

GT2006-90470

SYNGAS MIXTURE COMPOSITION EFFECTS UPON FLASHBACK AND BLOWOUT

David R. Noble, Qingguo Zhang, Akbar Shareef, Jeremiah Tootle, Andrew Meyers, Tim Lieuwen

School of Aerospace Engineering
 Georgia Institute of Technology
 Atlanta, GA 30332-0150

ABSTRACT

This paper reports experimental data on flashback and lean blowout characteristics of H₂/CO/CH₄ mixtures. Data were obtained over a range of fuel compositions at fixed approach or burned flow velocity, reactant temperature, and combustor pressure at several conditions up to 4.4 atm and 470 K inlet reactants temperature. Consistent with prior studies, these results indicate that the percentage of H₂ in the fuel dominates the mixture blowout characteristics. These blowout characteristics can be captured with classical Damköhler number scalings to predict blowoff equivalence ratios to within 10%. Counter-intuitively, the percentage of hydrogen had far less effect on flashback characteristics, at least for fuels with hydrogen mole fractions less than 60%. This is due to the fact that two mechanisms of “flashback” were noted: rapid flashback into the pre-mixer, presumably through the boundary layer, and movement of the static flame position upstream along the centerbody. The former and latter mechanisms were observed at high and low hydrogen concentrations. In the latter mechanism, flame temperature, not flame speed, appears to be the key parameter describing flashback tendencies. We suggest that this is due to an alteration of the vortex breakdown location by the adverse pressure gradient upstream of the flame, similar to the mechanism proposed by Sattelmayer and co-workers [1]. As such, a key conclusion here is that classical flashback scalings derived from, e.g., Bunsen flames, may not be relevant for many parameter regimes found in swirling flames.

NOMENCLATURE

A_A Cross sectional pre-mixer area at point A [m]
 A_B Cross sectional pre-mixer area at point B [m]
 C_D Drag coefficient [-]
 D Perturbation amplitude [m]

d Characteristic length scale [m]
 Da Damköhler number [-]
 Da_B Burned gas Damköhler number [-]
 Da_U Unburned gas Damköhler number [-]
 D_F Fuel mass diffusivity [m^2/s]
 D_{OX} Oxidizer mass diffusivity [m^2/s]
 k Wavenumber [$1/m$]
 P Combustor pressure [Pa]
 P_A Pressure at point A in pre-mixer [Pa]
 P_B Pressure at point B in pre-mixer [Pa]
 \bar{P}_b Mean burned gas pressure [Pa]
 \bar{P}_u Mean unburned gas pressure [Pa]
 P_u' Fluctuating unburned gas pressure [Pa]
 R Specific gas constant [$J/(g \cdot K)$]
 Re Reynolds number [-]
 S Swirl number [-]
 S_L Laminar flame speed [m/s]
 $S_{L,0}$ Unstretched laminar flame speed [m/s]
 S_T Turbulent flame speed [m/s]
 T_{ad} Adiabatic flame temperature [K]
 T_b Burned gas temperature [K]
 T_0 Reactant gas temperature [K]
 T_u Unburned gas temperature [K]
 U_0 Approach flow velocity [m/s]
 U_{ref} Characteristic velocity scale [m/s]
 U_u Unburned gas velocity [m/s]
 \bar{U}_u Mean unburned gas velocity [m/s]
 α Thermal diffusivity [m^2/s]
 ΔP Pressure rise [Pa]
 $\Delta\phi$ Equivalence ratio increase [-]
 ϕ Equivalence ratio [-]
 λ Thermal conductivity of mixture [$J/(s \cdot m \cdot K)$]
 λ_k Thermal conductivity of species k [$J/(s \cdot m \cdot K)$]

- τ_{chem} Chemical time scale [s]
- τ_{res} Residence time scale [s]
- χ_k Mole fraction of species k [-]
- \mathcal{R} Burned to unburned temperature ratio [-]

INTRODUCTION

This paper describes measurements of the dependence of flashback and lean blowout limits upon fuel composition. This work is motivated by interest in developing combustors capable of operating with synthetic fuels derived from coal and/or other feedstocks [2]. Current syngas combustion technology relies on diffusion flame combustors, with water injection technology for NO_x control.

The inherent variability in composition and heating value of synthetic gases is a significant barrier towards their usage. Syngas fuels are typically composed primarily of H₂, CO, and N₂, and may also contain smaller amounts of CH₄, O₂, CO₂, and other higher order hydrocarbons [3]. Depending upon the source and particular processing technique, these fuels can have significant ranges in relative composition of these constituents; e.g., volumetric H₂/CO ratio varies from 0.33-40, the percentage of diluent gases (e.g., N₂, CO₂, Ar) from 4 – 51%, and the percentage of water from 0-40% [4].

This variability is a significant problem because low emission combustion systems are optimized for operation within tight fuel specifications. Specifications for gaseous fuels cover parameters such as heating value, hydrogen content, and solid contaminant levels. This variability in fuel content, and resultant combustion kinetics, introduces substantial modifications in steady state (e.g. emissions, flame shape) and dynamic (e.g., blowoff, flashback, combustion instability) combustor behavior from one syngas to the next. This paper describes results from an experimental program that is investigating the dependence of flashback and blowout limits upon syngas composition.

Blowout refers to when the flame becomes detached from the location where it is anchored and is physically “blown out” of the combustor. Blowout is often referred to as the “static stability” limit of the reaction. Roughly speaking, blowout occurs when the characteristic chemical time becomes longer than the characteristic residence time. It is a concern in low emissions combustors that often operate very near the blowout limits of the combustor. Furthermore, the blowout limits of a combustor can vary significantly with fuel composition, due to their wide range in chemical kinetic rates. For example, many candidate fuels have similar heating values but also have chemical kinetic times that vary by an order of magnitude.

The other issue is flashback, where the flame physically propagates upstream of the region where it is supposed to anchor and into regions that are not designed for high temperatures. Flashback is an issue with high flame speed fuels, such as those containing high hydrogen levels.

BACKGROUND

Flame stabilization involves competition between the rates of the chemical reactions and the rates of turbulent diffusion of species and energy. While a significant amount of fundamental understanding of flame propagation and stability characteristics of lean, premixed systems has been gained in conventionally fueled, natural gas-air systems [5], little is known about these issues for alternate gaseous fuels, such as syngas or low BTU fuel mixtures. Furthermore, the majority of the fundamental investigations of the combustion characteristics of these synthetic gases are for non-premixed flame configurations [6,7,8,9,10]. Limited studies have been initiated relatively recent to investigate the characteristics of premixed, hydrogen-enriched methane fuels [11, 12, 13]. Additional studies are needed, however, to broaden the scope of fuels of interest.

Consider first the factors affecting blowout. Methods for developing blowout correlations using WSR scaling ideas have been studied extensively. Several different theories or physical considerations have been used in past blowout correlation studies, such as those of Zukoski and Marble [14], Spalding [15], Longwell [16] and others [17,18]. As noted by Glassman [19], however, they lead to essentially the same form of the correlation that relates the blowoff limits to a Damköhler number, i.e., ratio of a residence and chemical kinetic time, τ_{res}/τ_{chem} . This ratio is often referred to as a combustor loading parameter. It is possible that the recirculation regions that stabilize many high intensity flames, which may have flamelet properties at most other points along the flame, have distributed reactor-like properties; hence, the success in stirred reactor models in correlating blowout behavior.

When applied to blowoff limits of premixed flames, this chemical time can be estimated as:

$$\tau_{chem} = \alpha / S_L^2 \quad (1)$$

where S_L and α denote the laminar flame speed and thermal diffusivity, respectively [20, 21]. The residence time is generally scaled as d/U_{ref} , where d and U_{ref} denote a characteristic length scale (e.g., a recirculation zone length) and velocity scale, respectively. The Damköhler number is given by:

$$Da = \frac{\tau_{res}}{\tau_{chem}} = \frac{S_L^2 d}{\alpha U_{ref}} \quad (2)$$

The appropriate reference velocity, U_{ref} , is less clear. Note that U_{ref} need not directly scale with approach flow velocity, U_0 , due to the acceleration of the burned gas [20]. Since the burned gas velocity scale is given by $U_b = (T_b/T_0)U_0$, then $U_{ref} = f(U_0, T_b/T_0)$. Similar considerations apply for the recirculation zone scale, d . For this reason, prior workers have

often had to measure the recirculation zone length in order to use Eq. (2) (e.g., see Ref. 14).

The other problem besides lean blowoff is flashback, where the flame physically propagates upstream of the region where it is supposed to anchor and into premixing passages that are not designed for high temperatures. Similar to blowout, flashback is an issue because of the widely varying flame speeds of candidate fuels.

Flashback occurs when the flame propagates upstream into the premixing section. While this is a classical topic that has been extensively investigated [22,23,24], the complexity of the topic increases substantially in swirling flows. In particular, several potential modes of flashback occur in swirling flows, as discussed in a series of papers by Sattelmayer and co-workers [25,26,27]. They identify three mechanisms for flashback: flashback in the boundary layer, turbulent flame propagation in the core flow, and flashback due to combustion instabilities [28]. The first two mechanisms are captured partially by the laminar and/or turbulent flame propagation speed. A thorough investigation of boundary layer flashback in syngas fueled Bunsen flames has been detailed by Davu *et al.* [29]. When the local turbulent flame speed exceeds the local flow velocity, the flame can propagate upstream into the premixing section. This issue is complicated by the radial variation in flow velocity, quenching losses, and turbulent flame speed. Also related to the second mechanism is a phenomenon Sattelmayer and co-workers refer to as “combustion induced vortex breakdown”. The basic idea is that the flame contributes to vortex breakdown, and therefore a low or negative flow region ahead of it. The flame advances forward, causing the vortex breakdown region location to advance farther upstream. This process continues as the flame proceeds farther and farther upstream. In this scenario, flashback could occur even if S_T is everywhere less than the flow velocity. As will be discussed below, we believe that a similar phenomenon is occurring in many cases in the tests reported here. However, rather than the flame continuously propagating upstream, we have found that the static flame anchoring position monotonically moves upstream as the mixture fuel/air ratio increases, apparently due to a change in the location of vortex breakdown.

INSTRUMENTATION AND FACILITY

Blowout and flashback measurements were obtained with two similar, but slightly different combustors, as the facility was modified after the blowout measurements. The blowout measurements were obtained in a 5.1 x 5.1 cm (2" x 2") square combustor, previously described in Ref [30]. The combustor was subsequently replaced by a 7.6 cm (3") diameter quartz tube housed in a pressure vessel, see Figure 1. The premixer was essentially identical, although some additional instrumentation was added for the flashback measurements. This premixer is fully modular as the centerbody and swirler can be easily removed and replaced; tests reported here were performed with a single 12 vane, 35°

swirler. More details about the facility are in Ref. [31]. Although referred to here as a “premixer”, we actually mix the fuel and air far upstream to ensure a homogeneous mixture.

Fuels of arbitrary composition were generated with a blending facility consisting of six mass flow controllers, plumbed to bottles of H₂, CO, CH₄, CO₂, N₂, and/or any other arbitrary fuel.

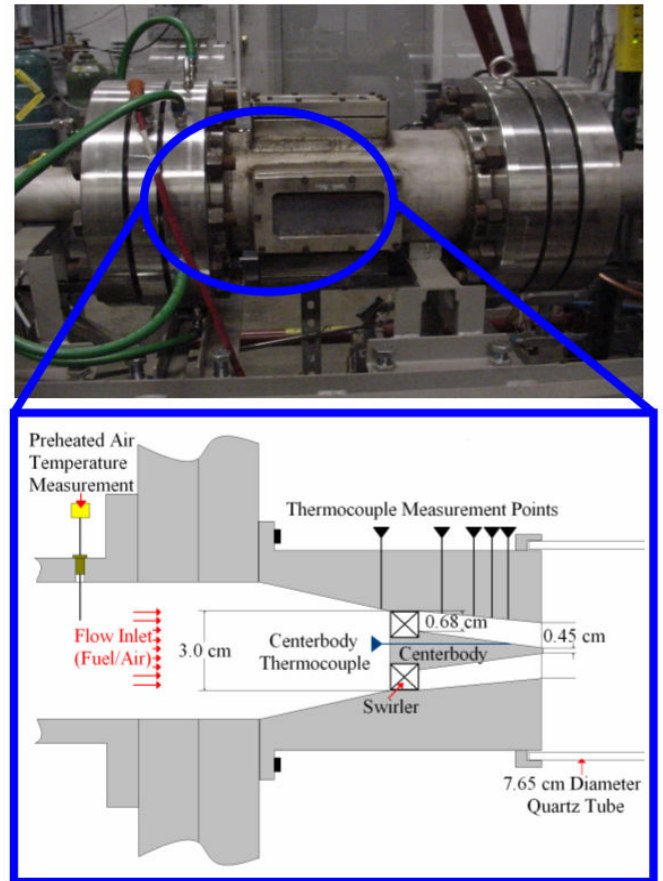


Figure 1: Photograph of high pressure combustor facility.

To detect flashback, a total of fifteen measurement points are arranged on the outer wall of the premixer, as shown below, five in a row at successive axial locations, with three locations at successive 120° azimuthal positions at each axial location. Also, from the schematic of the combustor, a thermocouple is mounted on the surface of the centerbody, approximately 1.9cm from the tip (see Figure 2). An additional thermocouple is located upstream of the premixer (see Figure 1).

Figure 2 shows the premixer with the three rows of five thermocouples. The first three thermocouples, along with the centerbody thermocouple, were used to determine flashback. The two end thermocouples were only used to determine the distance of flashback into the premixer. Once the flame moves upstream, it is sensed by the thermocouple, triggering a flashback alarm. The mixture is quickly leaned out, and the flashback procedure repeated. Note that target temperatures

were chosen based upon prior tests and visual observations of the flame shape and behavior.

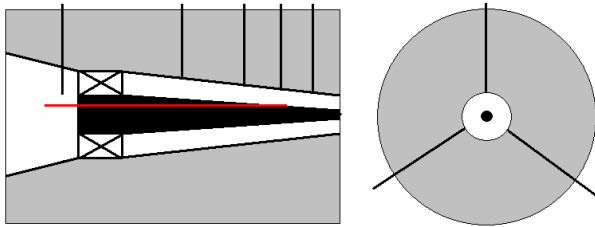


Figure 2: Premixer with swirler, centerbody, radial thermocouples, and centerbody thermocouple.

In order to facilitate presentation of results, we represent the mixture composition of $H_2/CO/CH_4$ by its color. Primary colors at the three vertices are used to represent each fuel constituent, where red, yellow, and blue denote H_2 , CO , and CH_4 , respectively. This is illustrated in the figure below. Unfortunately, Figure 3 will be difficult to interpret if reproduced in grayscale.

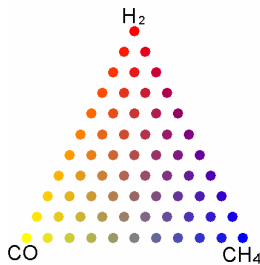


Figure 3: Primary color mixing scheme used to denote fuel blend composition.

The basic test sequence is to operate at uniformly spaced fuel compositions in $H_2/CO/CH_4$ space, such as is depicted in the figure above. At each fuel composition, the mixture equivalence ratio is adjusted at constant unburned velocity until the mixture flashes back or blows off. Obtaining this data was complicated by the need to keep the approach flow velocity, combustor pressure, and mixture temperature constant across the range of fuel compositions. As such, fixing the relative fuel compositions required simultaneously adjusting the air and three fuel flow rates in order to keep constant approach flow velocity. In addition, due to variations in mixture burned gas temperature, maintaining a constant combustor pressure required simultaneous adjustment of the back pressure valve. Finally, variations in molar volume of the fuel necessitated adjusting the air temperature in order to maintain a constant reactant temperature. For the data shown in the Results section, the approach flow velocity, pressure, and temperature remains constant to within 2%, 5%, and 20 K of their quoted values.

To clarify, combustor unburned flow velocities are quoted here, which equals the mass flow rate divided by the unburned gas density and combustor area – this is the combustor velocity if there is no flame. It should be emphasized that this

is purely a reference velocity, as the actual flow velocities may be different. The burned gas velocity simply equals this velocity multiplied by the theoretical temperature ratio across the flame. The velocity at the premixer exit, relevant for the flashback data, equals the unburned flow velocity multiplied by 18.

It should be emphasized that applying a consistently uniform definition of flashback and blowoff is complicated by the fact that the manner in which the flame flashed back and blew off varied with composition. Different flashback mechanisms were found for different fuel compositions. For low H_2 mixtures, the flame anchoring location moved gradually upstream (along the centerbody) with increased equivalence ratio, see Figure 4. In other words, flashback was not a discontinuous phenomenon, where the flame actually propagated upstream into the premixer in a rapid manner. For these cases, flashback is defined here as the point where the thermocouple closest to the exit plane of the premixer reaches 450K and 505K for the 300K and 460K reactant preheat cases, respectively.

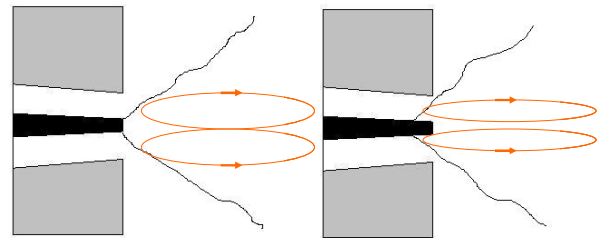


Figure 4: Flame front and postulated recirculation zone locations for normal flame (left) and with flame propagated upstream ("slow" flashback) (right).

However, for high H_2 mixtures, flashback occurred very abruptly – triggered by only a slight change in mixture stoichiometry. The flame would very rapidly propagate upstream, often all the way through the swirler where it triggered the thermocouple upstream of the premixer.

Similarly, the manner in which the flame blew off varied with fuel composition. In many cases, the blowoff event occurred abruptly with a small change in fuel composition, although sometimes preceded by slight liftoff of the flame from the burner. Defining the blowoff point was unambiguous in these instances; moreover, the point of blowoff and flame liftoff was nearly identical. This was the case for mixtures composed largely of CH_4 or CO . However, for mixtures with larger than about 60% H_2 , the blowoff and liftoff events were quite distinct. Usually, the flame became visibly weaker, lifted off from the holder, and moved progressively downstream with decreases in equivalence ratio before blowing off for good. As such, blowoff is defined here as the point where the flame is no longer visible in the 10.2 cm long optically accessible section of the combustor. This point should be kept in mind when comparing 0-60% H_2 and 60-100% H_2 containing fuels.

ANALYSIS APPROACH

This section describes the methods used to post-process the data and correlate blowout limits with the parameters identified in the Background section.

Adiabatic flame temperatures were calculated for a given mixture using standard methods. Laminar flame speeds and blowoff residence times were calculated with the PREMIX and AURORA application in CHEMKIN, using the GRI3.0 mechanism. While this mechanism was primarily optimized for methane/air mixtures, good comparisons between its results and measurements have been obtained for a range of H_2/CO mixtures as well [32]. At some lean mixtures where stable flames were observed, we were unable to get PREMIX to converge. At all other conditions, we found that the blowoff residence time from the well stirred reactor model and the chemical time estimated from the flame speed using Eq. (1) correlate quite well [31].

RESULTS AND DISCUSSION

Figure 5 and Figure 6 illustrate typical results showing the dependence of the blowoff and flashback boundaries upon the mole fraction of H_2 in the fuel. The circled points indicate points where flashback occurred very rapidly. For the remainder of the points, “flashback” corresponded to the upstream movement of the flame stabilization point, illustrated in Figure 4. Note that the rapid upstream propagation mechanism occurred at only the highest hydrogen concentration in the low preheat case, and when the percentage of H_2 is greater than 60% in the preheated case.

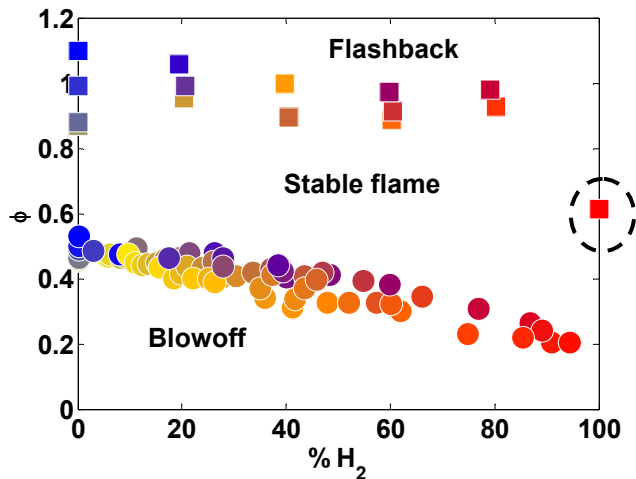


Figure 5: Dependence of LBO ($U_0=6\text{m/s}$) and flashback ($U_0=4\text{m/s}$ or equivalently, premixer velocity= 72 m/s) equivalence ratio upon H_2 mole fraction at reactants temperature 300 K and combustor pressure 1.7 atm . Circled flashback point indicates occurrence of rapid upstream propagation flashback mechanism.

Although these data were obtained at somewhat different pre-mixer velocities (however, the flashback limits do not change significantly with velocity), they are plotted together to illustrate the different sensitivities of these two phenomenon to hydrogen concentration. The flashback result is almost independent of percentage of H_2 , whereas the blowoff equivalence ratio is a very strong function of hydrogen levels, changing by a factor of almost three in the first figure.

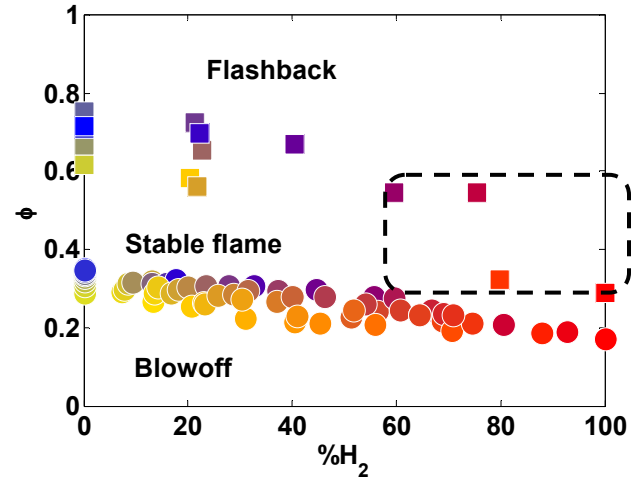


Figure 6: Dependence of LBO ($U_0=6\text{m/s}$) and flashback ($U_0=2\text{m/s}$ or equivalently, pre-mixer velocity= 36 m/s) equivalence ratio upon H_2 mole fraction at reactants temperature 460 K and combustor pressure 4.4 atm . Circled flashback points indicate occurrence of rapid upstream propagation flashback mechanism.

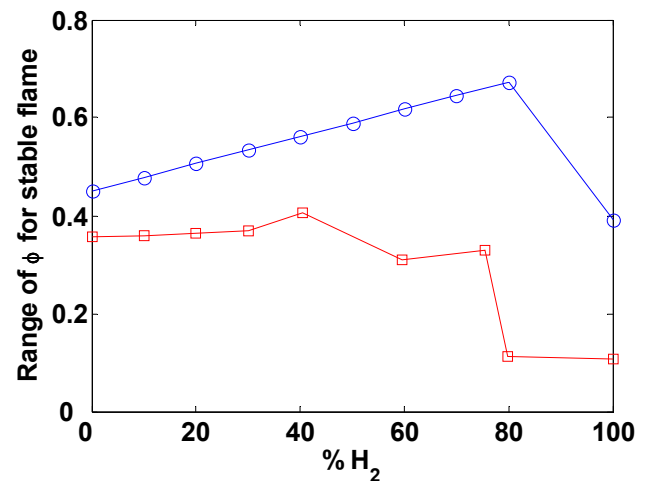


Figure 7: Dependence of range of equivalence ratios for which a stable flame can be achieved upon H_2 percentage. Circle: inlet temperature 300 K , pressure 1.7 atm ; Square: inlet temperature 460 K , pressure 4.4 atm .

These plots show the well known result that, in general, mixtures can be stabilized with lower equivalence ratios as the H_2 concentration increases. In addition, the mixture flashes back easier with H_2 addition, although this effect is very slight at low H_2 levels. Note also that the range of stable operation (i.e., the equivalence ratio range between flashback and blowoff) exhibits a non-monotonic dependence upon $\%H_2$. For low levels of H_2 addition, this stability range is enhanced, especially for the lower reactant temperature case. However, it is actually decreased at the highest hydrogen levels, due to the propensity of high H_2 mixtures to flashback, see Figure 7 .

We next consider correlations of the blowoff results. While a variety of other correlations were examined in our prior paper [31], we found Damköhler number correlations based upon the burned gas flow as a reference velocity to work best, using the combustor width, $D=0.0508m$, as the length scale. The chemical time is the blowoff residence time of a well stirred reactor. A typical result is shown in Figure 8, showing that blowoff occurs at a nearly constant value of Damköhler number, $Da_B \approx 0.82$, for low H_2 (<50%) mixtures. For high H_2 mixtures, Da_B decreases monotonically due to the significant change of blowoff time. Recall, however, that defining the blowoff point is somewhat ambiguous for H_2 levels greater than 60%.

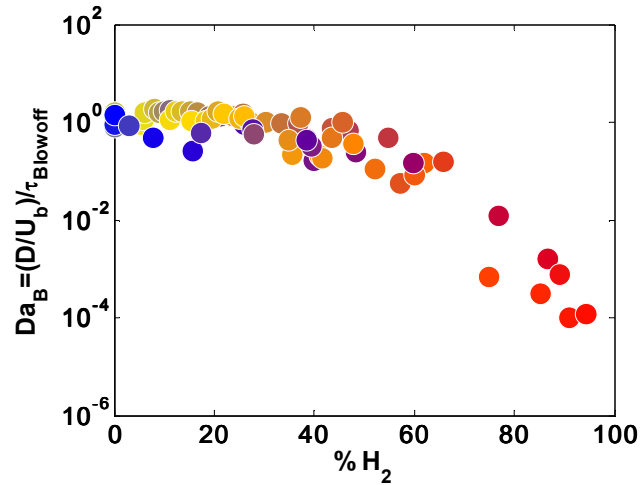


Figure 8: Damköhler numbers of mixtures at constant approach flow speeds. $U_0=6$ m/s, inlet temperature 300 K, pressure 1.7 atm.

Nonetheless, assuming a constant value of blowoff Damköhler number as a blowoff prediction tool works reasonably well. Although the blowoff Damköhler number changes by a factor of 100, it should be noted that the underlying change in chemical time corresponds to a change in equivalence ratio of only 0.1. Figure 9 plots the dependence of the predicted equivalence ratio, calculated using CHEMKIN AURORA results to determine what mixture equivalence ratio gives a $Da_B=0.82$ value, with the actual experimentally measured value. It can be seen that the error is generally less than 0.1, with the RMS error for all

points equaling 0.04. Only for the highest H_2 cases is there a clear deviation, as would be expected from Figure 8.

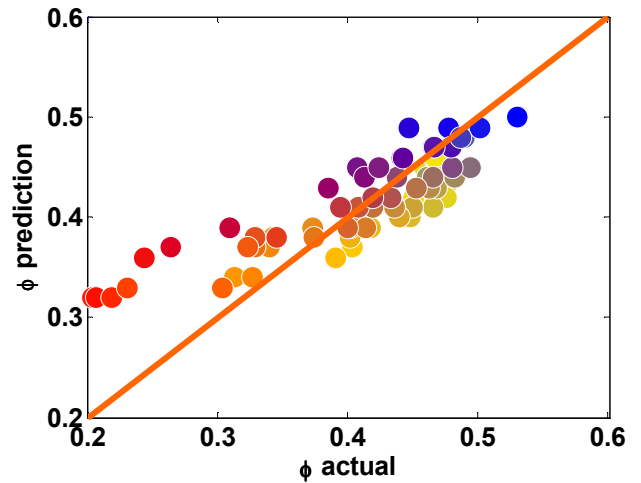


Figure 9: Predicted blowoff equivalence ratio at $Da_B=0.82$ with measured equivalence ratio in experiment for blowoff.

The change in blowoff Da value shown in Figure 8 may be due to preferential diffusion effects, a consideration that has also been used to scale changes in turbulent flame speed of mixtures whose constituents have significant variations in diffusivity. One approach for incorporating these effects is to note that the local equivalence ratio changes along the wrinkled flame, being both higher and lower than the average at different spatial locations. Kido and co-workers [33] suggested correlating mixture turbulent flame speeds by utilizing mixture properties at an adjusted equivalence ratio, equal to the actual value plus some $\Delta\phi$. They suggest the following relation for $\Delta\phi$:

$$\Delta\phi = C * \ln(D_F / D_{OX}) \quad (3)$$

where D_F and D_{OX} denote the mass diffusivity of fuel and oxygen, respectively, and C is a constant whose value they suggest as 0.3. We found that utilizing a value of $C=0.1$ gives a nearly constant blowoff Damköhler number for all of our data sets. For example, Figure 10 shows that blowoff occurs at a nearly constant value of local Damköhler number, which is based on local equivalence ratio, in this case $Da_B=2.1$.

Figure 11 compares the predicted and actual blowoff equivalence ratios, calculated assuming that all mixtures blow off at a constant local Damköhler number, $Da_B = 2.1$, (calculated using the adjusted equivalence ratio). It can be seen that the error is generally less than 0.05, with the RMS error equaling 0.03.

There are a variety of reasons that the remaining scatter could be present, such as inherent noise in the blowoff point. In addition, other more subtle factors, such as reference length

and reference flow velocity could easily change somewhat with approach flow velocity.

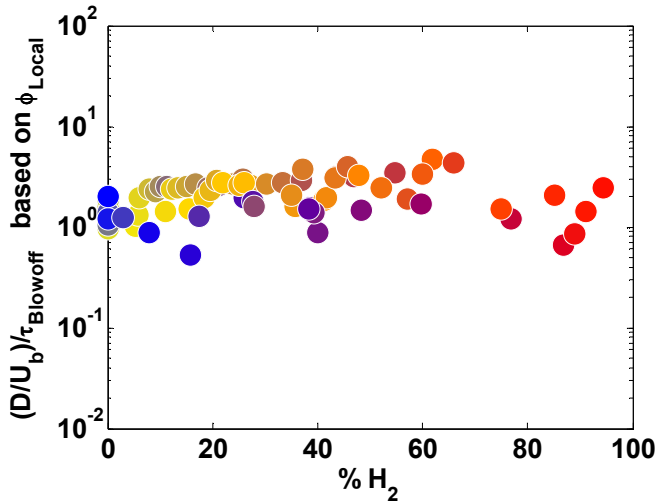


Figure 10: Damköhler numbers of mixtures based on local equivalence ratio at constant approach flow speeds. $U_0=6$ m/s, inlet temperature 300 K, pressure 1.7 atm.

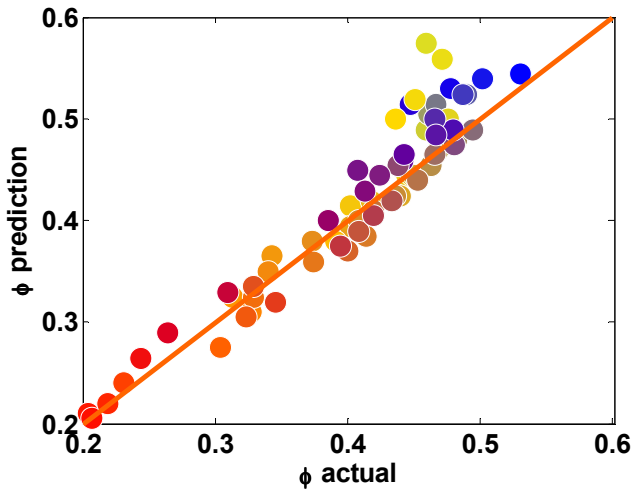


Figure 11: Prediction of blowoff equivalence ratio based on local equivalence ratio. $U_0=6$ m/s, inlet temperature 300 K, pressure 1.7 atm.

These results show that if the blowoff equivalence ratio of one fuel is known at a particular condition, the corresponding blowoff point of other fuels can be predicted with an accuracy of $\sim 10\%$ in equivalence ratio.

Test group		Da_B		Da_U	
		\overline{Da}_B	RMS of ϕ error	\overline{Da}_U	RMS of ϕ error
T =300 K $U_0=6$ m/s	without $\Delta\phi$	0.820	0.043	4.081	0.044
	with $\Delta\phi$ C=0.1	2.126	0.034	10.814	0.028
T 300 K $U_0=4$ m/s	without $\Delta\phi$	0.350	0.041	1.636	0.042
	with $\Delta\phi$ C=0.1	1.699	0.030	8.069	0.028
T 458 K $U_0=6$ m/s	without $\Delta\phi$	0.0513	0.027	0.145	0.028
	with $\Delta\phi$ C=0.1	0.350	0.026	1.041	0.027

Table 1: RMS of predicted equivalence ratio errors of LBO at different working conditions.

We next consider correlations of the flashback data. Figure 12 plots the dependence of the adiabatic flame temperature upon H_2 concentration at two unburned flow velocities. Notice how this flame temperature correlation collapses much of the variability present in the corresponding flashback equivalence ratio, see Figure 5 and Figure 6, at a fixed H_2 level and varying CO/CH₄ ratio. Furthermore, notice that for all the “slow flashback” cases, flashback occurs at nearly a constant value of flame temperature. As expected, the flame flashes back at lower equivalence ratios at the lower unburned flow speeds; however, this variation is not very significant and, furthermore does not correspond to a similar ratio of flame speeds.

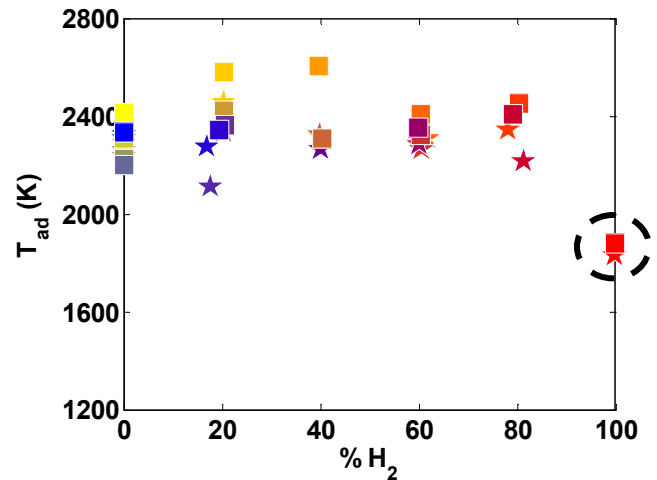


Figure 12: Dependence of ϕ at flashback upon percentage of H_2 . Star: $U_0=2$ m/s (premixer velocity = 36 m/s), inlet temperature 300 K, pressure 1.7 atm; Square: $U_0=4$ m/s (premixer velocity = 72 m/s), inlet temperature 300 K, pressure 1.7 atm; Circled flashback points indicate occurrence of rapid upstream propagation flashback mechanism.

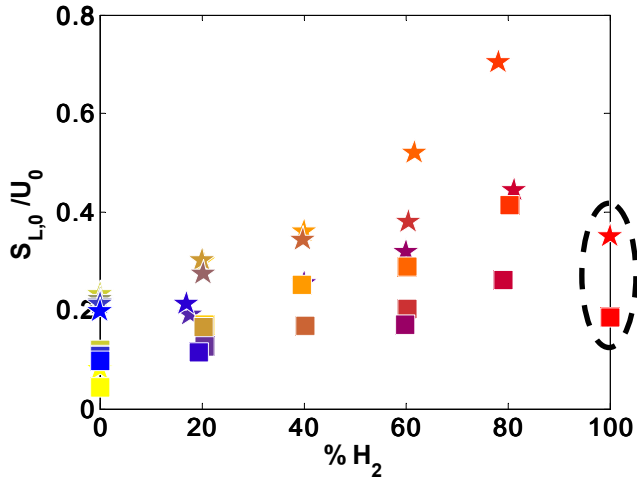


Figure 13: Dependence of $S_{L,0}/U_0$ at flashback upon percentage of H_2 . Star: $U_0=2$ m/s (premixer velocity = 36 m/s), inlet temperature 300 K, pressure 1.7 atm; Square: $U_0=4$ m/s (premixer velocity = 72 m/s), inlet temperature 300 K, pressure 1.7 atm; Circled flashback points indicate occurrence of rapid upstream propagation flashback mechanism.

Furthermore, correlations of these results with laminar flame speed, see Figure 13, increases the spread of the data, indicating that laminar flame speed is not an important parameter describing flashback limits – at least for the slow flashback mechanism.

We believe that these results support the assertions of Sattelmayer and co-workers regarding the impact of combustion on the vortex breakdown bubble. It is known that the vortex breakdown location favors regions of adverse pressure gradients, such as rapid flow expansions or equivalently, flow divergence [34]. In the same way, inclined flame fronts cause divergence of the upstream flow – as such, the flow upstream of the flame is actually decelerating and there is an adverse pressure gradient – even though the flow subsequently accelerates through the flame itself and the pressure drops. Unfortunately, this pressure rise upstream of the flame is very difficult to calculate. We can, however, use basic scaling analysis and reference to scaling laws from weakly perturbed flames to show that it scales with the temperature ratio across the flame, $f(T_b/T_u-1)$. For example, the appendix provides an approximate solution for one case amenable to analytic solution. A result from this analysis showing the spatial variation of the pressure through the flame is plotted in Figure 14. The key point to note from this figure is that convex flame orientation to the flow causes the pressure to actually rise upstream of the flame, followed by the pressure drop across the flame. Note that if the flame were perfectly normal to the flow, there is no pressure rise upstream of the flame.

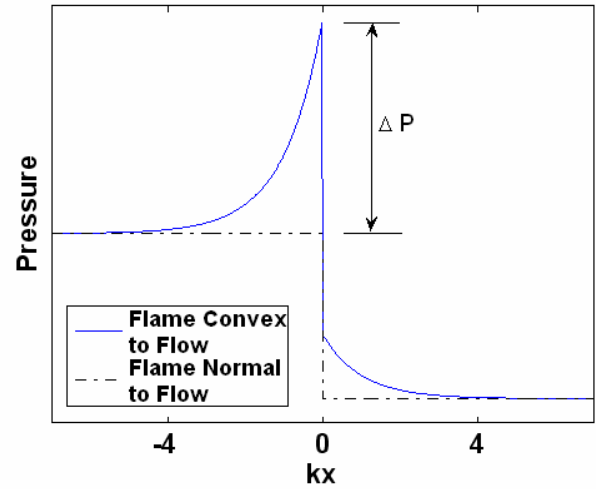


Figure 14: Total pressure (mean plus fluctuation) across the flame front.

Our argument regarding this slow flashback mechanism can be better understood with reference to Figure 15, which shows the hypothesized streamlines in the vicinity of the flame and recirculation bubble in more detail.

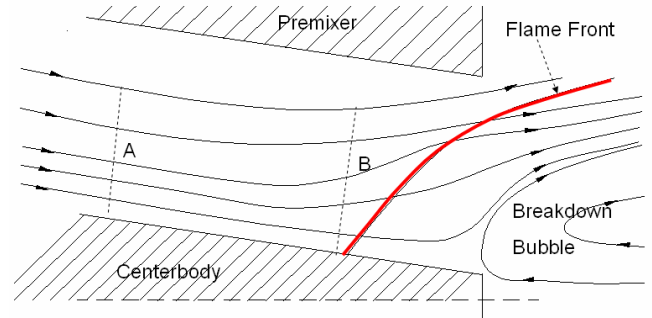


Figure 15: Hypothesized flow streamlines in the vicinity of the flame and recirculation bubble.

The conditions under which the recirculation bubble begins to move backward into the premixer, so that there is actually reverse flow in the premixer, can be understood by reference to the pressure drop in the premixer, P_A-P_B , where the locations “A” and “B” are illustrated in the figure above.

$$\frac{P_A - P_B}{P} = \frac{U_u^2}{RT_u} \left[C_D(\text{Re}, S) - \left(\frac{A_A}{A_B} \right)^2 - f \left(\frac{T_b}{T_u} - 1 \right) \right] \quad (4)$$

where C_D and (A_A/A_B) denote the contribution to the pressure drop due to viscous losses and the cross-section area change, respectively. As indicated, C_D is a function of Reynolds, Re , and swirl number, S . The burned and unburned gas properties are represented by u and b . Presumably, flow instability and vortex breakdown tendencies are enhanced as P_A-P_B decreases, which becomes more likely as T_b/T_u increases.

The results in Figure 12 are consistent with this picture. These results were obtained with a fixed upstream flow velocity and temperature, and a nearly constant Reynolds number – the only variable that changed was the gas composition. Recall that the one high H_2 point corresponds to a different flashback mechanism. The nearly constant value of T_b at which flashback occurs suggests that the vortex bubble moves into the premixer when P_A-P_B becomes small enough or negative.

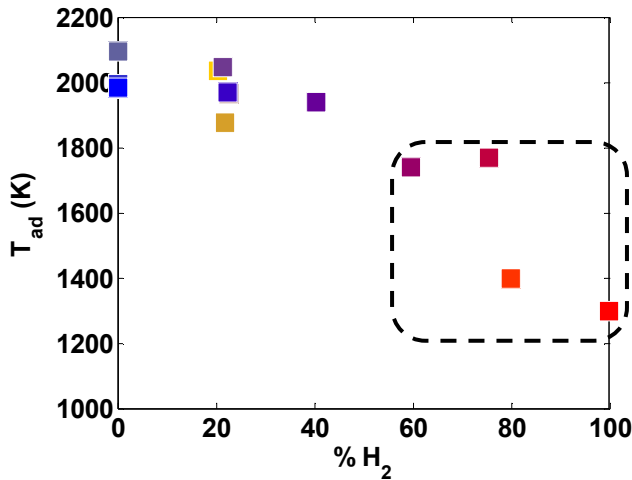


Figure 16: Dependence of adiabatic flame temperature at flashback upon percentage of H_2 . $U_0=2$ m/s (premixer velocity = 36 m/s), inlet temperature 460 K, pressure 4.4 atm. Circled flashback points indicate occurrence of rapid upstream propagation flashback mechanism.

In the same way, there is relatively little change in the flame temperature at flashback with H_2 concentration at a higher pressure and reactant temperature case, as shown in Figure 16. Note that the range of hydrogen levels over which the fast flashback mechanism occurs is expanded here. Because of this, the point of nearly constant flame temperature in the slow flashback cases are somewhat arguable, as the range is smaller and it could also be potentially argued that there is a monotonic decrease in T_{ad} with percentage of H_2 here.

This argument can also explain the measured pressure dependence of flashback limits. According to Eq.(4), the relative pressure change is independent of pressure – note that this is what we also observed in tests at two different preheat temperatures, see Figure 17.

These data also indicate that the flashback temperature decreases with increases in unburned gas temperature – i.e., T_b/T_u decreases from 7.6 at $T_u=300$ K to 4.3 at $T_b=460$ K. Thus, the temperature ratio stays nearly constant with variations in pressure, flow velocity, and fuel composition, but not with unburned gas temperature. Unfortunately, we do not quantitatively understand the unburned temperature scalings of the terms in Eq. (4), such as the C_D term (recall that the viscosity $\nu \sim T^{3/2}/P$) to determine if this result is inconsistent with our working hypothesis.

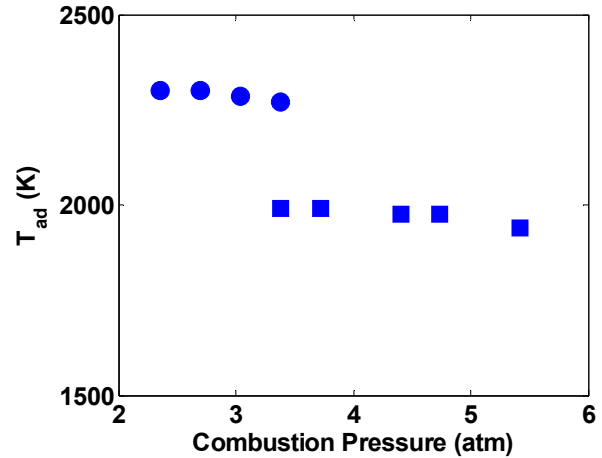


Figure 17: Dependence of adiabatic flame temperature of CH_4 at flashback upon combustion pressure at the same flow rate. Circle: inlet temperature 300 K (premixer velocity range is 36 to 52 m/s); Square: inlet temperature 460 K (premixer velocity range is 58 to 94 m/s).

To further establish whether the key parameter determining the slow flashback proclivity of the flame is dominated by the temperature ratio across the flame, as opposed to the flame speed, we performed a careful test with a high CO mixture, where the equivalence ratio at which the flame temperature peaks, $\phi=1.05$, is well separated from where the flame speed peaks, $\phi=1.24$. The flame position was monitored visually, as well as the centerbody flashback thermocouple. These tests showed that as the fuel-air ratio was swept from lean to rich, the flame moved farther into the premixer and occupied the farthest upstream point at the fuel/air ratio corresponding to maximum flame temperature. Further increases in fuel/air ratio, corresponding to conditions where the flame speed was still increasing but the flame temperature was decreasing, resulted in the flame moving back out of the premixer. This result seems to clearly show that upstream propagation of the flame closely correlates with the mixtures flame temperature, not its flame speed.

CONCLUDING REMARKS

These results show that blowout characteristics can be reasonably captured with classical Damköhler number scalings to predict blowoff equivalence ratios to within 10%. Counter-intuitively, the percentage of hydrogen had far less effect on flashback characteristics, at least for fuels with hydrogen mole fractions less than 60%. This is due to the fact that two mechanisms of “flashback” were noted: (i) rapid flashback into the premixer, presumably through the boundary layer, and (ii) movement of the static flame position upstream along the centerbody. The former and latter mechanisms were observed at high and low hydrogen concentrations, respectively.

The “fast flashback” mechanism was observed to occur at the highest hydrogen concentrations, with the range of H_2

levels over which it was observed increasing with reactant preheat. As such, we postulated that this mechanism occurred when the turbulent flame speed exceeded some bulk or boundary layer flow velocity. However, results suggested that flashback can also occur even if the flame speed was never high enough to propagate upstream. In these instances, the flame can possibly manipulate the region of vortex breakdown by imposing an adverse pressure gradient ahead of the flame. This can explain the fact that the percentage of H_2 did not greatly affect the slow flashback limits since such a mechanism would be far less sensitive to the flame speed, but a strong function of the temperature ratio across the flame, as shown by these measurements.

APPENDIX

This appendix details a perturbation solution extracted from the Darrius-Landau flame stability analysis[†] [35] for a flame with small sinusoidal wrinkles of spatial wavenumber k and amplitude D (see Figure 18), with flame temperature ratio $\mathcal{R} = T_b/T_u$. The pressure upstream of the flame equals its nominal value, plus a small perturbation due to the wrinkle, $P(x) = \bar{P} + P'(x)$. The acceleration of the gases through the flame causes the nominal burned gas pressure to drop, as given by the following expression:

$$\bar{P}_b = \bar{P}_u - (\mathcal{R} - 1) \bar{\rho}_u U_u^2 \quad (5)$$

The alteration of the upstream pressure field by the flame wrinkle along the indicated line in the figure below is given by:

$$\frac{P'_u(x)}{\left(\frac{1}{2} \bar{\rho}_u U_u^2\right)(kD)} = \frac{-(\mathcal{R} - 1)(\sigma - \mathcal{R})e^{kx}}{2 \left(\mathcal{R} \frac{(\sigma - 1)}{(\sigma + \mathcal{R})} [1 + \sigma] + \left(1 - \frac{\sigma}{\mathcal{R}}\right) \right)} \quad (6)$$

where

$$\sigma = \frac{-\mathcal{R}}{1 + \mathcal{R}} \left[\sqrt{1 + \mathcal{R} + \frac{1}{\mathcal{R}}} - 1 \right] \quad (7)$$

The spatial dependence of the pressure through the flame along the dashed line in Figure 18 is plotted in Figure 14.

The magnitude of the pressure rise upstream of the flame, indicated in Figure 14, is given by the expression:

$$\frac{\Delta P'}{\left(\frac{1}{2} \bar{\rho}_u U_u^2\right)(kD)} = \frac{-(\mathcal{R} - 1)(\sigma - \mathcal{R})}{2 \left(\mathcal{R} \frac{(\sigma - 1)}{(\sigma + \mathcal{R})} [1 + \sigma] + \left(1 - \frac{\sigma}{\mathcal{R}}\right) \right)} \quad (8)$$

[†] Note that this stability theory shows that such a perturbation is unstable. However, the corresponding pressure profiles are correct for the flame front whose instantaneous perturbation amplitude is D .

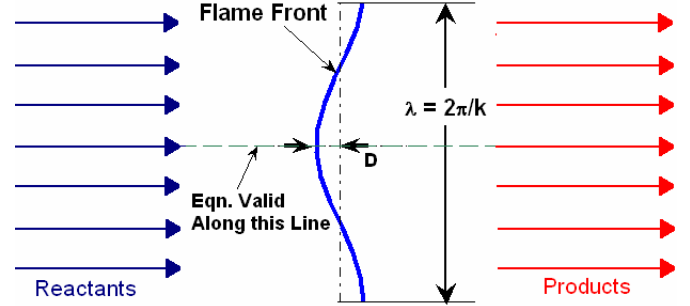


Figure 18: Schematic of flame front with small perturbation (Dashed line: x axis, Dot-dashed line: y axis).

The dependence of this pressure rise upon the temperature ratio across the flame is plotted in Figure 19:

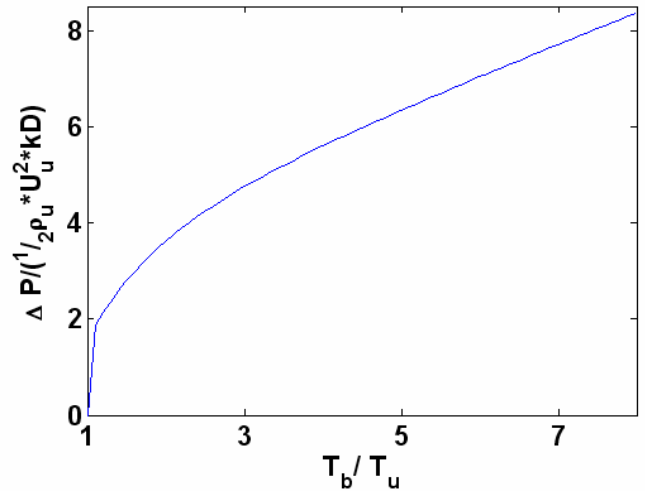


Figure 19: Dependence of pressure rise upstream of the flame upon flame temperature ratio.

This result shows that the adverse pressure gradient ahead of the flame grows monotonically with temperature ratio across the flame, as well as the relative inclination angle of the flame with respect to the flow, related to kD .

ACKNOWLEDGEMENTS

This publication was prepared with the support of the US Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, under contract 03-01-SR111 and DE-FG26-04NT42176 (Dr. Richard Wenglarz and Ron Harp, contract monitors). Any opinions, findings, conclusions, or recommendations included herein are those of the authors and do not necessarily reflect the views of the DOE.

REFERENCES

- 1 Kroner, M., Fritz, J., Sattelmayer, T., "Flashback Limits for Combustion Induced Vortex Breakdown in a Swirl Burner," *ASME Paper # GT-2002-30075*
- 2 Richards, G.A., McMillian, M.M., Gemmen, R.S., Rogers, W.A., and Cully, S.R., "Issues for Low-Emission, Fuel-Flexible Power System," *Prog. Energy Comb. Sci.*, 27, 2001, pp. 141-169
- 3 Klimstra, Jacob, "Interchangeability of Gaseous Fuels – The Importance of the Wobbe Index," *SAE paper # 861578*, 1986.
- 4 Moliere, M., "Benefiting from the Wide Fuel Capability of Gas Turbines: A Review of Application Opportunities," *ASME Paper # GT-2002-30017*.
- 5 Durbin, M., Ballal, D., "Studies of Lean Blowout in a Step Swirl Combustor," *J. Engr. Gas Turbines and Power*, Vol. 118, 1996.
- 6 Barlow, R.S., Fiechtner, G.J., Carter, C.D., Chen, J.Y., "Experiments on the Scalar Structure of Turbulent CO/H₂/N₂ Jet Flames," *Comb. Flame*, Vol. 120, 2000.
- 7 Correa, S.M., Gulati, A. "Non-premixed Turbulent CO/H₂ flames at local extinction conditions," *Proc. Comb. Inst.* Vol. 22, 1988, pp. 599-606.
- 8 Drake, M.C., "Stretched Laminar Flamelet Analysis of Turbulent H₂ and CO/H₂/N₂ Diffusion Flames," *Proc. Comb. Inst.*, Vol. 21, 1986, pp. 1579-1589.
- 9 Correa, S.M., Gulati, A., Pope, S.B., "Assessment of a Partial Equilibrium/Monte Carlo Model for Turbulent Syngas Flames," *Comb. Flame*, Vol. 72, 1988, pp. 159-173.
- 10 Masri, A. R., Dibble, R. W., "Spontaneous Raman Measurements in Turbulent CO/H₂/N₂ Flames Near Extinction," *Proc. Comb. Inst.* Vol. 22, 1988, pp. 607-618.
- 11 Maloney, D., "The Simulation Validation Project at NETL," *DOE Report*, 2002.
- 12 Schefer, R. W., "Hydrogen Enrichment for Improved Lean Flame Stability," *International Journal of Hydrogen Energy*, 28, 2003, pp. 1131-1141.
- 13 Wicksall, D., Agrawal, A., "Effects of Fuel Composition on Flammability Limit of a Lean, Premixed Combustor," *ASME Paper #2001-GT-0007*
- 14 Zukoski, E.E., "Afterburners," in *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, G. Oates, Ed., 1997.
- 15 Spaulding, D., *Some Fundamentals of Combustion*, Ch. 5, Butterworth Press: London, 1955
- 16 Longwell, J., Frost, E., Weiss, M., "Flame Stability in Bluff-Body Recirculation Zones," *Ind. Eng. Chem.*, Vol. 45 (8), pp. 1629-1633.
- 17 Putnam, A., Jensen, R., "Application of Dimensionless Numbers to Flash-back and Other Combustion Phenomena," *Proc. Comb. Inst.*, 3rd, 1949, pp. 89-98
- 18 Hoffmann, S., Habisreuther, P., Lenze, B., "Development and Assessment of Correlations for Predicting Stability Limits of Swirling Flames," *Chemical Engineering and Processing*, 33 (1994), pp. 393-400
- 19 Glassman, I., *Combustion*, Academic Press: New York, 1996.
- 20 Plee, S.L., Mellor, A.M., "Characteristic Time Correlation for Lean Blowoff of Bluff Body Stabilized Flames," *Comb. Flame*, 35, 1979, pp. 61-80.
- 21 Radhakrishnan, K., Heywood, J., Tabaczynski, R., "Premixed Turbulent Flame Blowoff Velocity Correlation Based on Coherent Structures in Turbulent Flows," *Comb. Flame*, 42, 1981, pp. 19-33.
- 22 Wohl, K., "Quenching, Flash-Back, Blow-Off Theory and Experiment," *4th Symposium (Int.) on Combustion*, 1952, pp. 69-89.
- 23 Putnam, A., and Jensen, R., "Application of Dimensionless Numbers to Flash-Back and Other Combustion Phenomena," *3rd Symposium on Combustion, Flame, and Explosion Phenomena*, 1948, pp. 89-98.
- 24 Plee, S. L., and Mellor, A. M., "Review of Flashback Reported in Pre-vaporizing/Premixing Combustors," *Combustion and Flame*, Vol. 32, 1978, pp. 193-203.
- 25 Fritz, J., Kroner, M., and Sattelmayer, T., "Flashback in a Swirl Burner with Cylindrical Premixing Zone," *Proceedings of ASME Turbo Expo 2001*, June 4-7, 2001.
- 26 Kroner, M., Fritz, J., and Sattelmayer, T., "Flashback Limits for Combustion Induced Vortex Breakdown in a Swirl Burner," *Proceedings of ASME Turbo Expo 2002*, June 3-6, 2002.
- 27 Kiesewetter, F., Kirsch, C., Fritz, J., Kroner, M., and Sattelmayer, T., "Two-Dimensional Flashback Simulation in Strongly Swirling Flows," *Proceedings of ASME Turbo Expo 2003*, June 16-19, 2003.
- 28 Thibaut, D., and Candel, S., "Numerical Study of Unsteady Turbulent Premixed Combustion: Application to Flashback Simulation," *Combustion and Flame*, Vol. 113, 1998, pp. 53-65.
- 29 Davu, D., Franco, R., Choudhuri, A., Lewis, A., "Investigation on Flashback Propensity of Syngas Premixed Flames," *AIAA Paper # 2005-3585*.
- 30 Lieuwen, T., Torres, H., Johnson, C., Daniel, B.R., Zinn, B.T., "A Mechanism for Combustion Instabilities in Lean Premixed Gas Turbine Combustors," *Journal of Engineering for Gas Turbines and Power*, 123(1), 2001, pp. 182-190
- 31 Zhang, Q., Noble, D.R., Meyers, A., Xu, K., Lieuwen, T., "Characterization Of Fuel Composition Effects In H₂/CO/CH₄ Mixtures Upon Lean Blowout," *ASME Paper # GT2005-689017*
- 32 J. Natarajan, S. Nandula, T. Lieuwen and J. Seitzman, "Laminar Flame Speeds of Synthetic Gas Fuel Mixtures," *ASME Paper # GT2005-68917*.
- 33 Kido, Hiroyuki, Nakahara, Masaya, "A Model of Turbulent Burning Velocity Taking the Preferential

Diffusion Effect into Consideration,” *JSME International Journal*, Vol. 41, No.3, 1998, pp. 666-673

34 Brown, G., Lopez, J., “Axisymmetric Vortex Breakdown Part 2: Physical Mechanisms,” *J. Fluid Mech.*, Vol. 221, pp. 553-576.

35 Williams, F., *Combustion Theory*, Addison Wesley Publishing Co., 2nd Ed., 1985.