COMBINED EFFECTS OF STRETCH AND RADIATIVE HEAT LOSS IN LEAN METHANE - AIR

FLAMES

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The following is a continuation of an investigation [1], by way of axisymmetric opposed flow configurations, of the combined effects of stretch and radiative loss on the properties of laminar premixed methane-air flames near the lean flammability limit. Because of perceived relevance to such limits as normally encountered, the major part of the earlier work (as yet unpublished other than in [1]) examined the behaviour and extinction limits of single flames in the unburnt-to-burnt (UTB) counterflow configuration, in which the unburnt stream is opposed by its own combution products, with all three of the unburnt and product streams, and the surroundings, at a temperature T = 295K. The behaviour of the symmetric unburnt-to-unburnt (UTU) configuration was considered only briefly, for a single equivalence ratio $\phi = 0.57$. It was there shown that the high stretch extinction limit of the UTU flame is not appreciably affected by radiative loss at realistic levels.

The present paper describes a more detailed numerical investigation of the flame behaviour in the UTU system. The computational approach employed is as described by Dixon-Lewis [2]. The reaction mechanism and rate parameters are those given by Dixon-Lewis and Islam [3], with additional use of an "optically thin" model for radiative loss [1]. As previously, the initial unburnt temperature and the radiative "sink" temperature were fixed at 295 K. Computationally, it was found that the domain of convergence for full Newton solutions was so small that full implementation of the continuation method [2] was unrealistic. Individual solutions, from a combination of which extinction limits could be estimated with moderate acuracy, were therefore obtained solely by convergence of a time-dependent approach. Of course, this precluded mapping of the unstable branches of the isolae which represent the steady state flame properties. Stretch rates are characterized as radial velocity

gradients a_e , related to the eigenvalue pressure curvature J by $a_e = (-J/\rho_e)^{\frac{1}{2}}$, ρ_e being the density of the unburnt stream. Axial stretch rates in the axisymmetric system are twice these values.

The geneal features of the lean methane UTU behaviour have already been outlined by, amongst others, Sung and Law [4], Buckmaster [5], and Ju et al. [6]. Particularly significant at low stretch rates is the extension of the flammable region to compositions considerably leaner than the flammability limit as normally encountered. This situation is illustrated in Fig. 1, in which the presently computed lean extinction limit compositions are plotted as functions of stretch rate for both the UTU and UTB configurations. The flammable region in each case is to the right of the appropriate curve, ABCD or DCE. The unstretched lean methane-air limit corresponding with the input conditions employed is at $\phi = 0.52767$. At stretch rates below about 1 s⁻¹ the UTB extinction limit and the appropriate low stretch UTU limit corresponding with section CD of Fig.1 (see below) are more or less identical, with the UTB curve showing a vertical tangent at $\phi = 0.5265$ [1]. At these extremely low stretch rates the flames in both systems are far from the stagnation plane. In the UTB circumstances increasing stretch steepens the temperature gradient, associated with radiative loss, that lies between the flame and the stagnation plane. It thereby also increases downstream conductive heat loss from the flame itself. It is this more or less purely radiative effect which is primarily responsible for the attenuation of the UTB flammable region above $a_e \approx$ 1 s^{-1} . However, to this must be added a Lewis number effect. In stretched, lean methane-air flames (Le < 1) preferential diffusive retention of the deficient, light component of the initial mixture leads to enrichment in the region near the flow axis, to an extent again dependent on a_{ρ} .

The effect here opposes the radiative loss effect, and leads in this case to the observed slight augmentation of the flammable region at very low stretch rates.

The situation in the UTU flames is more complex. As the stretch rate increases, so the flames are pushed closer together, the depth of the intermediate temperature well is reduced, and the well is eventually eliminated, as noted earlier [1]. That is, downstream radiative loss is attenuated and eventually removed. Finally, a high stretch, purely stretch-induced ectinction limit is obtained which is virtually identical with that for the adiabatic flame of the same composition.

Depending on Lewis number, the attenuation of radiative loss at higher stretch rates may be assisted or countered by preferential diffusion effects. Lean methane-air flames are assisted in this way, with the result that high stretch extinction limits are observed at compositions well outside the standard flammability limit (see Fig. 1). Figure 2 shows the stable branches of the "maximum temperature" isolae for several methane-air compositions up to $\phi =$ 0.53. The high stretch limits and the low stretch limits A form the branches AB and BC of Fig. 1. The computed temperature profiles of the flames at all the limits are such that the maximum temperature is at the stagnation plane. The low stretch limits A are thus stretch-induced limits in which the flame also suffers radiative loss, but with the loss now restricted to upstream of T_{max} . Residence time conditions are such that these flames are able to propagate with much lower T_{max} than at the standard flammability limit. Note also that the low stretch limits [5,6].

Next, examination of the full temperature profiles associated with the flames of Fig. 2 reveals:

1) That at the three leaner compositions $\phi = 0.46$, 0.48 and 0.50 none of the flames at any stretch rate suffers downstream radiative loss. T_{max} is always at the stagnation plane.

2) At $\phi = 0.52$ and 0.525 the same applies for radial stretch rates outside the approximate range $a_e = 2.5$ to 14 s⁻¹. Between these stretch rates, and dependent on both the composition and a_e , the T_{max} separate by up to about 9 mm. The additional downstream radiative loss on this account gives rise to the observed dips in the "maximum temperature" isolae. At these compositions the T_{max} are unable to depart from the stagnation plane by more than about 3.0 and 4.5 mm, for $\phi = 0.52$ and 0.525 respectively.

3) The same overall behaviour persists right up to and beyond $\phi = 0.53$, with one important addition. Commencing at a composition consistent with the line CD of Fig. 1, the isolae of Fig. 2 develop an upper lobe E which, at and inside the standard flammability limt, will reach back to zero stretch. It is recognized that the isola at each composition is completed by the presence of an unstable branch which joins the low and high stretch limits at A and B. The lobes E similarly have a stable upper and an unstable lower branch. The locations of unstable branches are denoted by the dashed lines in Fig. 2. The flames along the branch DE are hotter and stronger than those along the branch AF. They are separated by larger distances, and all suffer from both upstream and downstream radiative loss. At sufficiently small stretch rates they are effectively single flames.



Fig. 1. Extinction limits of opposed flow methaneair flames.

Fig. 2. Maximum temperatures achieved in flames at equivalence ratios shown.

4) It remains to consider the high stretch limit at F, designated the "jump" limit by Ju *et al.* For $\phi = 0.53$, trajectories on Fig. 2 were examined, with potential flow boundary conditions, for the same nozzle velocity of 9.86 cm s⁻¹ and a series of three nozzle separations: 37.0, 40.9 and 44.2 mm. The largest separation led to a steady state flame on branch AF, with $a_e = 2.8 \text{ s}^{-1}$. The intermediate separation led to uniform oscillations with a clockwise path around the left-hand dotted trajectory near F. These apparent oscillations may be an artifact of the computation due to proximity to the turning point at F. On the other hand, they do give the impression of a flame trying unsuccessfully to make the jump to branch DE.

The smallest of the three nozzle separations leads to a successful jump as shown by the RH trajectory near F (this starts below the $\phi = 0.53$ curve AF to which it is related). During the jump the flame separation increases to about 18 mm, and a_{ρ} from around 3.5 to about 4.5 s⁻¹. On moving from left to right along the curve AF at constant methane-air composition, the effect of increasing stretch is to increase the flame strength on two counts: first, diminution of the upstream radiative loss, and secondly, the Lewis number effect.. The requirement for the jump is analogous to that for an ignition. The jump takes place at the stretch threshold where the flame has acquired sufficient resources to withstand the additional, downstream radiative loss involved - though this is mitigated to an extent by diminished upstream loss.. Near the standard flammability limit for mixtures with Lewis number of the deficient component less than unity, the effects both of mixture enrichment and reduction of the Lewis number are to move the jump limit to lower stretch rates. Conversely, at constant composition, increasing Lewis number will move the limit towards higher stretch rates, and at some Le > 1 the effect may completely separate the system into two isolae, as has been observed [7]. The separation is a precursor to progressive shrinkage of both isolae, particularly that associated with the twin flames, with further increased Le. The effect of mixture enrichment is to reverse this shrinkage. Translated to Fig. 1 (where point D is approximately fixed) increasing Le thus has the effects of rotating the curve segment DC slightly in a clockwise direction, and simultaneously of moving the whole UTU curve differentially to the right. For methane chemistry, the equivalent points to B and C reach the same composition at Le ≈ 1.4 [5,7].

References

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