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Weak Extinction Limits of Large Scale Flameholders

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ABSTRACT

Weak extinction data obtained from an experimental apparatus designed to simulate the characteristics of practical afterburner combustion systems are presented. The apparatus supplies mixtures of varied composition (equivalence ratio and degree of vitiation), temperature and velocity to Vee-gutter flame holders of various widths and shapes similar to those found in jet engine systems. The fuel employed is a liquid hydrocarbon whose chemical composition and physical properties correspond to those of aviation kerosine, JP5. An equation for predicting weak extinction limits which accounts for upstream vitiation and the chemical characteristics of the fuel is derived from stirred reactor theory. The correlation between the predictions and experimental results indicates that the stirred reactor approach can provide a framework for predicting the lean blowout limits of practical flameholders over wide ranges of engine operating conditions.

NOMENCLATURE

B_a	= flameholder aerodynamic blockage
B_g	= flameholder geometric blockage
C	= constant in Eqs. (14) and (15)
C_1	= constant in Eq. (13)
C_D	= flameholder drag coefficient
C_F	= reaction rate constant
E	= activation energy, k cal/kg mole
K_w	= water/fuel ratio by mass
L	= flameholder length perpendicular to flow, m
m	= fuel mole fraction exponent in rate equation
\dot{m}	= inlet mixture mass flow rate, kg/s
\dot{m}_e	= mass entrainment rate, kg/s
\dot{m}_D	= duct mass flow rate, kg/s
Mn	= Mach number
MW_f	= molecular weight of fuel, kg/kg mole
\dot{N}_{O_2}	= inlet molar flow rate of oxygen, kg mole/s
n	= global reaction order
P	= pressure, atm
R	= universal gas constant, 1.986 k cal/kg mole K
T	= reaction temperature, K
T_0	= test section inlet mixture temperature, K

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\bar{U}	= mainstream velocity, m/s
V	= reaction volume, m ³
w	= flameholder geometric width, m
w_a	= flameholder aerodynamic width, m
x	= fuel carbon molar content
x_f	= fuel mole fraction
x_o	= oxygen mole fraction
y	= fuel hydrogen molar content
y_{O_2}	= inlet stream oxygen mass fraction
β	= fraction of fuel burned
ϵ	= flameholder shape factor
ϕ_1	= preheater equivalence ratio
ϕ_2	= overall equivalence ratio
ϕ_D	= duct equivalence ratio, $\phi_2 - \phi_1$
ϕ_{WE}	= duct weak extinction equivalence ratio
ρ	= density, kg/m ³
Θ	= flameholder total included angle

INTRODUCTION

One of the main problems encountered in jet engine afterburners is that of maintaining a stable flame in a fast flowing stream where the Mach number can attain values approaching 0.3. A widely-used method of stabilizing flames in combustible mixtures flowing at such high velocities is by the insertion of bluff objects such as cones or "Vee" - gutters, which produce in their wake a sheltered region in which stable combustion can proceed at low velocities although surrounded by a stream of high velocity gas.

The practical importance of the bluff-body stabilization process has given rise to a large number of theoretical and experimental studies. Much of our present understanding of the flame stabilization process is due to the pioneering studies carried out in the 1950's by Longwell et al. (1949, 1953) Zukowski and Marble (1955), Williams et al. (1949), Barrère and Mestre (1954), De Zubay (1950), and Spalding (1955). More recent studies include those of Ballal and Lefebvre (1979, 1980) and Rao and Lefebvre (1982) whose work led to the development of equations for predicting stability limits in terms of bluff-body dimensions, blockage ratio, and the pressure, temperature, velocity, turbulence properties, and equivalence ratio of the incoming fresh mixture. Plee and Mellor (1979) have correlated successfully lean blowout data for bluff-body stabilized flames, using a characteristic time model.

The present study attempts to remedy a perceived deficiency in previous experimental studies on bluff-body flame stabilization. It employs large-scale flameholders, of the size and shape that are widely used in practical afterburner and ramjet systems, in conjunction with a preheat combustor and heat exchanger to vary the oxygen concentration in the high temperature gases approaching the flameholder. The analytical objective of this study is to ascertain if an approximation of the wake region as a well-stirred reactor can satisfactorily model the stability characteristics of large-scale practical flameholders operating at realistic conditions of velocity, temperature, and degree of vitiation.

EXPERIMENTAL

A schematic diagram of the test facility used in the present investigation is shown in Fig. 1. The basic system consists of an air supply at essentially atmospheric pressure, an in-line preheater, a duct which contains all the components needed to produce a uniform mixture of vaporized fuel and air at the desired levels of velocity, temperature and equivalence ratio and, finally, a test section in which the flameholder is located. In normal operation, the flameholder is mounted horizontally, spanning the 0.15 m width of the test section.

The preheat combustor is a modified tubular gas turbine combustor approximately 0.46 m in length and 0.27 m in diameter. Since the flow capacity of this combustor is much larger than was required for this program, both the combustor and the fuel injector were modified to achieve the desired liner pressure drop for good mixing and good atomization over the entire range of combustor operating conditions. A series of detailed exit temperature profile measurements were performed at various preheat fuel/air ratios and air mass flow rates to establish a preheat combustor efficiency correlation. This correlation was then used to calculate the preheat combustor's efficiency and equivalence ratio, ϕ_1 , during extinction testing. Unburnt fuel arising from preheater inefficiency is assumed to enrich the mixture reaching the test section.

Several alternative methods of duct fuel injection were investigated in attempting to achieve a perfectly uniform fuel distribution in the mixture flowing into the test section. The fuel injection system finally adopted consists of a converging-diverging duct (see Fig. 1) in conjunction with six pressure-swirl atomizers. The flow number of the atomizers was selected to ensure that atomization quality is always satisfactory at the point of flame extinction. Two perforated plates are located downstream of the diverging section and adequate length is provided to fully prevaporize the fuel and completely mix the fuel vapor with air upstream of the test section. Uniformity of distribution is assessed by injecting water through the fuel injectors into a hot gas stream and carrying out temperature traverses in the plane of the flameholder.

A heat exchanger was constructed to allow the level of inlet air vitiation, and consequently inlet oxygen concentration, to be varied while maintaining a specified test section inlet temperature. It is a simple tube-in-shell design, with four sets of tubular coils, each set consisting of two coils. The eight coils were fabricated from 12.7 mm stainless steel tubing and employ water as a coolant. This internal cooling is supplemented by an array of nozzles mounted above the ducting which spray water downward over its external surface. The water flow from these nozzles is such that a film of water always covers the ducting.

Pressure loss considerations limited the size of the heat exchanger that could be fitted into the duct. To extend the range of attainable vitiation levels for a specified inlet temperature, water is injected in a finely atomized form from eight equispaced pressure-swirl nozzles directly into the vitiated air stream upstream of the fuel injectors. As the water droplets evaporate, they simultaneously lower the mixture temperature and decrease the oxygen concentration, thereby simulating a more highly vitiated air stream.

The flow conditions over which weak extinction data have been obtained are listed below along with details of the various test section geometries employed in the study.

Mainstream Mach number:	0.18 to 0.26
Inlet temperature:	650 to 850 K
Preheater equivalence ratio:	0.15 to 0.6
Flameholder width:	25.4 to 65.1 mm
Flameholder angle:	45, 60 and 90

degrees

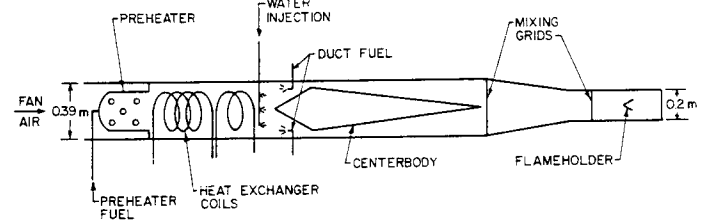


Fig. 1. Experimental test facility.

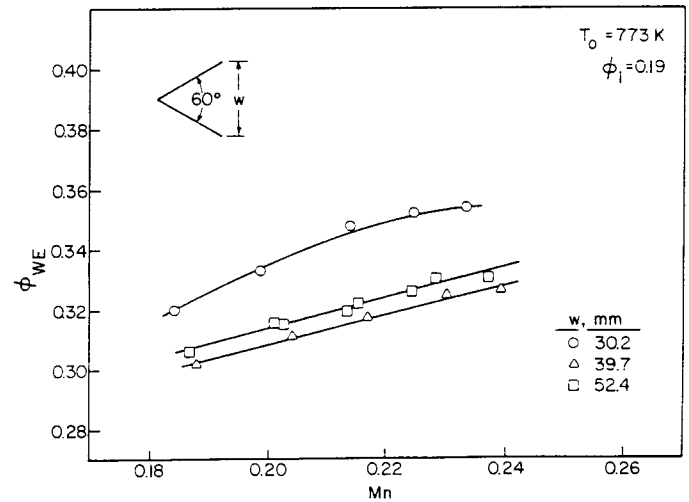


Fig. 2. Influence of approach stream Mach number and flameholder width on weak extinction limits.

Flameholder geometric blockage: 0.125 to 0.32

The lowest values of Mach number, inlet temperature and preheater equivalence ratio are set by the combustion performance of the preheater which deteriorates at extremely low air and fuel flow rates. Another controlling factor is the requirement that the duct stream be hot enough to fully vaporize the injected fuel and water droplets. The maximum attainable approach Mach number is dictated by the capacity of the air blower, while the maximum inlet gas temperature is limited by the onset of flashback or autoignition upstream of the flameholder. As the test section area is fixed, any increase in flameholder width creates a corresponding increase in flameholder blockage.

The test procedure for acquiring lean blowout data is quite simple. For any given flameholder, the inlet conditions are established, and an oxygen-propane torch is used to ignite a flame in the wake region of the gutter. The duct fuel flow is then gradually decreased until flame extinction occurs. At extinction, all pertinent mass flow rates and auxiliary raw data are recorded. This raw data is then fed into a data reduction routine which processes the data into its final form.

RESULTS

The results shown in Figs. 2 to 6 are typical of those obtained during this investigation. They have been selected to illustrate the effects of various inlet parameters and flameholder geometry on weak extinction characteristics. The data shown in Fig. 6 were obtained with the heat exchanger coils in situ. For the data presented in Figs. 2 to 5, these coils were removed to minimize the pressure drop through the system.

A flow parameter of importance to weak extinction limits is the velocity of the combustible mixture as it approaches the flameholder.

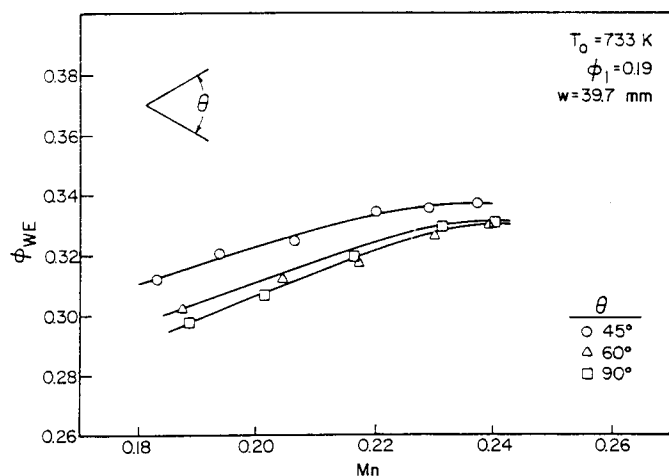


Fig. 3. Influence of approach stream Mach number and flameholder shape on weak extinction limits.

Generally, it is found that any increase in approach stream velocity invariably has an adverse effect on flame stability by reducing the residence time of the reactants in the wake region. This effect is evident in Fig. 2, which also shows that stability is improved by an increase in gutter width due to the additional residence time provided by a larger wake region. Figure 2 also serves to demonstrate that for a flameholder located in a duct, which is the usual practical situation, an additional parameter affecting stability characteristics is the *blockage ratio*, B_g , which is defined as the ratio of the projected area of the flameholder to the cross-sectional area of the duct. All stability theories show that stability limits are widened as the characteristic flameholder dimension increases. In a ducted system, however, the rigid walls restrict the free movement of air over the body and, in consequence, the axial velocity in its vicinity is higher than it would be if the body were located in an unlimited stream. One effect of this high axial velocity is a reduction in the width of the recirculation zone. Thus, for a fixed flameholder width, any increase in geometric blockage - obtained, for example, by decreasing the duct size - will reduce the size of the recirculation zone and thereby impair flame stability. The influence of blockage on weak extinction limits is illustrated in Fig. 2. This figure shows that an increase in gutter width from 30.2 to 39.7 mm reduces ϕ_{WE} , i.e. improves stability, but a further increase in w from 39.7 to 52.4 mm has an adverse effect on stability due to the blockage effect discussed above.

The shape of a bluff-body flameholder affects its stability characteristics through its influence on the size and shape of the wake region. The effect of shape is illustrated in Fig. 3, which shows weak extinction data for three gutters having different included angles but the same projected width. These data confirm the results of Barrere and Mestre, (1954) in showing that the characteristic dimension of a bluff-body flameholder should be not its geometric width, w , but rather the maximum width of the wake created behind it, w_a . The ratio w_a/w increases with increase in gutter included angle, thereby improving stability performance by enlarging the recirculation-zone volume.

The influence of inlet mixture temperature on weak extinction limits is illustrated in Figs. 4 and 5. Both figures are based on data obtained from two Vee-gutters of the same included angle (60°), but having different widths of 30.2 and 39.7 mm. In view of the well-known exponential dependence of chemical reaction rates on reaction temperature, it would be expected that an increase in inlet mixture temperature should lead to a widening of the stability limits and a reduction in ϕ_{WE} . This expectation is fully borne out by the results shown in Fig. 4 for a constant approach stream Mach number of 0.23, and in Fig. 5 for a constant approach stream velocity of 120 m/s.

It should be noted that, for the data shown in Figs. 4 and 5, an increase in temperature is always accompanied by an increase in inlet-

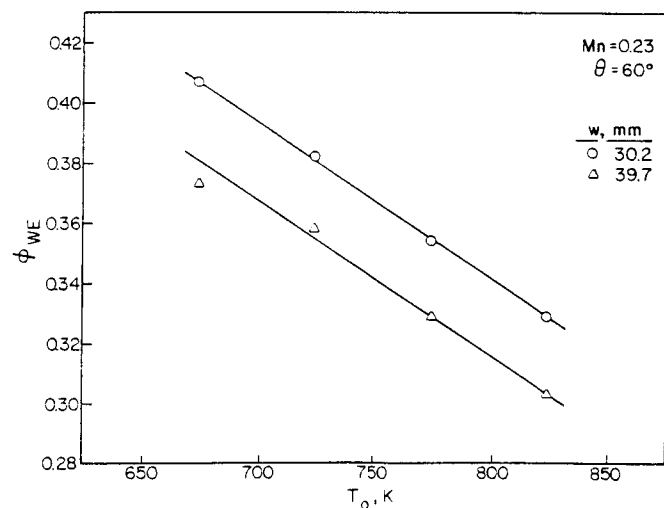


Fig. 4. Influence of inlet temperature at constant Mach number on weak extinction limits.

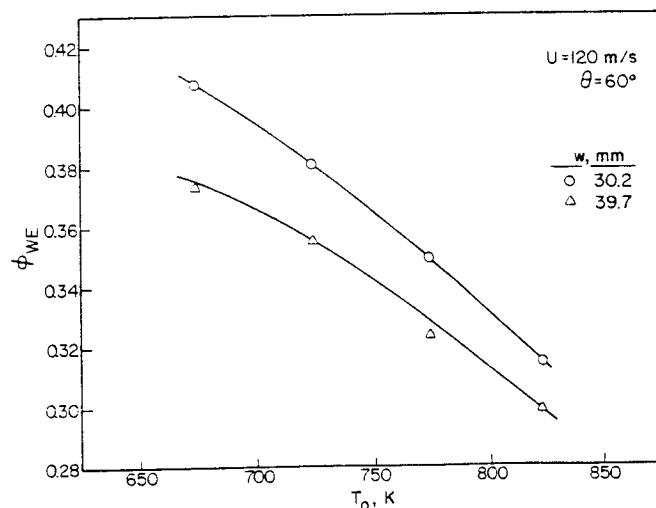


Fig. 5. Influence of inlet temperature at constant velocity on weak extinction limits.

air vitiation. The effects of vitiation on flame stability are shown more directly in Fig. 6. The data contained in this figure for the higher equivalence ratios (> 0.3) were obtained with water injection, and an analytical approach, as described below, was used to calculate the effective values of ϕ_1 . An interesting feature of Fig. 6 is that the slopes of the lines drawn through the data points become quite steep at the highest values of ϕ_1 . This would appear to suggest that the stability loops are attaining their peak values, an event which, for unvitiated combustible mixtures, is normally associated with near-stoichiometric fuel/air ratios. However, it should be borne in mind that, due to the exceptionally high levels of inlet air vitiation encountered in these experiments, effective fuel/oxygen ratios at these high ϕ_1 conditions are very close to the stoichiometric values. The fact that inlet air vitiation has a strong adverse effect on weak extinction limits, as illustrated in Fig. 6, is clearly of practical importance to the designers of advanced afterburner systems.

Inspection of all the data contained in Figs. 2 to 6 indicates that weak extinction limits are governed mainly by inlet mixture temperature and, to a lesser extent, by mixture velocity and the degree

of upstream vitiation. Over the range of conditions examined, increases in inlet mixture temperature tend to lower weak extinction limits, while increases in velocity or vitiation levels tend to raise the weak extinction limits. Increases in flameholder width serve to lower extinction limits until a critical blockage ratio is reached. Further increases in flameholder width beyond this critical point raise the weak extinction limits.

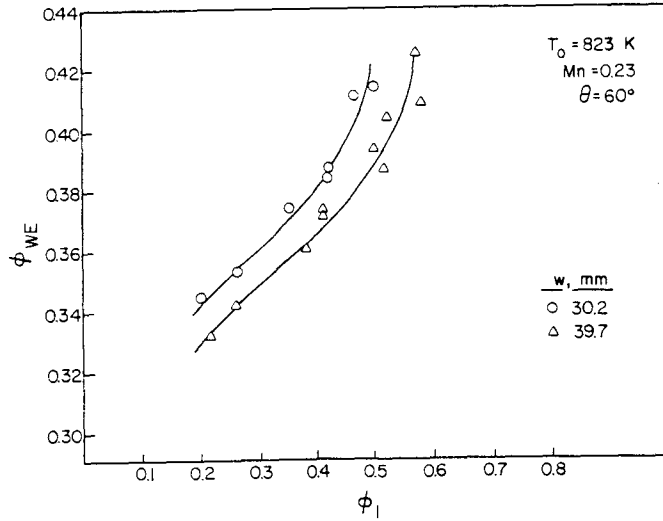


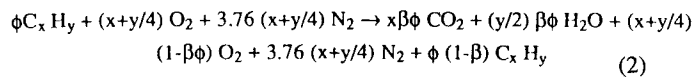
Fig. 6. Influence of upstream vitiation level on weak extinction limits.

ANALYSIS

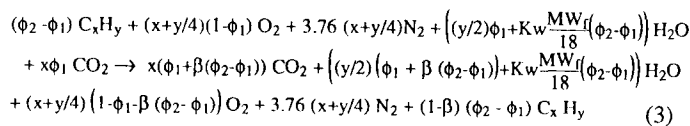
In the analysis described below, weak extinction is postulated to occur when the amount of energy required to ignite the fresh mixture being entrained into the flameholder's wake region just exceeds the energy being liberated by combustion in that region. Following Longwell et al. (1953), the wake reaction zone is considered to approximate a well-stirred reactor. This premise leads to the material balance equation below which equates the molar consumption rate of oxygen to the rate of reaction for weak mixtures ($\phi < 1$) of fuel and air:

$$\beta \phi \dot{N}_{O_2} = C_F VT^{0.5} \exp(-E/RT) \left(\frac{P}{RT} \right)^n x_f^m x_o^{n-m} \quad (1)$$

For weak mixtures of a hydrocarbon fuel and air:



In turbojet afterburner systems the reactant mixture consists of fuel and air that is vitiated by combustion products issuing from the main engine combustion chamber. If the preheater is assumed to burn with 100 percent combustion efficiency at an equivalence ratio of ϕ_1 , and one allows for water dilution, the reaction rate equation becomes:



where ϕ_2 is the overall equivalence ratio. Defining the duct equivalence ratio ϕ_D as $\phi_2 - \phi_1$ yields the following expressions for the product mole fractions:

$$x_f = \frac{(1-\beta)\phi_D}{(x+y/2)(\phi_1 + \beta\phi_D) + \left((1-\beta) + Kw \frac{MW_f}{18} \right) \phi_D + (x+y/4)(4.76 - \phi_1 - \beta\phi_D)} \quad (4)$$

and

$$x_o = \frac{(x+y/4)(1-\phi_1 - \beta\phi_D)}{(x+y/2)(\phi_1 + \beta\phi_D) + \left((1-\beta) + Kw \frac{MW_f}{18} \right) \phi_D + (x+y/4)(4.76 - \phi_1 - \beta\phi_D)} \quad (5)$$

If Y_{O_2} is the mass fraction of oxygen in the inlet mixture stream, \dot{m} , then clearly

$$\dot{N}_{O_2} = \frac{Y_{O_2} \dot{m}}{32} \quad (6)$$

Substituting this expression for the molar influx of oxygen and the oxygen and fuel mole fraction relations into Eq. (1) yields:

$$\frac{\dot{m}}{VP^n} = \frac{C_F \exp(-E/RT)}{R^n T^{n-0.5}} \frac{32}{Y_{O_2} \beta \phi_D^{1-m}} \left\{ (x+y/2)(\phi_1 + \beta\phi_D) + \left((1-\beta) + Kw \frac{MW_f}{18} \right) \phi_D + (x+y/4)(4.76 - \phi_1 - \beta\phi_D) \right\}^{n-m} \quad (7)$$

Lefebvre (1985) noted that lean blowout data from a number of practical combustion systems conformed to an apparent overall reaction order, n , of 1.3 when operating near lean blowout, while Longwell and Weiss (1955) found that a value of $n=1.8$ provided the best correlation of their complete stability loop data (both lean and rich) from their spherical reactor experiments. Clarke et al. (1965), in a set of similar spherical reactor studies, correlated peak blowout data with values of $n=2$ and $m=1$. Since the present study concerns lean blowout, the peak blowout value of $n=2$ is inappropriate. However, as is shown in Fig. 6, the stability loops obtained at high vitiation levels exhibit the characteristic curvature which occurs as the peak blowout point is approached. Consequently an intermediate value of $n=1.75$ was chosen for the analysis. The value of m was maintained at unity, since it is considered that the fuel concentration should be no less rate determining at weak extinction than at peak blowout conditions. It is perhaps worthy of mention that an attempt was made to correlate the weak extinction data using a lower value of n of 1.3. This was found to give a very satisfactory fit to the data acquired under conditions of low air vitiation, and is fully consistent with the values of 1.25 and 1.3 obtained by Ballal and Lefebvre (1979) and Lefebvre (1985) for unvitiated inlet air mixtures. However, the data fit was much less satisfactory when a value for n of 1.3 was applied to the highly vitiated inlet mixtures selected for this study due to their relevance to advanced afterburner systems.

The utilization of kerosine as the fuel presents the dilemma of attempting to chemically model a combustion reaction which has no precise chemical formula. According to Sutton et al. (1984) a mean chemical formula for the type of fuel employed is $C_{14.3}H_{26.0}$, and this composition was used in the formulation of Eq. (7) along with an activation energy of 54,000 kcal/kg mole as recommended by Ballal and Lefebvre (1979).

The reaction temperature T for Eq. (7) is readily calculated using heat balance methods for any stipulated values of β , ϕ_D , ϕ_1 , Kw and inlet mixture temperature T_o . Substitution of corresponding values of T , β , ϕ_D , ϕ_1 , and Kw into Eq. (7) allows plots of $(\dot{m}/VP^{1.75})$ vs β to be generated for various inlet conditions, as shown in Fig. 7. Attention is focused on the peak of each curve since it represents the highest possible heat release rate for the given inlet conditions.

Values of $(\dot{m}/VP^{1.75})_{\max}$ were calculated for various combinations of inlet conditions. The inlet conditions examined were ϕ_1 from 0 to 0.9, ϕ_2 from 0.2 to 0.9, T_0 from 300 to 1000 K, and Kw from 0 to 2. For these ranges of inlet conditions a least squares analysis yielded the following correlation for $(\dot{m}/VP^{1.75})_{\max}$

$$\left(\frac{\dot{m}}{VP^{1.75}}\right)_{\max} \propto \frac{(1-\phi_1)^{1.36} \phi_D^{6.18} \exp(T_0/125)}{(1+Kw)^{0.8}} \quad (8)$$

or

$$\dot{m}_{\max} \propto \frac{VP^{1.75} (1-\phi_1)^{1.36} \phi_D^{6.18} \exp(T_0/125)}{(1+Kw)^{0.8}} \quad (9)$$

In the above expression, \dot{m}_{\max} represents the maximum mixture flow rate the combustion zone can tolerate before extinction. Clearly, at the point of flame blowout, it must equal the entrainment rate of fresh mixture into the wake region. The methods adopted for estimating the entrainment rate and the volume of the wake region are described below.

A relatively large amount of data exists concerning the aerodynamic structure of the flowfield in the wake of a bluffbody. Much of the data, unfortunately, are from axisymmetric flameholders, taken under cold flow conditions, making their translation to the present two-dimensional geometry and hot flow conditions difficult. However, some two-dimensional studies on conventional Vee-gutters exist and provide a basis for estimating the entrainment rate and recirculation-zone volume.

The volume of the recirculation region per unit length of flameholder may be considered proportional to the region's aerodynamic width, w_a , and length, L_a . According to Lefebvre (1965), the relationship between the aerodynamic blockage of a bluff body flameholder and its corresponding geometric blockage is given by

$$\left[\frac{1}{(1-B_a)^2} - 1\right] = 3.7 C_D \frac{B_g}{(1-B_g)^2} \quad (10)$$

In the above equation the drag coefficient, C_D , is determined mainly by the forebody shape of the flameholder. Rizk and Lefebvre (1986), in an aerodynamic study using the present test section geometry, developed for double sided vee-gutters the following expression for C_D :

$$C_D = 2 \sin(\theta/2) \quad (11)$$

where θ is the total included angle of the gutter.

For any given geometric gutter width, Eqs. (10) and (11) allow the aerodynamic width to be estimated. The other parameter needed to estimate the volume of the wake region is its length, which corresponds to the furthest distance downstream of the flameholder where reverse flow exists. Wright (1959) performed a number of measurements on flames stabilized by flat plates in a ducted stream. He found that recirculation length varied in proportion to aerodynamic width (i.e. $L_a \propto w_a$). Thus, for straight Vee-gutters, it is reasonable to assume that the volume per unit length of gutter is proportional to w_a^2 .

Zhang (1980) developed the following correlation for estimating the gas entrainment rates of Vee-gutter flameholders:

$$\frac{\dot{m}_e}{\dot{m}_D} = \left(0.155 + 0.08 \left(\frac{\theta}{30} - 1.0\right) \left(\frac{B_g}{1-B_g}\right)\right) \quad (12)$$

The above correlation stems from an experimental study performed under cold flow conditions at a single velocity. If it is expanded to

include the effects of stream velocity and temperature on entrainment fraction, as determined experimentally by Lefebvre et al. (1960), then Eq. (12) may be rewritten as

$$\frac{\dot{m}_e}{\dot{m}_D} = C_1 Z \quad (13)$$

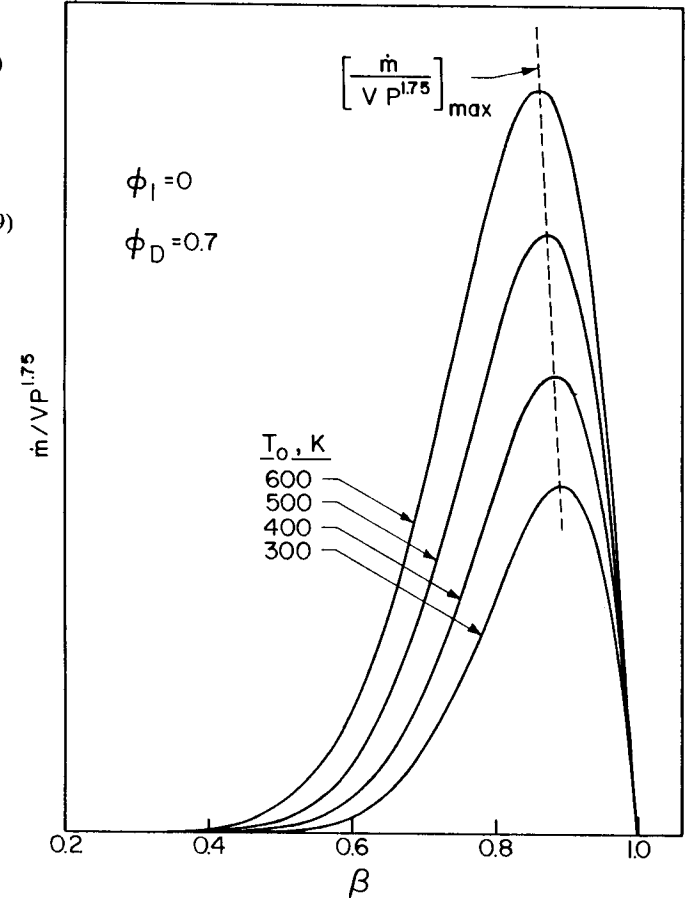


Fig. 7. Reaction rate curves for various values of inlet mixture temperature.

$$\text{where } Z = \left[0.155 + 0.08 \left(\frac{\theta}{30} - 1\right) \left(\frac{B_g}{1-B_g}\right) \left(\frac{U}{T_0^{0.75}}\right)\right]$$

Equating at lean blowout the mixture mass entrainment rate from Eq. (13) to the maximum sustainable loading from Eq. (9), and noting that the wake region volume per unit length is proportional to w_a^2 , yields the following correlation for ϕ_{WE} :

$$\phi_{WE} = C \left[\frac{\dot{m}_D Z (1+Kw)^{0.8}}{P^{0.75} \exp(T_0/125) (1-\phi_1)^{1.36} w_a^2} \right]^{0.16} \quad (14)$$

The above equation includes a term Kw to account for the injected water used to extend the range of attainable vitiation levels for a specified test section inlet temperature. As water injection is seldom used in practical combustion systems, it may be simplified to

$$\phi_{WE} = C \left[\frac{\dot{m}_p Z}{P^{0.75} \exp(T_o/125) (1-\phi_1)^{1.36} w_a^2} \right]^{0.16} \quad (15)$$

The constant C in Eqs. (14) and (15) embodies the constant C₁ from Eq. (13). Its value depends on the turbulence properties of the duct flow and on acoustic interactions that are combustor unique and are not modeled in the present analysis.

COMPARISON WITH EXPERIMENT

Figure 8 shows the values of ϕ_{WE} obtained experimentally for various values of w , ϕ , B_g , T_o , ϕ_1 , and Mn plotted against the corresponding values calculated from Eq. (15) using a value for C of 0.52. The level of agreement demonstrated in Fig. 8 is generally good and may be regarded as support for the validity of the assumptions employed in the analytical derivation of Eq. (15). The minor discrepancies between theory and experiment observed in Fig. 8 may be due to a combination of several factors. For example, the analysis takes no account of the blockage created by the boundary layers on the duct walls. These boundary layers decrease slightly the effective cross sectional area of the duct, thereby increasing the aerodynamic blockage of the flameholder. This could explain why the optimum value for the aerodynamic blockage of a two-dimensional flameholder, as determined experimentally, was slightly less (0.40 to 0.45) than the value of 0.50 predicted by the analysis.

Another factor influencing the experimental data is the aspect ratio, i.e. the ratio of gutter length to gutter width. For the larger gutters, their low aspect ratio of less than 3 most likely precludes a true two-dimensional comparison. Heat loss from the recirculation zone at the ends of the flameholder to the test section walls is also more significant for the wider flameholders. These flameholders are characterized by larger flames which increase the area for heat loss to the walls. This effect may also contribute to the bias toward a lower optimum gutter width, as discussed above, since near the lean blowout limit small variations in the amount of heat loss can significantly affect the sustainable loading.

In any case, the measurements indicate that an optimum blockage ratio exists beyond which any further increase in gutter width is detrimental. The analysis confirms this expectation but predicts a slightly higher optimum blockage ratio. If consideration is given to the need to minimize pressure losses in any afterburner design, the optimum blockage ratio is probably close to that observed experimentally. Also worthy of note is that, as the optimum blockage ratio is approached, any stability improvements achieved by further increases in gutter width tend to be minor and unattractive when considered alongside the concurrent increase in flow pressure loss.

CONCLUSIONS

From an analysis based on simplifying assumptions for the rates of heat liberation and heat loss in the wake region of a baffle-stabilized flame, it is concluded that the influence of operating conditions, inlet-air vitiation, and flameholder dimensions on weak extinction limits is adequately described by the relationship:

$$\phi_{WE} = C \left[\frac{\dot{m}_p Z}{P^{0.75} \exp(T_o/125) (1-\phi_1)^{1.36} w_a^2} \right]^{0.16}$$

The value of C in the above equation is dependent on the geometrical and flow factors that govern the acoustic and turbulence properties of the system, and must be determined experimentally. The results of the present study show that weak extinction limits are governed mainly by inlet mixture temperature and to a lesser extent by mixture velocity and upstream vitiation level. Also, for a constant duct cross-sectional area, weak extinction limits are extended by an increase in flameholder width up to a critical value after which blockage effects start to outweigh and eventually override the beneficial effect of the increased flameholder width.

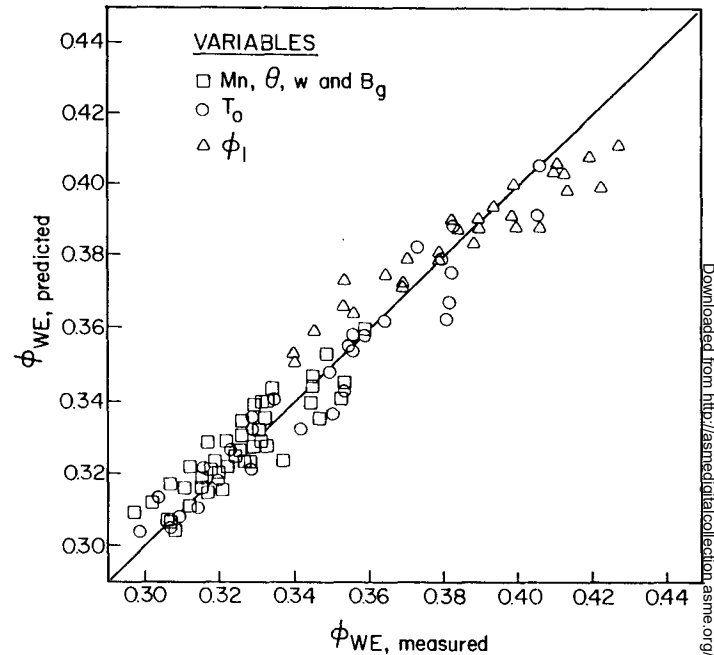


Fig. 8. Comparison of measured and predicted values of weak extinction limits.

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