Planar Flame on a Porous-plug Burner: Onset of Oscillations and Flame Restabilization

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1 Introduction

In recent studies [1, 2] of edge-flames, stabilized either in the wake of the fuel injector or in a corner region of two perpendicular streams, it was found that the flame often looses stability when the Lewis numbers associated with the reactants are sufficiently larger than unity. The control parameter in such circumstances is the intensity of the flow field. At low flow rates the flame is stabilized at a fixed distance from the injector or from the corner. When the characteristic gas velocity exceeds a critical value the flame undergoes spontaneous oscillations. But the oscillations do not always persist as the flow rate increases further. Under certain conditions the oscillations are amplified as the flow rate increases leading eventually to flame blowoff. Under other conditions the flame oscillations, which are at first amplified, reach a maximum amplitude and then decrease by further increasing the flow rate until the flame re-stabilizes. Flame restabilization has not been predicted before neither in this context nor in simpler flame problems.

The two-dimensional structure of the edge-flame and of the underlying flow field prevents one from performing a complete stability analysis so that the results just quoted were obtained numerically. The flow field computed based on the Navier Stokes equations was assumed to remain undisturbed by the presence of the flame. The flame dynamics was then described by the unsteady transport equations of mass and energy with the prescribed flow. If the long time behavior of the solution converged to a steady-state, that state was identified as stable. For the unstable case it was found that the long time behavior of the solution was a limit cycle with well-defined frequency and amplitude.

To further understand the re-stabilization phenomenon we re-examine in this paper the problem of a flat premixed flame on a porous-plug burner. Because of the one-dimensional simplicity one can not only study the existence of steady states but also their stability. We show the dependence of all possible steady states on the parameters that include the mass flow rate, the effective Lewis number of the mixture, the overall activation energy and the extent of heat release. A linear stability analysis is then carried out to examine whether these steady states are stable to small disturbances. The analysis determines the critical conditions for the onset of an instability as well as the nature of the instability. In the present study the focus has been on the onset of oscillations. For steady conditions, the fractional mass flux of a reactant at the porous-plug boundary may be considered as prescribed. But for time-dependent conditions the fractional mass flux of a reactant at the flameholder is a result of the details of mass transport occurring within the porous plate which depend on the properties of the reactants as well as those of the porous plug including, in particular, the thickness of the plate and its porosity. We show that these parameters also play a significant role on flame stabilization.

Finally we note that the problem has important practical applications: a porous-plug burner is used experimentally to observe steady flat flames [3]-[6] and is often used to measure the laminar flame speed.

2 Planar flames

A premixed combustible mixture is passing through a porous plate of finite thickness as shown in Fig. 1(a). The gas stream emerging from the downstream exit of the plate is uniform. The plate is a semi-permeable porous plug that allows free passage of the combustible mixture but prevents back diffusion of combustion products into the unreacted gas. It also serves as a heat sink extracting heat from the combustion field [7, 8]. The thermal conductivity of the plate is assumed sufficiently high so as to maintain the gas temperature in the plug constant and equal to T_0. It is assumed that the mixture is deficient in fuel so that it is enough to follow its mass fraction denoted by Y, with the oxidizer mass fraction remaining nearly constant. The mass fraction of fuel just upstream of the plug is prescribed as Y_0. Variations in the mass fraction across the plug depend on the molecular diffusivity of the fuel and on the porosity of the plug. The chemical reaction in the gas phase is modelled by a one-step reaction which converts the fuel to product and proceeds at a rate proportional to Y with an Arrhenius temperature dependence.

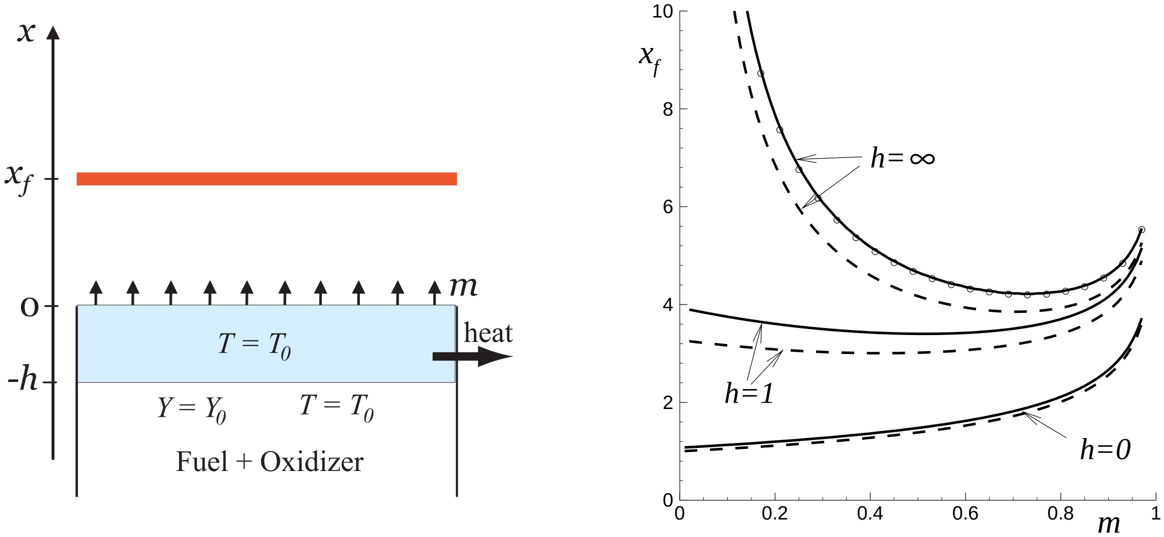
With the diffusion length chosen as the characteristic length and the laminar flame speed S_L as a characteristic speed, the governing equations are:

$$-h < x < 0: \qquad \theta = 0 \qquad \frac{\partial Y}{\partial t} + m\frac{\partial Y}{\partial x} - \mu Le^{-1}\,\nabla^2 Y = 0$$

$$0 < x < \infty: \qquad \frac{\partial \theta}{\partial t} + m\frac{\partial \theta}{\partial x} - \nabla^2\theta = \omega \qquad \frac{\partial Y}{\partial t} + m\frac{\partial Y}{\partial x} - Le^{-1}\nabla^2 Y = -\omega$$

where m is the constant mass flux and $\theta = (T - T_0)/(T_a - T_0)$ the dimensionless temperature with T_a the adiabatic flame temperature. The parameters in this formulation are the Lewis number Le, or the ratio of thermal-to-molecular diffusivities, h and μ which stand for the thickness and porosity of the plug, and β and γ which are the Zel'dovich number and the heat release parameter (the latter appear in the expression for the reaction rate ω).

The steady equations were solved (i) using a flame sheet approximation, or a large Zel'dovich number, and (ii) numerically for finite values of β. In Fig. 1(b) we show the dependence of the standoff distance x_f on the mass flux m. The solid curves are obtained from the numerical computation and the dashed curves from the analytical approximate expressions. The graph also illustrates the influence of the plate thickness h on the flame location. At high flow rates, the planar flame is stabilized at large distances from the burner. The limit $m \to 1$ corresponds to a planar adiabatic flame; the gas velocity is equal to the laminar flame speed and the burner has practically no influence on the flame. At lower values of m the flame is stabilized closer to the flameholder which extracts heat from the combustion field lowering the flame temperature. Consequently, the flame can be sustained by a lower mass flux. In general there is a minimum distance that the flame can approach the flameholder. The minimum standoff distance $(x_f)_{\min}$ is reached at a value $m = m_*$ that depends on h. When $h \to \infty$, $m_* \approx 0.75$ and $(x_f)_{\min}$ is nearly four units of length. Both m_* and $(x_f)_{\min}$ decrease as h decreases and when $h \to 0$, $m_* \to 0$ with $(x_f)_{\min} \to 1$. The standoff distance results shown in Fig. 1(b) are in qualitative agreement with the experimental record [5]. Note that typical plugs used in experiments are few millimeter thick, which correspond to a significantly large h.



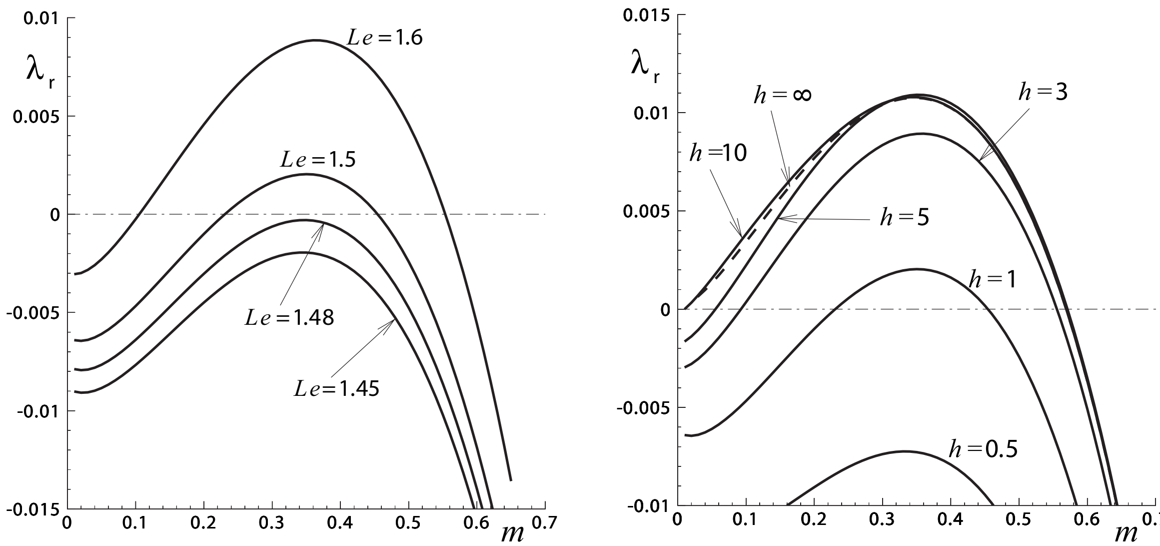
(a) (b)

Figure 1: (a) Schematic diagram of the porous-plug burner. (b) The dependence of the standoff distance of a flat flame on the mass flux for various values of h (computed for $\beta = 10, Le = 1$ and $\gamma = 5$). The solid curves are numerically calculated for finite rate chemistry and the dashed curves are obtained from the asymptotic formulas.

3 Stability results

A linear stability analysis has been performed by introducing small disturbances $\sim \exp(iky + \lambda t)$ to the basic steady states, with k the transverse wavenumber and λ the (complex) growth rate. Non-trivial solutions of the linearized problem can be found only when a solvability condition of the form $\mathcal{F}(\lambda, k; m, Le, \beta, \gamma, h, \mu) = 0$ is satisfied. The latter is a dispersion relation that determines, for a given set of parameters, the growth rate λ of a disturbance as a function of the wavenumber k. The dispersion relation has been analyzed for a wide range of parameters that are of interest physically. Here we present only limited results showing the onset of oscillations and the phenomenon of flame restabilization. As usual the flame is considered stable when the real part of *all* the eigenvalues is negative. An instability results when $\lambda_r > 0$ for some value of k. The analysis of the dispersion relation shows that for Le larger than one the fastest growing (most dangerous) mode always corresponds to $k = 0$ and the imaginary part of λ at the marginal state is non-zero. This suggests that at the onset of the instability the flame remains planar but oscillates back and forth normal to itself.

The growth rate λ_r is plotted in Fig. 2(a) as a function of the mass flux m for several values of Le. The results are presented for $h = 1$ with $\beta = 10, \gamma = 5$. For $Le \leq 1.48$ the flame remains stable for all values of m. It becomes unstable only when Le exceeds a critical value sufficiently larger than one. For example, the flame in a mixture with $Le = 1.5$ is stabilized at a large but finite distance from the flameholder as long as $0.47 < m < 1$. When $m \approx 0.47$ spontaneous oscillations develop and are sustained when m is further decreased. However when m is reduced below ≈ 0.24 the flame is re-stabilized. The instability mechanism is diffusive-thermal resulting from the competing effects of heat conduction away from, and mass diffusion towards the front. For larger values of Le the unstable range in m is wider. The growth rate λ_r is plotted in Fig. 2(b) as a function of the mass flux m for several values of h. When the plate is sufficiently thin a flat flame can always be stabilized at a finite distance away, provided $m < 1$. But for larger values of h an instability may arise. Consider, for example, $h = 1$ starting at a sufficiently large $m < 1$. The flame at first is stabilized at a finite distance x_f which decreases as m is



(a) (b)

Figure 2: The growth rate λ_r as a function of the mass flux m for (a) fixed $h = 1$ and several values of Le, and (b) fixed $Le = 1.5$ and several values of h. Calculated for $\beta = 10, \gamma = 5$.

reduced. When $m \approx 0.5$ spontaneous oscillations develop and are sustained when m is further decreased. However when m is reduced below ≈ 0.22 the flame is re-stabilized. For larger values of h the range of instability widens. In thicker porous plates one may anticipate fluctuations in mass flux which induce similar fluctuations in the gas-phase, thus promoting the instability.

References

[1] Kurdyumov V.N. and Matalon M. 2007 Stabilization and onset of oscillation of an edge-flame in the near-wake of a fuel injector *Proceedings of the Combustion Institute*, 31, 909-917.

[2] Kurdyumov V.N. and Matalon M. 2007 Dynamics of an edge-flame in the corner region of two mutually perpendicular streams *Proceedings of the Combustion Institute* 31, 929-938.

[3] Botha J.P and Spalding D.B. 1954 The laminar flame speed of propane/air mixtures with heat extraction from the flame *Proceedings of the Royal Society of London A.*, 225:71-96.

[4] Kaskan W.E. 1957 The dependence of flame temperature on mass burning velocity *Proceedings of the Combustion Institute*, 6:134.

[5] Ferguson C.R. and Keck J.C. 1979 Stand-off distances on a flat burner *Combustion and Flame*, 34:85-98.

[6] De-Goey L.P.H., van Maaren A. and Quax R.M. 1993 Stabilization of adiabatic premixed laminar flames on a flat flame burner *Combustion Science and Technology*, 92:201-207.

[7] Hirschfelder J.O., Curtiss C.F. and Campbell D.E. 1953 The theory of flames and detonations *Proceedings of the Combustion Institute*, 4:190-211.

[8] Clarke J.F. and McIntosh 1980 The influence of a flameholder on a plane flame, including its static stability *Proceedings of the Royal Society of London A.*, 372:367-392.