Further results on oscillating edge-flames

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Abstract

We examine a simple model of an edge-flame in non-premixed combustion in order to understand why it is that such flames are often seen to oscillate. Examples include the edge of a near-limit flame propagating over a liquid fuel, and the edge of a near-limit microgravity candle flame. We investigate further an earlier hypothesis that these oscillations are a 2D manifestation of oscillations long known to occur in 1D configurations because of Lewis number and heat loss effects close to extinction. We explore the effects of a head wind on the edge, and the consequences of introducing a heat sink into the neighborhood of the edge, obtaining results consistent with the hypothesis.

Introduction

It has been known for some years that when a near-limit flame spreads over a liquid pool of fuel, the edge of the flame can oscillate relative to a frame moving with the mean speed [1]. Each period of oscillation is characterized by long intervals of modest motion during which the edge gases radiate like those of a diffusion flame, punctuated by bursts of rapid advance during which the edge gases radiate like those in a deflagration [2]. Substantial resources have been brought to bear on this issue, both experimental and numerical [3],[4].

It is also known that when a near-asphyxiated candle-flame burns at zero gravity, the edge of the (hemispherical) flame can oscillate violently prior to extinction. A description of experiments carried out on board both the Space-shuttle and the Russian space station Mir can be found at the NASA website http://microgravity.msfc.nasa.gov, and a brief report can also be found in [5].

Edge-flame oscillations are also observed in the combustion of PMMA cylinders in a convective flux of air [6]. A reduction of the oxygen level leads to extinction at the front stagnation point, and the twin edges of the surviving flame retreat towards the rear of the cylinder where part of the flame is held in the wake. But then they reverse direction and a number of oscillations occur in which the edges advance and retreat.

Similar behavior is seen in a flame supported by injection of ethane through the porous surface of a plate over which air is blown [7]. When conditions are close to blow-off, the leading edge of the flame oscillates violently.

In all of these configurations it is the edge that oscillates, not the diffusion flame that trails behind the edge; and the oscillations only occur under near-limit conditions. Moreover, the fuel Lewis number in each case is greater than 1 (~ 1.4 for ethane (P.Ronney, private communication), ~ 1.6 for PMMA vapors (J.Goldmeer, private communication)).

Hypothesis

It is useful to briefly summarize certain one-dimensional results. Chemical reactor theory [8] can predict the kind of response shown in Fig.1 for a system with heat losses and large Lewis number(s). Steady stable solutions characterized by points on the upper branch change to oscillating solutions when the Input is reduced to values below that defined by the N(eutral)S(stability)P(oint), a point not far from the S(tatic)Q(uenching)P(oint). In a combustion context, oscillating instabilities were first reported for diffusion flames in a theoretical study in [9], and here also the the instabilities are associated with near-extinction conditions, large Lewis numbers, and heat losses. And deflagrations will oscillate if the

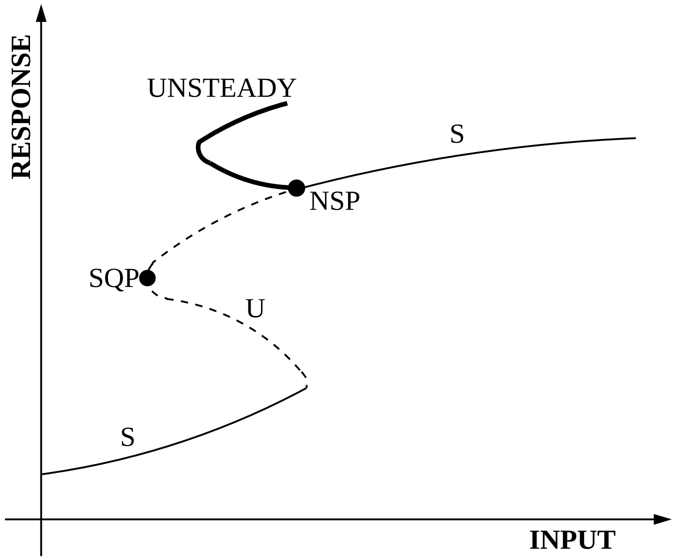

Figure 1: Response diagram for a reactive system. NSP = neutral stability point; SQP = static quenching point.

Lewis number is large enough, oscillations that are exacerbated when heat losses are present, whether global or to a surface [10], [11].

In all of these situations, reaction weakening by approach to a quenching or blow-off point, together with heat losses, is a common ingredient. The relevance of this observation is that the edge of a flame with an edge will be weakened by the edge curvature if the fuel Lewis number is greater than 1: Increased conductive heat losses from the edge arising from the curvature are not compensated by increased fluxes of fuel to the edge. Consequently, we hypothesize, following [12], that all the edge-flame oscillations described in the *Introduction* are a consequence of the heat loss/large Lewis number mechanism. Evidence presented in [12] is here expanded.

The Model

Our model is designed to capture only the most basic elements of a diffusion flame with an edge, within a framework that is consistent with the experimental configurations. We confine the flame within two boundaries, a fuel-supply boundary at $y = 1/2$ and an oxygen-supply boundary at $y = -1/2$. The former plays the role of the /pool-surface/wick/cylinder-surface/plate-surface/, the latter plays the role of the surrounding oxygen-laden atmosphere. Both X and Y, the reactant mass fractions, are specified at these boundaries. On the upper boundary X is zero everywhere, on the lower boundary Y is zero everywhere. We introduce an anchor point at $x = 0$ by setting $Y \equiv 0$ on the half-line $x < 0$ at the upper boundary, but otherwise $Y = Y_o$ there. On the lower boundary, $X = X_o$ everywhere. The point $x = 0, y = 1/2$ corresponds to the base of the wick, the transition point between fuel-laden wick and the solid wax (experiment 2); to the stagnation point of experiment 3; and to the dividing point between the impermeable portion of the plate and the porous portion in the fourth experiment. The connection with the flame-spread configuration is less sharp, but ahead of the edge there is little evaporation, for the flame provides the heat for this. Both boundaries act as heat sinks, and we specify the temperature at each of them.

We adopt a constant density model, partly to avoid what we believe are unnecessary fluid-mechanical complications, and we seek unsteady two-dimensional solutions governed by the system of equations:

$$(\frac{\partial}{\partial t} + U\frac{\partial}{\partial x})(X, Y, T) = \nabla^2(\frac{X}{Le_X}, \frac{Y}{Le_Y}, T) + (-\frac{1}{2}, -\frac{1}{2}, 1)DXYe^{-\theta/T}\,. \quad (1)$$

This differs from that discussed in [12] by the addition of the convective (U) term. There are no convective fluxes between the flame and the boundaries for this model, but there is no reason to believe that the convective fluxes in the physical configurations play a role that is fundamentally different from that played by the diffusive fluxes, so that their omission should be of little qualitative consequence.

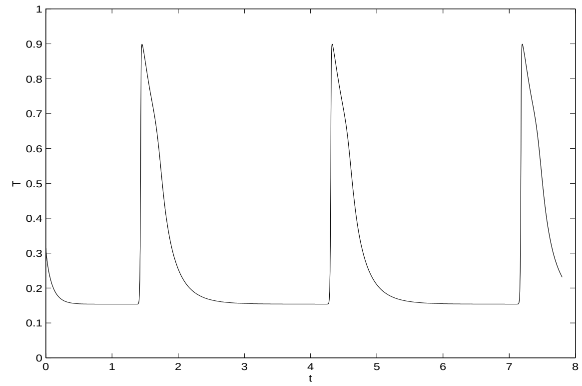

Figure 2: T vs. t at a fixed point.

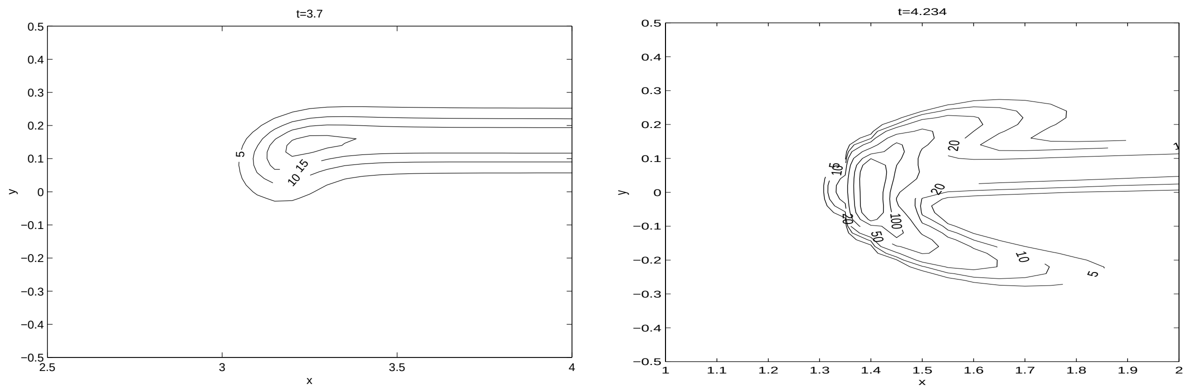

Figure 3: Reaction rate contours during retreat (a) and advance (b).

The equations are solved on the domain $[-5, 5] \times [-1/2, 1/2]$ with the supply conditions that we have described above applied at the boundaries $y = \pm 1/2$. At $x = \pm 5$ we assume that the solution is locally one-dimensional and apply Dirichlet data defined by the two appropriate 1D solutions. At the left boundary, this is the frozen solution. At the right boundary it is a strong flame solution, determined numerically but differing only a little from the asymptotic Burke-Schumann solution. For some of the calculations we have introduced a 'cold rectangle' into the interior of the domain, a rectangle of mesh points at which the temperature is set to the boundary value. This simulates the insertion of a cold probe into the combustion field.

Results

We would expect, if the core hypothesis ([12]) is correct, that a convective flow in the $x-$direction ($U > 0$) will encourage the oscillation. The convective cooling in the absence of convectively-enhanced fuel flux (there is no fuel-supply in $x < 0$) will weaken the edge. Indeed, with the choices $Le_X = 1$, $Le_Y = 1.7$, we find that there are values of the Damköhler number D for which steady stable solutions are obtained when $U = 0$, but oscillating solutions are generated when $U = 1$. On the other hand, if Le_X is fixed at 1 but Le_Y is reduced to 1.5, an increase in U merely leads to blow-off without oscillation for any value of D, consistent with the role envisaged for the Lewis number. Reversal of the flow ($U < 0$) baths the edge in hot reactants, strengthening it. We expect this to suppress the instability, and that is what we find.

Turning to the heat-sink (cold rectangle), we would expect that if this is placed in the vicinity of the edge, an otherwise stable edge could be destabilized, and this is what we find. The details, both of the effects of U and of the cold rectangle, will be published elsewhere, but here we describe some of the characteristics of the unsteady oscillating flame.

Figure 2 shows temperature variations at a fixed point, typical of those for an oscillating edge. For much of each period the point is ahead of the edge and so the temperature is low, but during a brief interval the edge passes through the point and then retreats, creating a sharp temperature spike.

Figure 3 shows reaction rate contours typical of those for a retreating edge (a) and an advancing edge (b). The retreating edge is nothing but a rounded diffusion flame; the advancing edge is a tribrachial flame, one with strong premixed branches. Thus Figs.3 are consistent with the observations made in [2], noted in the *Introduction*.

A final comment. According to the hypothesis, a large increase in the Lewis numbers should have a marked effect on the edge behavior. Indeed it is known from one-dimensional flame studies and associated experiments [13] that large Lewis numbers lead to high frequencies. It is therefore relevant to note that when nitrogen is replaced by helium in pool flame-spread experiments, the frequency of edge pulsations increases dramatically [14].

Acknowledgement

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