MODELING OF MICROGRAVITY COMBUSTION EXPERIMENTS

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N93-20197

Introduction

Modeling plays a vital role in providing physical insights into behavior revealed by experiment. The program at the University of Illinois is designed to improve our understanding of basic combustion phenomena through the analytical and numerical modeling of a variety of configurations undergoing experimental study in NASA's microgravity combustion program. Significant progress has been made in two areas: (i) flame-balls, studied experimentally by Ronney and his co-workers [1]; (ii) particle-cloud flames studied by Berlad and his collaborators [2]. Additional work is mentioned below. NASA funding for the U. of Illinois program commenced in February 1991 but work was initiated prior to that date and the program can only be understood with this foundation exposed. Accordingly, we start with a brief description of some key results obtained in the pre - 2/91 work.

Flame Balls - Results Prior to 2/91

Flame-balls are stationary, premixed spherical flames observed in certain near-limit mixtures [1]. They have zero flame-speed. Their study is likely to lead to an improved understanding of flammability limits. The configuration is sketched in Fig. 1.

Reference [3], *The structure and stability of non adiabatic flame-balls,* provides the first description of mathematically stable flame-balls. The stabilizing mechanism is heat loss by thermal radiation. The analysis assumes that the Lewis number (*Le*) is significantly less than 1. Only for such mixtures are flame-balls observed.

Reference [4], *The structure and stability of non adiabatic flame-balls: II. Effects of far-field losses,* is an extension of Ref. [3]. For physical flames there will be losses in the near-field (in and near the burnt gas) and the far-field. Dealing simultaneously with both leads to technical (mathematical) difficulties and these are dealt with here. Differences in the effects of the two losses are revealed by Fig. 2. Near-field losses can generate a three-dimensional instability (the upper thick portion of curve A), far-field losses do not. The lower thick portions of both curves define regions of one-dimensional instability. Note that for curve B this includes a portion of the top solution branch.

Flame-balls are only observed if *Le* is sufficiently small (≤ 0.5?) In Ref. [5], *The structure and stability of flame-balls: A near-equidiffusional flame analysis,* it is shown that radiation is not stabilizing when $Le = 1$ and there is a critical Lewis number Le_C (< 1) such that stability requires $Le < Le_C$. The closer *Le* is to Le_C the smaller is the range of parameter values for which stable solutions exist.

Flame-balls can be stabilized by heat loss other than by radiation. Convective heat losses generated by weak shear or straining flows are discussed in Ref. [6], *Flame balls stabilized by suspension in fluid with a steady linear ambient velocity distribution.* These are far-field losses. As noted earlier, a key difference between near-field and far-field losses is that the former can give rise to three-dimensional instabilities, the latter do not (see Ref. [9], discussed below).

Flame-Balls - Post 2/91 Results

In flame-ball experiments carried out in the KC-135 (see Ronney, this proceedings), unsteady flame-strings have been observed. A straight flame-string is a cylindrical counterpart to the spherical flame-ball. Flame-strings display a sausage or peristaltic instability. These instabilities are analyzed in Ref. [7]. For perturbations $\sim e^{\alpha t+ikx}$ where x is distance measured along the cylinder axis, Fig. 3 shows the manner in which α varies with the wave-number k. The flame structures must have a minimum length if they are to support unstable waves, i.e. short cylinders are stable.

Reference [8], *Influence of boundary-induced losses on the structure and dynamics of flame-balls*, shows that conductive heat losses to a cold wall can stabilize flame-balls. Configurations of this kind might well be important for space experiments designed to examine the structure of a stationary flame-ball.

The results of Ref. [3], [4] imply the response sketched in Fig. 4. This shows the maximum temperature in a flame-ball as a function of mixture strength. The stable region lies between points A and B. The implication is that insufficiently reactive mixtures can not support flame balls (static quenching at A' or dynamic quenching at A); and that overly reactive mixtures will lead to non-spherical flame-balls. These conclusions are consistent with experiment.

The point B is a neutral stability point for three-dimensional instabilities and a transcritical bifurcation analysis can be carried out, valid in the neighborhood of B, which describes unsteady three-dimensional, weakly-nonlinear deformations of the flame-ball. In Ref. [9], *The three-dimensional dynamics of flame-balls,* an equation for the flame-ball shape is derived:

$$\frac{x^2}{1+\frac{42}{4}\cdot\frac{\delta K}{(t_c-t)}}+\frac{(y^2+z^2)}{1-\frac{21}{4}\cdot\frac{\delta K}{(t_c-t)}}=1 \qquad (1)$$

where δK is a positive parameter that vanishes at B, and t_c is a critical time at which 'blow-up' occurs. Equation (1) describes the first observable manifestation of the instability, and corresponds to an elongating prolate spheroid. Prolate spheroids have been observed by Ronney. The experimental spheroids, once they become long enough, neck and split. We believe that this is due to the flame-string instability discussed in Ref. [7].

The analytical work of Ref. [3] - [9] has been remarkably successful in providing a description of flame-balls that agrees, qualitatively, with the experimental observations. Quantitative comparisons are only meaningful with detailed numerical simulations, and a program of this kind has recently been embarked upon in collaboration with M. Smooke. Figure 5 shows the variations of maximum temperature with mixture strength described in Ref. [10], *Analytical and numerical modeling of flame-balls in H_2/air mixtures*. This work predicts a static flammability limit of 3.5% H_2 by volume. This is close to the experimental value. Predicted flame-ball sizes are consistent with observations but precise comparison is not possible at this time since the nature of the experimental image is uncertain.

It is clear that at this time an unusually strong synthesis of experiment, theory and numerical work has elucidated the physics of flame-balls.

Flame-Balls - Future Plans

In all the work completed to date radiation losses are only accounted for within the framework of an optically thin field. There is reason to believe that this is not always correct, and a more general approach is under development.

Additional numerical work is planned. It would be appropriate to construct steady solutions for the various mixtures that have been used experimentally. Moreover, because of the importance of the stability boundaries in defining the existence of flame-balls it is important to identify them numerically. This would not be excessively difficult for the one-dimensional stability boundary, but the three-dimensional boundary is a different matter. Reduced chemistry schemes might be useful in this connection.

Particle Cloud Flames

Reference [2] describes experiments on flames propagating in particle-air mixtures. A mixture of lycopodium and air in a tube that is open at one end, closed at the other, is ignited at the open end. For some mixture strengths and flame locations unsteady propagation is observed which, we believe, is driven by an acoustic instability. Reference [11], *An acoustic instability theory for particle-cloud flames,* contains a mathematical description of a plausible mechanism. Because of slip (thermal and kinematic) between the two phases, an acoustic wave generates fluctuations in the mixture flux fraction entering the flame; there are time dependent fluctuations in the difference between the particle velocity and the gas velocity relative to the flame. These fluctuations generate variations in the heat generated by combustion, and these can drive the acoustic wave *via* the well-known Rayleigh criterion. Apart from the inclusion of slip the flame model is similar to that of Seshadri *et al* (this proceedings).

Additional theoretical aspects are briefly discussed in Ref. [12], *The structure and stability of laminar flames.* It is well known that a classical (gaseous) unbounded deflagration can support a pulsating instability if *Le* is large enough, but this constraint demands exotic mixtures. However, modifications to the flame configuration can move the domain of instability and make it accessible to certain everyday mixtures. Heat loss to a burner is such a modification. Supplying the fuel in particle form is another. It is possible, therefore, that the instability observed by Berlad *et al* is intrinsic in nature, albeit modified by the acoustic constraints, rather than the acoustic creature discussed in Ref. [11]. These and related aspects are presently being explored. However, the termination of the experimental program limits the progress that can be expected in our understanding of these flames. In view of the importance of particle cloud burning, and recognizing that the microgravity environment is exceptionally congenial for its study, this author believes that a new initiative in the area would be most valuable, preferably one tied closely to modeling efforts.

Self-Extinguishing Flames

Self-extinguishing flames (SEFs) are generated by the point ignition of certain near-limit mixtures [13]. An essential characteristic of a SEF is that it extinguishes at a radius of several centimeters after the release of chemical energy several orders of magnitude greater than the spark initiation energy. Because of this disparity one might expect that the final behavior of these flames is independent of the spark energy, but that is not the case. A SEF which extinguishes after releasing energy equal to 10^3 times the spark energy can be converted to a non-extinguishing flame by doubling the spark energy. We have been engaged in attempts to understand this sensitivity by the use of simple asymptotic treatments. In Ref. [14], *The effects of confinement and heat loss on outwardly propagating spherical flames,* asymptotic methods are used to derive a model equation for the evolution of the spherical flame:

$$\frac{dV}{dR} = \frac{2V}{R} - L + V^2\left[\frac{1}{3}kR^3 - \ln V\right], \quad \frac{dR}{dt} = V. \tag{2}$$

Here R is the flame radius, t is time, L is a heat-loss parameter that accounts for radiative losses, and k is a confinement parameter that accounts for the pressure rise in the fixed volume chamber.

Solutions to equation (2) can display extreme sensitivity to the initial data, as exemplified by Fig. 6. However, we are not prepared to claim that confinement effects are significant in Ronney's experiments, but merely present these results as a simple example of sensitivity.

Acknowledgment

The work described here was supported by the NASA-Lewis Research Center, and by AFOSR. It owes its genesis to the unusual intellectual generosity of Paul Ronney. After discovering flame-balls in the laboratory, he came to the opinion that radiation plays a key role in their existence and invited me to Princeton and asked me if I thought that it would be possible to do some modeling. That question, his videotapes, and his physical insights, have fueled this endeavor.

References

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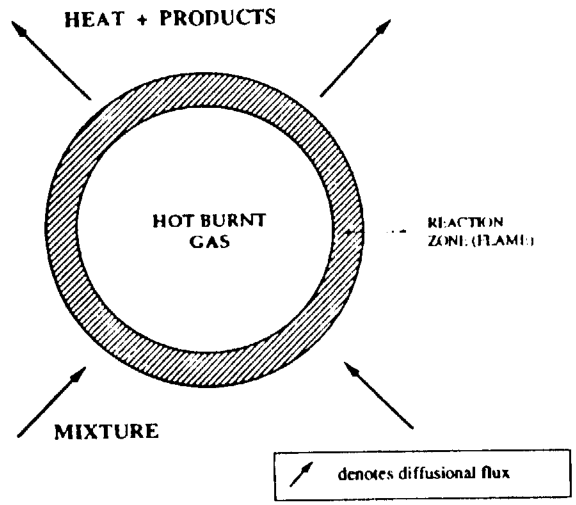

Fig.1. Stationary flame ball. The flame-speed is zero and mixture reaches the reaction zone by diffusion.

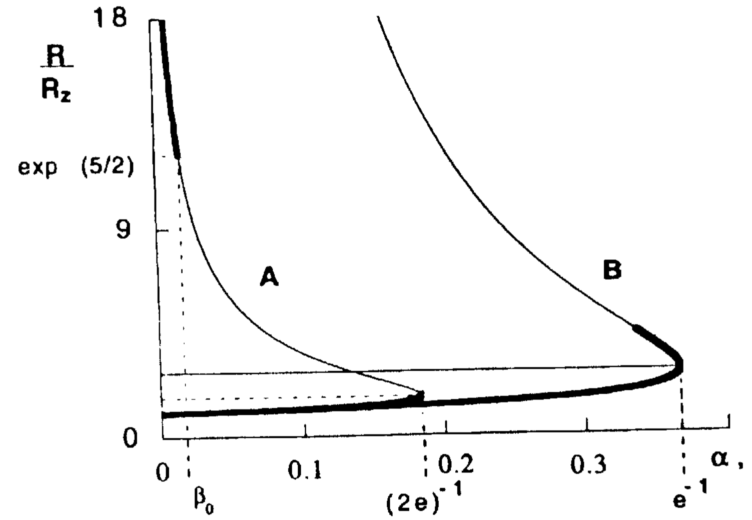

Fig.2. Flame-ball radius vs. heat loss. Curve A is appropriate for near-field losses, cuve B for far-field losses.

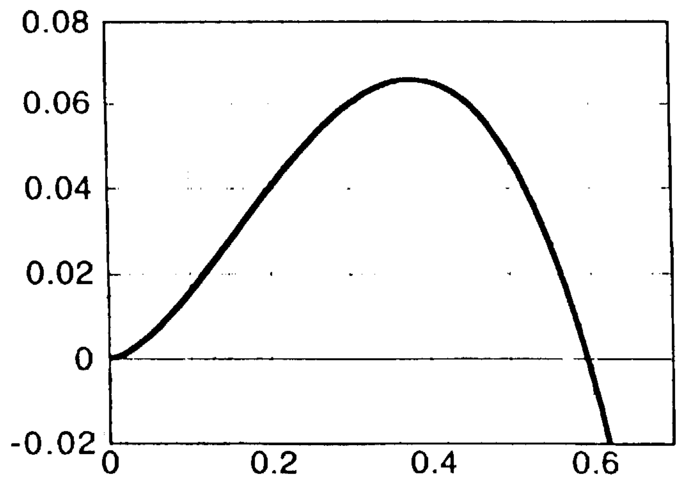

Fig.3. Growth rate α vs. wave-number k for flame-cylinders. Short cylinders will be stable.

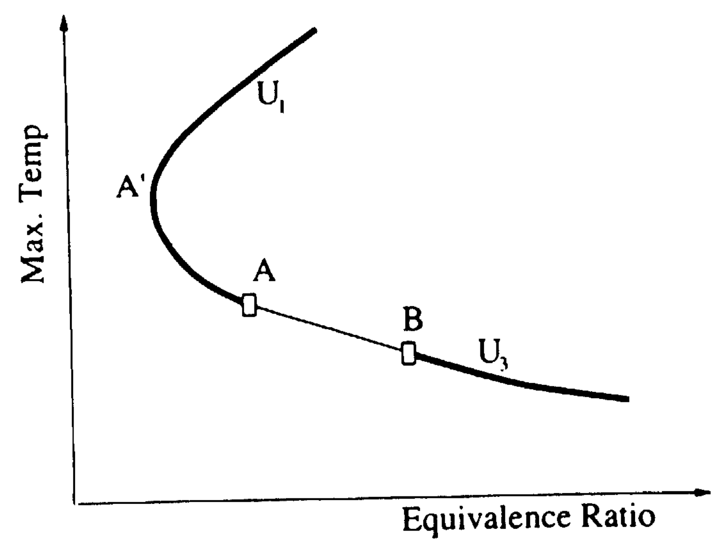

Fig.4. Flame-ball response showing a stable region between the points A and B.

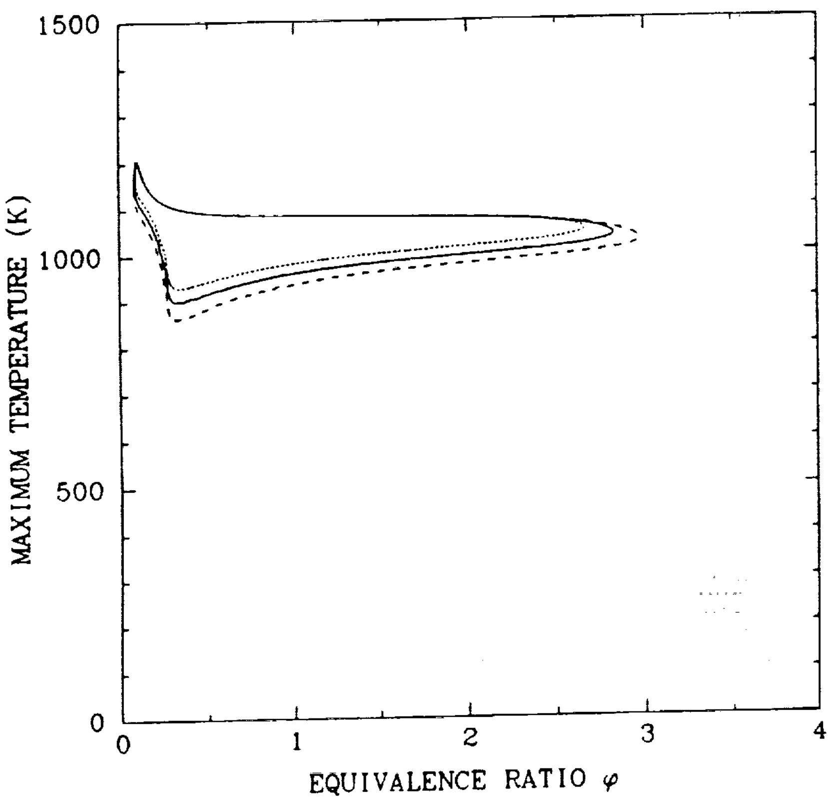

Fig.5. Numerical results for flame-balls in hydrogen/air mixtures, showing the maximum temperature vs. equivalence ratio (solid line).

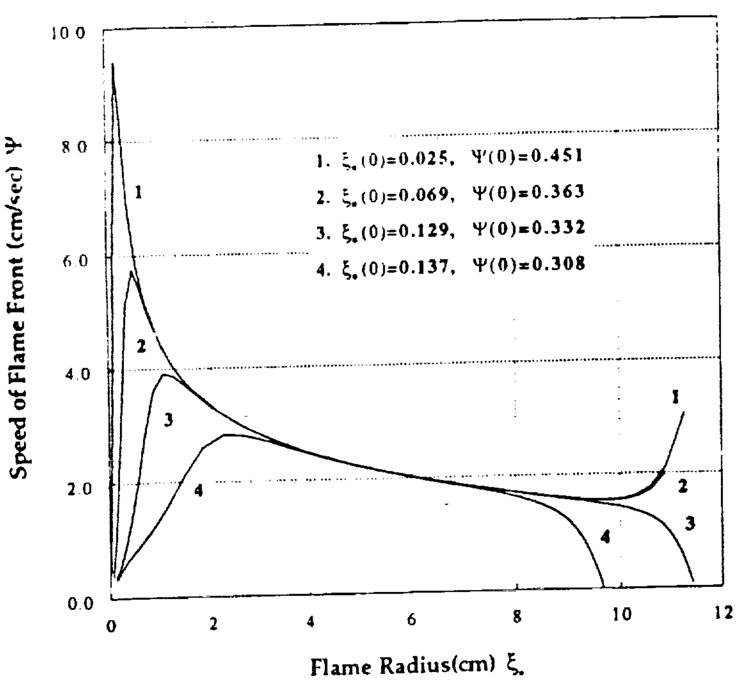

Fig.6. Flame front speed vs. flame radius for different initial conditions showing sensitivity when confinement effects are accounted for. At first the curves come together, but their final fate depends on the initial data.