FLAMEHOLDING IN NON-PREMIXED SUPERSONIC FLOWS

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1 Introduction

A balance between the flame propagation speed and the fluid velocity must be maintained to maintain the flame in a chemically reacting flow. Since the fluid velocity exceeds the flame speed in supersonic combustion applications, the flameholding issue is solved by generation of some sort of recirculation region which ensures sufficient residence time so that the processes involved - fuel-air mixing, ignition and chemical reactions propagation – can take place to completion. These processes are determined by local conditions of gas composition, temperature and velocity and are substantially different in non-premixed cases, such as encountered in most practical applications, than in premixed cases which are easier to analyze and predict.

A substantial database of flame stability exists for premixed gases (Ozawa, 1971, Huelmantell et al, 1957, Ogorodnikov et al, 2001) from which stability limits for the rich and lean flames have been obtained for a number of fuel/air systems. The stability limit is usually cast in terms of a flameholding boundary on an equivalence ratio vs. a stability parameter plane. The stability parameter depends, in general, on the flow velocity, temperature, size and shape of the flameholder and has received various formulations in different studies, from empirical formulations to expressions that reflect global Damkhöler numbers.

In the case of non-premixed gases the determination of stability limits is less straightforward, mostly due to the non-homogeneity of the parameters in the recirculation region behind the flameholder. It is difficult to estimate the spatial species concentration and temperature distribution in the recirculation regions of these flows due to the presence of large gradients and the complex, three-dimensional, flow structure. These difficulties are compounded by the uncertainty in the shape of the recirculation region, which depends on the amount of heat release which, in turn, is dictated by the local mixing and combustion efficiencies. The following discussion is focused on the characteristics of the flowfield in the region of a recirculation region with implications on the flameholding analysis and modeling.

2 Recirculation region flowfield

A simple recirculation region is the rearward facing step shown schematically in Figure 1. The rearward facing step has been among the early solutions for flameholding in supersonic flows and continues to exist in combination with other geometrical configurations in most currently proposed flameholders. Among the advantages offered by the rearward facing step is (i) the good separation between the increased pressure due to combustion in its base and the upstream incoming flow and, (ii) the absence of intrusive devices that may generate stagnation pressure loss and require internal cooling.

Paper presented at the RTO AVT Lecture Series on "Critical Technologies for Hypersonic Vehicle Development", held at the von Kármán Institute, Rhode-St-Genèse, Belgium, 10-14 May, 2004, and published in RTO-EN-AVT-116.

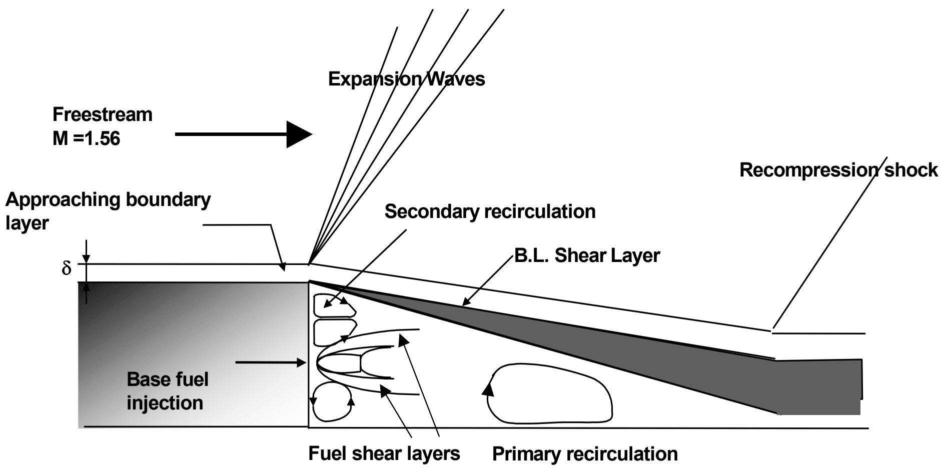


Figure 1. A two-dimensional recirculation region flowfield schematic. The boundary layer formed upstream of the step is pushed by the expansion towards the test section wall. A shear layer forming between the boundary layer and the recirculation region brings fresh air in the region. The fuel is injected into the recirculation region and a barrel shock forms at each injection orifice with shear layers in which the flame is initiated following mixing and heat exchange between the hot gases in the region. A primary recirculation of gases exists that engulfs the recirculation region with additional smaller recirculations present. Additional 3-d flow patterns, not shown in the figure, exist.

Although the flow is highly three-dimensional even for a two-dimensional flameholder due to the effects of the side walls which are generally present, only a two dimensional description is included here, for simplicity. The boundary layer formed upstream of the step arrives at the recirculation region and is pushed by the expansion towards the wall. A shear layer forms between this boundary layer and the recirculation region bringing fresh air in the region and allowing the propagation of burned gases into the main flow. A primary recirculation of gases exists that engulfs the recirculation region, as is indicated in the figure, with additional smaller recirculations present close to the walls. If fuel is injected in this region, it is usually an underexpanded jet, as shown in the figure and a barrel shock forms at each injection orifice. Other forms of refueling of the recirculation region exist, for example, injection from the wall downstream of the reattachment point or upstream fueling of the boundary layer. In both these cases fuel and fresh air arrive into the recirculation region by mass transfer through the shear layer. Any species concentration within a unit volume in this shear layer can have a broad range of values, at a given instance, increasing the difficulty to predict the gas exchange (Dimotakis, 1991). In the case shown in the figure, shear layers develop at the jet-gas boundary in which the flame is initiated following mixing and heat exchange between the hot gases in the region. The fuel jet may transition from underexpanded to sonic and even subsonic with significant implications on the development of the local shear layers, hence on mixing and local heat release. In turn, this heat release modifies the structure of the recirculation region, further affecting mixing.

Morrison et al. (1997) offered an empirical estimate of fuel-air mass exchanges in the recirculation region formed behind a flameholder such as the one in fig. 1 by correlating the size of the recirculation region and the estimated residence time to obtain a local equivalence ratio. Along with other local parameters responsible for flame stability, such as temperature and pressure, a stability parameter of the type suggested by Ozawa (1971) for premixed gases, was proposed for this case. With the observation that the recirculation region remains subsonic Morrison et al. (1997) suggest that stability parameters derived for subsonic, premixed gases can be applied to a certain extent for non-premixed flows, as well. The underlying assumption is that mixing of the fuel injected into the recirculation region is complete and the region has uniform properties.

The dominant effect in the development of shear layers between the fuel jets and the surrounding gases is indicated in Figure 2 which shows the pressure change in the recirculation region as the fuel flow is reduced (Ortwerth, et al, 1999). In the absence of local information the equivalence ratio in this plot, Φ_{Base}, is based on the entire mass of air flowing through the device, P_{Base} is the pressure measured in the base of the rearward-facing step and P_s is the static pressure upstream of the step, used here as a normalizing factor. The relation to the local equivalence ratio will be discussed in a subsequent section. At high equivalence ratios large amounts of fuel are expected to leave the recirculation region and continue to burn in the high-speed flow region (Write and Zukoski, 1960). Below $\Phi_{Base} = 0.07$ the fuel flow rate is sufficiently low to mix and burn within the recirculation region without flame propagation as indicated by the "kink" in the curve. This limit also indicates the domain below which the recirculation region length remains unaffected by combustion.

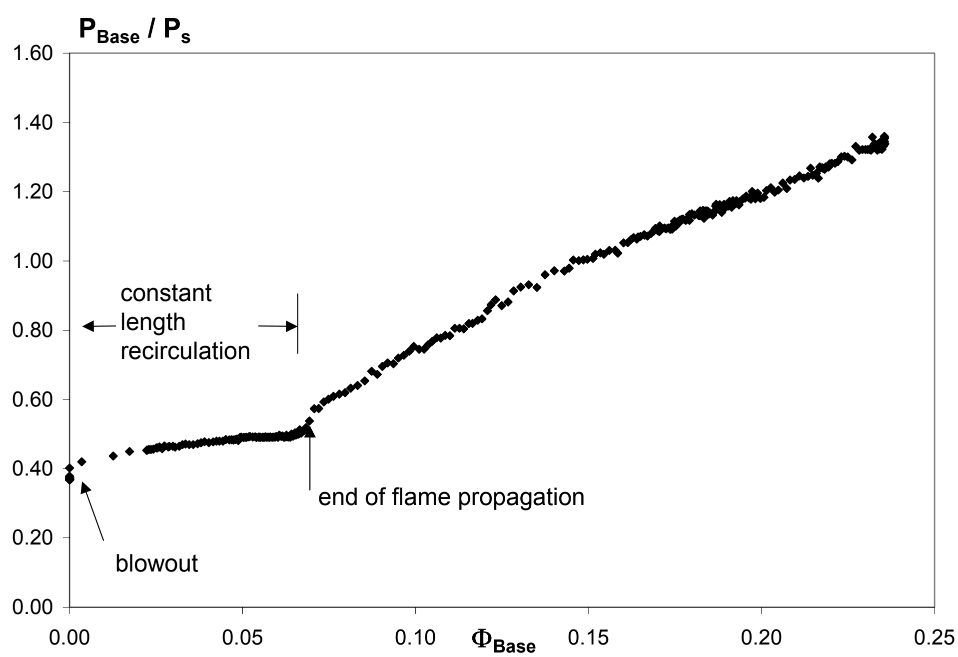


Figure 2. Normalized base pressure rise vs. a global equivalence ratio. The "kink" in the curve indicates the limit of flame propagation through the recirculation region. At lower Φ_{Base} the recirculation region length remains constant (Ortwerth et al, 1999).

It can be concluded, therefore, based on these, mostly qualitative, observations that stability parameters based on conditions external to the bluff-body, e.g., the upstream conditions, in particular velocity and stagnation temperature with assumptions of fixed recirculation region length (Ozawa, 1971), may introduce large uncertainties in the analyses of non-premixed flows.

Figure 2 helps to identify a distinction that should be made between two conditions of importance in the operation of a supersonic combustion chamber: (i) a boundary of flame spreading, represented by the boundary beyond which the flame extends beyond the recirculation region and (ii) a boundary of residual flame (Ogorodnikov et al, 1998) below which the flame is lost altogether. The beginning of pressure increase in the combustion chamber identifies the first condition, also called *blowoff*, as heat is continuously added to the flow. The sharp drop in temperature measured in the recirculation region identifies the latter, also known as *blowout*.

3 Recirculation Region Temperature

There are sharp gradients of temperature in the recirculation region and they change location as the heat release and the geometric shape of the recirculation region change (Ogorodnikov et al, 1998). Thus the assumption of a uniform temperature in the recirculation region based, for example, on a single point measurement is only indicative and may not represent correctly average or global properties. For example, Figure 3 (Owens et al, 1997) shows a measurement taken at ½H from the step in an axial direction and ½H above the chamber wall for a configuration that included distributed fuel injection from small, base orifices. This type of injection achieves rapid two-dimensional fuel distribution at low equivalence ratios, resulting in good flameholding characteristics. The temperature, T_{Flame}, in fig. 3 is related to the overall equivalence ratio, Φ, during fuel throttling from large-to-low Φ. This equivalence ratio is based on the total amount of fuel injected and the total amount of air traveling through the combustion chamber; therefore, it indicates significantly lower values than are actually present in the recirculation region. As can be seen in the figure, temperatures close to adiabatic flame values for stoichiometric mixtures are noticed, reflecting the substantial difference in the local equivalence ratio experienced and the values estimated based on global conditions. The sharp drop in the highest indicated temperature, as the equivalence ratio was reduced, corresponded to the physical destruction of the thermocouple as the local temperature approaches stoichiometric values.

Simultaneous measurements at multiple locations in the recirculation region (Owens et al, 1997) indicate the substantial gradients present in the small region occupied by the recirculation region. The resulting reacting flow was, thus, imbedded in a supersonic airflow with parameters upstream of the flameholder characterized by Mach 1.8 and stagnation temperatures in the range of 600K to 1000 K. The combustor operated in the pseudo shock mode as first described by Shchetinkov (1973) and later by Heiser and Pratt (1994).

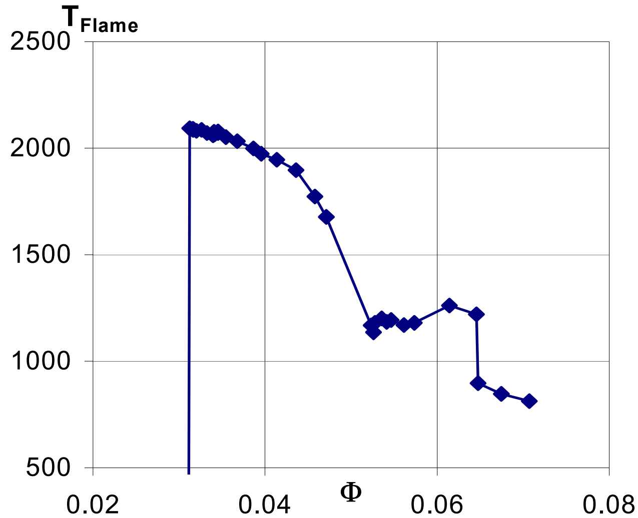


Figure 3. Temperature measured with a thin, B-type thermocouple (Owens et al 1997) as a function of the global equivalence ratio, Φ indicates values close to adiabatic flame temperatures for stoichiometric mixtures.

Figure 4, taken from Owens et al (1998), shows these temperature changes recorded simultaneously at three different locations, indicated in the figure in terms of step height, *h*, as the amount of fuel injected was changed. Also included in the figure is the change in the fuel injection pressure, P_{H2}, as a measure of fuel throtlling. Although the local pressure, *P*, remained constant, therefore indicating a fixed size recirculation region, the temperatures, measured at 1.2, 1.8 and 2.3 step heights from the step, respectively, show large gradients in time and space. Furthermore, the increase in local temperature as the overall injected fuel flow is reduced indicates that, locally, the mixture is fuel-rich, in contrast to the conclusion that would be drawn based on the global combustion chamber equivalence ratio. Therefore a direct correlation between the flameholding region gas composition and the global parameters is not straightforward available.

4. Local Equivalence Ratio Analysis

The equivalence ratio in the stability analysis that follows for the data provided by Owens et al (1998) is based on the total incoming airflow. Using the analysis suggested by Morrison et al (1997) the estimated air replenishment flow into the recirculation region is about 3.7% of the total device airflow for simple, rearward facing recirculation regions, as discussed here, when the recirculation length is *5h*, and 1% when the recirculation region shrinks to *1h* as the fuel flow and, consequently, the heat released are reduced. Additional analysis can be performed based on shear layer development under the assumption that the transfer of fresh air and burned gases into and from the recirculation region is controlled by the development of the shear layer at the recirculation region boundary. Pitz and Daily (1983) indicate that the rate of growth of shear layers for a given duct expansion is insensitive to effects of combustion in the shear layer itself and remains constant to about $\delta/h = 0.28$. Correcting for the compressibility effects (Dimotakis, 1991) via Mach and Reynolds numbers at the experimental conditions of Owens et al (1998) study from which the data in fig. 4 has been taken, i.e., $M = 1.8$ and $Re = 1.2 \cdot 10^6$, the following correction factors for the shear layer development are found:

$$f_{Re} = 0.75;\ f_M = 0.4 \qquad (1)$$

With this data the air mass flow in the shear layer at reattachment, which is responsible for replenishment of the recirculation region, can be calculated. Assuming a reattachment length of *5h* (Morrison et al 1997) and with the velocity and density ratios estimated from the experimental data as $r = 0.57$ and $s = 0.25$, respectively, the equivalence ratio correction becomes,

$$\phi_{factor} = \tfrac{1}{2} \cdot (\delta/h) \cdot (x_r/h) \cdot f_{Re} \cdot f_M \cdot r \cdot s = 0.03. \qquad (2)$$

with ½ reflecting the symmetry of the test section. This equivalence ratio estimate is in remarkable well agreement with the observed peak recirculation zone temperature which indicates local stoichiometry.

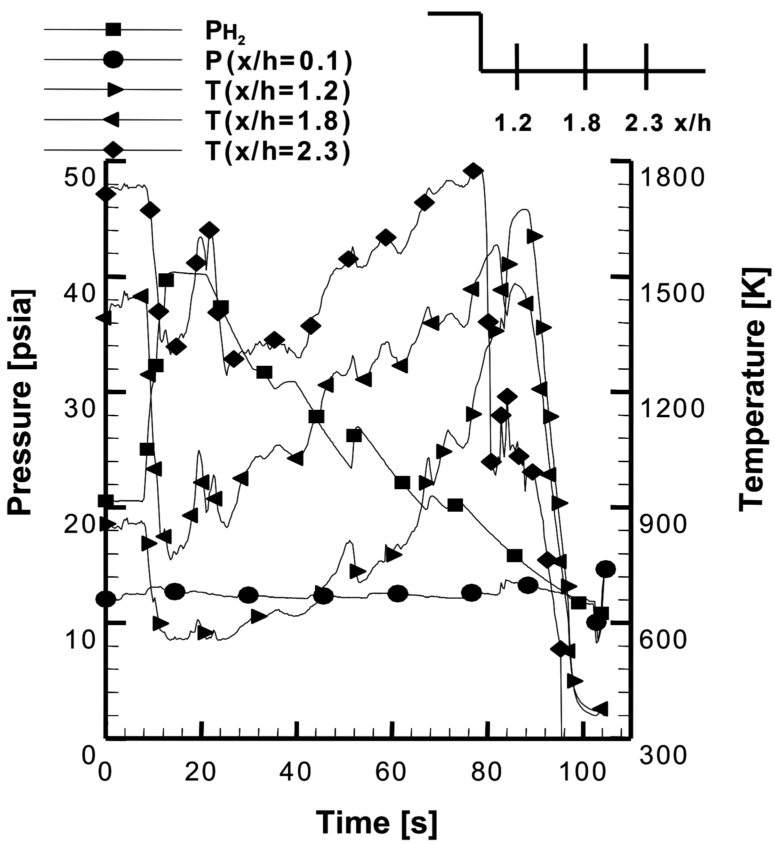


Figure 4. Although the local pressure, *P*, remains constant, therefore indicating a fixed size recirculation region, the temperatures show large gradients in time and space.

5 Recirculation Region Composition Analysis

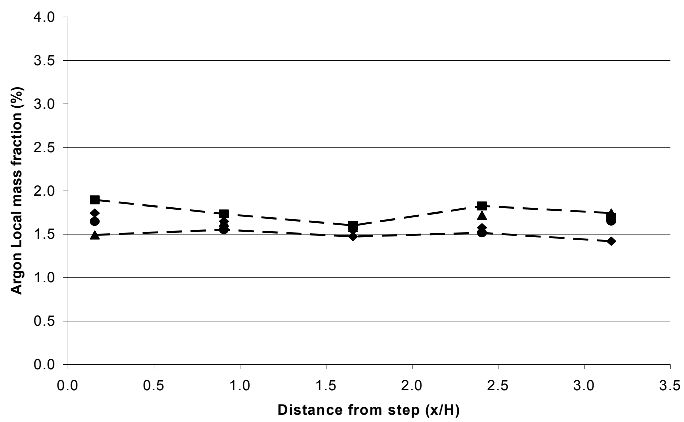
An example of gas composition in the recirculation region analysis is offered by Thakur and Segal (2003) who measured through mass spectroscopic sampling the distribution of an inert injectant – argon in this case - in the recirculation region formed behind a sudden expansion in a supersonic flow. Sampling from the wall along a region extending beyond the physical size of the recirculation region and transverse, into the recirculation region at selected locations confirmed that, locally, the injectant concentration is substantially larger than estimated based on global parameters. Figure 5 shows the argon mass distribution samples from the wall at locations extending beyond 3h, at flow condition that resulted in a recirculation region length of <2h. The figure indicates that the local argon mass fraction is found between 3-8 times larger than the estimate based on global conditions at both experimental cases, which included a higher and a lower injection pressure. It is interesting to note that although some variation exists in the axial direction with a drop towards the end of the recirculation region an a slight increase beyond it, the differences are not significant, indicating that sufficient argon propagation beyond the recirculation region took place. Thakur and Segal (2003) results show that sampling in a transverse direction to the flow in the recirculation region indicates a variation of local concentration caused by a, clearly, three-dimensional flow and an in-flow argon concentration exceeding the wall sampling by 20-30% depending on the injection pressure.

6 Stability Parameter Formulations

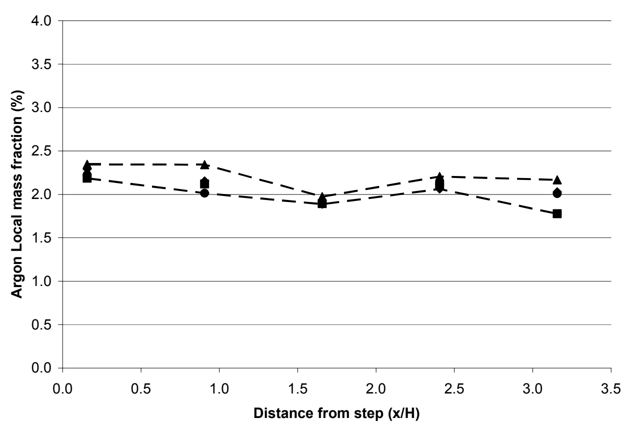
It has been suggested (Morrison et al, 1997)) that, since the flow remains subsonic in the recirculation region, flame stability parameters obtained from subsonic flows can be applied to subsonic flameholder flow regions that are imbedded in a supersonic flow. The local equivalence ratio ambiguity can be, then, solved by estimating the amount of fresh air that enters the recirculation region, treated as homogeneous. This includes the underlying assumption that mixing is fast and uniform, which is reasonable at low equivalence ratios. Citing a large database of previous studies, Ozawa (1973) formulated an empirical equation that relates the amount of air massflow into the recirculation region to the total massflow and the geometrical shape at the flameholder. A stability parameter is then defined by Ozawa for premixed gases taking the following formulation:

$$SP = \frac{V}{d} f_d \frac{1}{P} \left(\frac{1000}{T_0} \right)^{1.5} \tag{3}$$

where, SP is the stability parameter, V is the air velocity arriving at the flameholder, d is the physical size of the flameholder, f_d, a factor depending on the shape of the flameholder, P is the gas static pressure and T_0 the stagnation temperature upstream of the flameholder. The thermodynamic parameters involved in the stability parameter equation have a clear and intuitively expected effect on flame stability. On a plot of



(a) P_{argon} = 5.4 atm, global $MassFr_{argon}$ = 0.25%.



(b) P_{argon} = 2.2 atm, global $MassFr_{argon}$ = 0.61%.

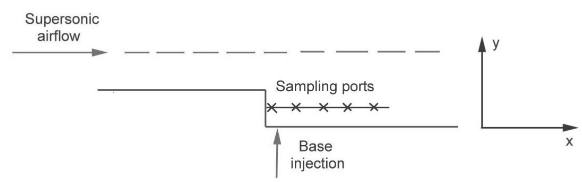


Figure 5. Argon mass distribution obtained with argon injection in the recirculation region at two different pressures. A slight decrease towards x/H = 1.5, which marks the end of the recirculation region, is noticed followed by an increase in the injectant concentration beyond it.

equivalence ratio, Φ vs. the stability parameter, *SP*, a curve called "*the stability loop*" separates the region of stable flames from the region when the flames blowout. These curves have a maximum at stoichiometric conditions.

Other stability parameters formulations have been suggested for flameholders imbedded in supersonic flows with parameters measured both upstream and in the recirculation region. For example, Wright and Zukoski (1960) suggested a stability criterion for cavity flameholders of length *L* that depends both on the local pressure in the cavity, P_l and the upstream parameters, i.e., velocity, V and stagnation temperature T_0. This parameter is, then, plotted as a function of the local equivalence ratio, measured in the cavity, as:

$$K_s = \frac{V}{P_l^{1.45} T_0^2 L} \tag{4}$$

Other formulations have been suggested based on an exponential temperature dependence (Strokin and Grachov, 1997) as follows,

$$K_{da} = \frac{V \,.\, dF/dx}{P \exp^{(-1.12 T_o / 1000)}} \tag{5}$$

where dF/dx is the local combustion chamber cross sectional area change.

A stability criterion that directly describes a local, global Damköhler number has been formulated by Ogorodnikov et al (1998) as:

$$K_{da'} = \frac{V}{P_{inj} \exp^{(-1000/T_{local})}} \tag{6}$$

where P_{inj} is the local injection pressure and T_{local} is the local flame temperature measured in the recirculation region. The fuel injection pressure is used in this expression to indicate the dependence of the mixing processes on the local shear layer development. The shortcomings of the formulation appear in the residence time, introduced by the use of the air velocity immediately upstream of the flameholder and an assumed constant recirculation region length. Nevertheless, although largely simplifying the complex processes that take place in the flameholding region, this stability criterion includes local flow parameters responsible for mixing and combustion and captures the major physical processes involved.

It is interesting to pay attention to the effect the development of the shear layer at the flameholder has on the flame stability. Figure 6 shows the global equivalence ratio at blowout, Φ_b, vs. a shear-layer parameter responsible for mixing (Ortwerth, 1999), where V_{max}, V_{min} are the velocities and s the density ratio on the two sides of the shear layer at the experimental conditions described by Ortwerth et al (1999). Two types of recirculation regions have been used in this study with essentially the same flameholding results which are shown in the figure at two different air stagnation temperatures. There appear to be separated regimes dictated by the changes in the shear layer's development which is responsible for changes in the mixing length and hence on the flame stability. A vertical boundary appears to form in all cases when the fuel was injected in large quantities; thus fuel in large amounts and high velocity may leave the recirculation region without participating in the local combustion. The horizontal limits correspond to the low fuel-rates, when the mixing is assumed to complete within the recirculation region.

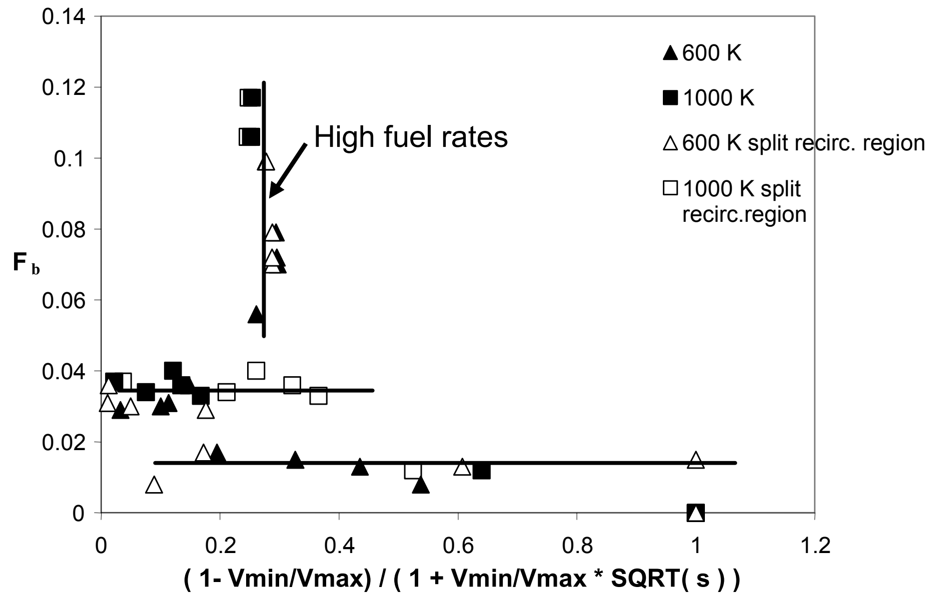


Figure 6. Blowout equivalence ratio vs. shear layer growth parameter. V_{min}, V_{max} are the velocities across the shear layer and *s* is the density ratio. The plateaus indicate mixings regimes dictating the flame blowout. The vertical line corresponds to high fuel flowrates indicating that large quantities of fuel leave the recirculation region before mixing is complete.

In a global sense, based on the dynamic pressure ratio of the fuel to the air at the thermodynamic conditions upstream of the flameholder, q_r, , Figure 7 shows a region of linear dependence of the equivalence ratio at blowout on the dynamic pressure ratio at high equivalence ratios. Otherwise, at low dynamic pressure ratios the blowout limit appears to be insensitive to this parameter.

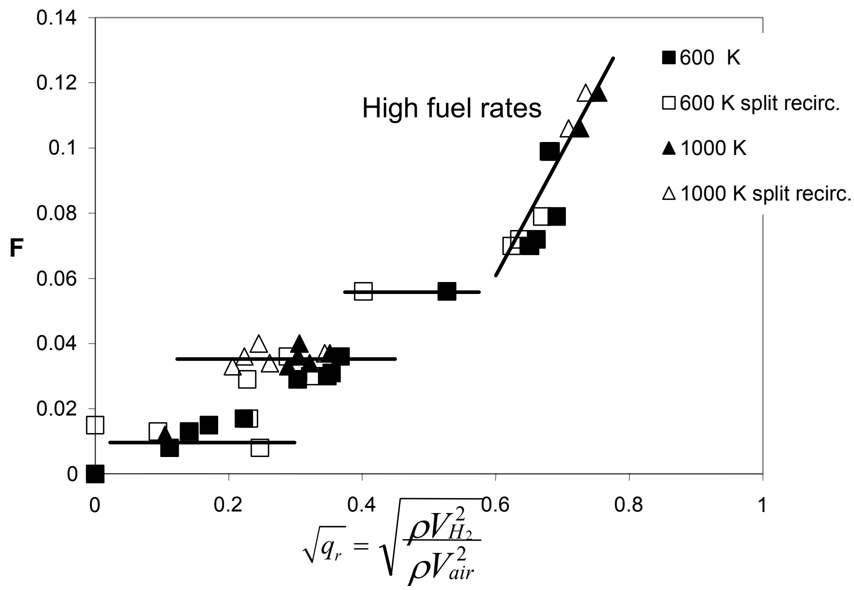


Figure 7. Blowout equivalence ratios appear insensitive to the jet-to-upstream air dynamic pressure ratio at low fuel rates and linearly dependent at large fuel flows.

7. Summary

Flame stability in non-premixed flames depends on local thermodynamic conditions that are responsible for the development of shear layers at the fuel-air boundary and cannot be correlated easily with stability parameters developed for premixed flames. The uncertainty in defining a flame stability parameter for non-premixed gases is compounded by the variable length of the recirculation region and by the uncertainty of the amount of fuel that penetrates into the recirculation region through the shear layers. Estimates of local equivalence ratio based on replenishment due to the development of the shear layer at the recirculation region boundary correlate surprisingly well with the estimates based on local temperature measurements and should be, perhaps, used as a basis for the formulation of new stability parameters for these types of flows. When the fuel is injected at high rates directly into the recirculation region the stability becomes essentially independent of the shear-layer development, a result of the presence of rich mixtures even when, globally, the fuel rates are low. Therefore, stability parameters, determined primarily from global data, fail, in general, to describe the flameholding process. However, limited local information, acquired in the recirculation region itself, provide correction factors that reproduce some of the physical processes, in certain cases, with satisfactory accuracy.

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