams. The key feature that distinguishes the opposed-jet from bluff-body flameholders is the influence of the jet composition on flame stability. The combustor operating range can be extended to very lean or rich main stream conditions by using a rich or lean jet, respectively.⁵

The purpose of this work is to construct a characteristic time model describing the opposed-jet flowfield. The model is then used to determine blowoff conditions in a laboratory opposed-jet combustor. The results are also examined with the aim of clarifying the mechanism of flame stabilization by an opposing jet.

Model Formulation

In an early effort to explain the flameholding characteristics of the opposed jet, Schaffer and Cambel⁵ introduced the concept of a "critical zone" which occupies a small volume at the nose of the flame and determines the overall stability. The strong influence of the jet properties on flame stability suggested that the region contains a homogeneous mixture of the jet and main streams and some recirculated combustion products. Subsequent analyses by Noreen and Martin⁶ and Bellamy et al.⁷ modeled the critical zone as a well-stirred reactor and used a reactor loading parameter to predict blowoff.

In the present analysis we also assume that the predominant flameholding processes operate in the vicinity of the recirculation zone. The requirement for flame stabilization is that the residence time of the reactants exceeds the mixture ignition time. Our primary task is to evaluate the time scale associated with the governing fluid dynamic and chemical processes. Various simplifying assumptions and empirical relationships for evaluating combustor properties are adopted whenever appropriate to generalize the model and to facilitate the analysis.

The results of Zukoski and Marble⁸ suggest that the fluid dynamic time corresponds to the period for the unburned reactants to travel past the recirculation zone. This period is quantified by assuming it is directly proportional to a geometric dimension and inversely proportional to a convective velocity. For small-scale turbulence, the length of the recirculation zone, which is proportional to the jet penetration into the main stream, is the appropriate characteristic dimension.⁹ The convective velocity is simply the velocity of the bulk flow past the recirculation zone.

It has recently been shown¹⁰ that the upstream penetration of a round turbulent jet into a counterflowing turbulent pipe flow is a function of the momentum flux ratio, Z , of the incoming jet and the main stream. For the high jet momentum regime the penetration distance, x_p , is given by¹⁰

$$x_p/d_m = 1.8Z^{1/6} \quad (1)$$

where $Z = \rho_j U_j^2 d_j^2 / \rho_m U_m^2 d_m^2$ evaluated at the inlet conditions. The annular flow velocity is approximated by the average

Fig. 1 Opposed-jet combustor schematic.

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*Assistant Professor, Department of Mechanical Engineering.

†Associate Professor and Chair, Mechanical Engineering. Member AIAA.

main stream velocity adjusted for density changes due to combustion.

The chemical reaction time coincides with the ignition phase of the combustion process and depends directly on the mixture composition. Specification of the properties in the critical flame stabilization zone is thus a prerequisite to determining the time scale. The equivalence ratio is fixed by the relative mass contribution ($\dot{m}_j/\dot{m}_m$) of the jet and main stream to the critical zone. Here we adopt a slightly modified form of $\dot{m}_j/\dot{m}_m = f(Z)$ and calculate the critical zone equivalence ratio, ϕ_c , using the following expression⁷:

$$7.0Z^{0.3} = \frac{\phi_j - \phi_c}{\phi_c - \phi_m} \cdot \frac{1 + (F/A)_s \phi_m}{1 + (F/A)_s \phi_j} \quad (2)$$

The critical temperature, T_c , controlling the reaction rate is determined by substituting the adiabatic flame temperature, $T_{ad}(\phi_c)$, into the following expression⁹:

$$T_c = T_{m_0} + 0.74 [T_{ad}(\phi_c) - T_{m_0}] \quad (3)$$

which has been found incidentally to depict the bulk gas temperature in the opposed jet. Following Plee and Mellor,² the proportionality between the chemical time, τ_{cr} , and a reciprocal reaction rate evaluated at T_c is expressed as

$$\tau_{cr} \sim (T_c/T_{m_0}) (e^{E/RT_c}/\phi_c) \quad (4)$$

The preexponential factor (T_c/T_{m_0}) accounts for the acceleration of the bulk flow due to rising temperatures and segregates the dynamics and chemical processes.

Results and Discussion

The characteristic time model of flame stabilization is tested by comparison to lean blowoff data obtained from a bench-scale, propane-fired, opposed-jet combustor. The primary reaction zone is contained in a 51-mm-i.d. $\times$ 460-mm-long quartz tube in which the incoming flow of premixed propane and air is opposed by a high-velocity jet ($\dot{m}_j/\dot{m}_m \approx 0.01$) issuing from a 1.3-mm-i.d. (6.4-mm-o.d.) water-cooled, stainless-steel tube. The jet is coincident with the combustor axis and located 80 mm upstream from the combustor exit. The jet momentum ranges from about 5 to 50 percent of the main stream.

Since all experiments are conducted at atmospheric pressure with the inlet temperatures (T_{m_0} and T_{j_0}) maintained at about 300 K, the independent variables in the flammability tests are the jet and main stream velocity and equivalence ratio. The jet velocity, U_{j_0} , was fixed at 135 m/s and the main stream velocity, U_{m_0} , ranged from about 5 to 15 m/s. The jet stream equivalence ratio, ϕ_j , was varied widely from 0.8 to 1.8. The selected main stream equivalence ratios, ϕ_m , are biased toward the fuel lean side because of the interest in lean combustor performance. Figure 2 presents the blowout map for the current experimental configuration and selected conditions. The data were obtained for fixed U_{m_0} , U_{j_0} , and ϕ_j by reducing ϕ_m until extinction occurred. The beneficial effect of enriched jet operation to extend the lean flammability limit is clearly evident.

The analysis is accomplished by determining the model times for the preceding experimental conditions. The characteristic fluid dynamic time, τ_{fm} , is computed from

$$\tau_{fm} = (x_p/U_{m_0}) \times 10^3 \text{ ms} \quad (5)$$

where the value of x_p is obtained from Eq. (1). An activation energy of 100 kJ/mole for propane oxidation is inserted in Eq. (4) to complete the chemical reaction time calculation from

$$\tau_{cr} = (T_c/T_{m_0}) (e^{12,000/T_c}/\phi_c) \times 10^{-4} \text{ ms} \quad (6)$$

Fig. 2 Blowout map for propane-air.

Fig. 3 Flame stability correlation.

with the temperature in K. The correspondence between the characteristic fluid dynamic time and the chemical reaction time for the experimental blowoff data is presented in Fig. 3.

The results indicate a linear correlation of the lean blowoff data from an opposed-jet combustor. Deviations at elevated jet momentum and equivalence ratios are attributed to extrapolating the empirical elements of the model or to imprecise measurements of ϕ_j and ϕ_m . An error in stoichiometry, for example, can be exaggerated over five times in the calculated reaction time. The results of the present simplified analysis of a complex reacting, recirculating flowfield based on elementary combustion theory and information available in the literature generally display a good representation of the governing physical and chemical processes in the opposed-jet flameholder.

It is noted that little effort was expended toward obtaining the best fit as the goal was to demonstrate the applicability of the model for the opposed-jet combustor. Improved results could be obtained by optimizing the choice of activation energy for the fuel of interest and by determining the effect of

heat release on the characteristic length scale. A correction for the freestream acceleration past the obstructing jet would further reduce the discrepancies. Finally, a larger data set that excludes ambiguous jet inlet conditions found in earlier work would also improve the correlation.

Conclusions

A characteristic time model of flame stabilization has been developed for an opposed-jet combustor. The model indicates a linear relationship between dynamic and chemical processes over a range of blowoff data. The corresponding Damköhler similarity group is on the order of unity. The simplified model also provides a useful phenomenological description of the opposed reacting jet and a practical method of estimating stability limits for an aerodynamic flameholder.

Acknowledgment

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Performance of Tornado Wind Energy Conversion Systems

Tyler Volk*

New York University, New York, N.Y.

Introduction

AN experimental investigation was performed to examine the flow characteristics and power production capabilities of the Tornado Wind Energy Conversion System

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*Research Assistant, Graduate Student, Department of Applied Science.

(TWECS). The results indicate that the confined vortex in the tower of TWECS rotates approximately as a solid body and only supplements total power production, most of which comes from the tower acting as a bluff body. This raises questions about the validity of major assumptions that have served as foundations of TWECS theory since its beginning.

Experimental Facility

The 1.2-m-high lexan model, which incorporates the basic features of past theoretical and experimental TWECS, as described in the literature,¹⁻³ is shown in Fig. 1 during flow visualization in the New York University Environmental Wind Tunnel. The louvers of the tower create a confined vortex from the ambient flow entering the tower. Smoke released horizontally into the bottom inlet region is drawn by a pressure gradient upwards through the duct and then vertically through the tower and out the tower exit into the ambient flow.

Flow velocity measurements were made using 0.3-cm-diam pitot tubes positioned from below or through the leeward side of the tower. Flow visualization using tufts on the pitot tubes allowed them to be secured parallel to the flow at any position. Calibration of the pitot tubes' angular sensitivity ensured that this method was sufficiently accurate to elucidate the general structure of the vortex.

Power was measured with a calibrated turbine-dynamometer located in the duct and instrumented to produce simultaneous torque (Q) and angular velocity (ω) data. The torque was varied to find the maximum power dissipation ($Q\omega$)_{peak} by the turbine.

Velocity Distribution Inside TWECS

Figure 2 is a map of the vortex translational velocity (V_v) within the tower at the level of the duct exit, composed from measurements at distances of 12.7, 15.2, 17.8, 20.3, and 22.9 cm from the axis along 12 equally spaced radii. At this level, V_v is virtually horizontal. Higher in the tower, V_v has a slight vertical component, which is of greatest value just inside the louvers, and which was compensated by a decrease in the horizontal component value from the continuity equation.

Significantly, throughout the tower, the vortex has a velocity distribution most similar to solid-body rotation, in which, if r is the distance from the vortex center, $V_v \propto r$.

Fig. 1 TWECS during flow visualization. V_∞ is from the left and is 5.9 m/s.