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MODELING OF MICROGRAVITY COMBUSTION EXPERIMENTS

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Introduction

This program started in February 1991, and is designed to improve our understanding of basic combustion phenomena by the modeling of various configurations undergoing experimental study by others. Results through 1992 were reported in the second workshop [1] and incomplete citations therein are listed, in complete form, below, [2] - [7]. Work since that time has examined the following topics: Flame-balls; Intrinsic and acoustic instabilities in multiphase mixtures; Radiation effects in premixed combustion; Smouldering, both forward and reverse, as well as two-dimensional smoulder.

Flame-balls

Flame-balls are stationary, premixed spherical flames observed in certain near-limit mixtures, [1] page 157 and page 165, [8]. Their analytic study is now a mature subject, and future work should probably emphasize a numerical strategy [9]. Variations of flame-radius with equivalence ratio for hydrogen/air mixtures have been calculated in [4] and are indicated schematically in Fig. 1, curve A. A small portion of the upper branch near the lean limit corresponds to stable solutions. This result, like all results obtained previously, neglects absorption of radiation from the flame-ball in the surrounding gas, a matter addressed in [10]. The motivation for [10] is two-fold: In Ronney's experimental program, SF_6, a strong absorber of its own emission, has been used as a diluent [11]; and, if one accepts the proposition that an ideal one-dimensional unbounded flame for which all radiation losses are ultimately absorbed by the gas mixture will not display a flammability limit, this raises the question of the significance that can be attached to the lean limit of Fig. 1, curve A, when all radiation from the flame-ball is absorbed.

The effects of absorption upon the response are shown in Fig. 1, curves B and C. The lean flammability limit survives in the sense that no *local* stable solutions exist to the left of the turning point P. But, even to the left of P, a sufficiently large ignition source could push the system above the top-most (unstable) branch, and lead to a thick, loss-less propagating flame.

Instabilities in multi-phase mixtures

A preliminary investigation of acoustic instabilities in particle-cloud flames was reported in [5], and is believed to be relevant to instabilities that were observed in [12]. The essential mechanism is slip between the carrying gas and the particles. A more comprehensive treatment is presented in [13].

In this work, acoustic eigenvalue locii are calculated for a flame that moves down a tube from the open end to the closed end. Mode transition can occur. Thus, for example, a mode can start as the second harmonic but finish as the fundamental, (Fig. 2). An intrinsic (non-acoustic) instability that arises because of nonsimilarity between the temperature and fuel-concentration fields is also discussed, and it is shown that transitions can occur between the intrinsic mode and the acoustic modes. All of these instabilities tend to be suppressed in spherical flames generated by point ignition in a confinement vessel, (Fig. 3). The triggering of acoustic instabilities in gas turbines by slip between fuel drops and air is discussed, and we show that the role of slip is quite different when the condensed phase is injected at a finite point rather than being dispersed throughout the gas phase.

A more elaborate discussion of the gas-turbine spray problem (a 'spin-off' problem not directly related to the current microgravity program) is presented in [14] and [15].

Radiation effects in premixed combustion

The role that radiation can play in defining flammability limits is an important one, and the addition of fine inert particles to flammable mixtures can introduce a measure of control of emission and absorption that is otherwise not possible. The current experimental program includes studies of this nature, and our theoretical program is designed to provide useful physical insights. Reference [16] examines the effects of radiation on the classical thermal-diffusive stability boundaries of premixed flames. The calculations are numerical in nature, and cover a wide range of Planck lengths and Boltzmann numbers. It is shown that radiation tends to suppress the cellular instability, in agreement with experiment [17]. And the pulsating/traveling-wave instability associated with Lewis numbers greater than 1 can be enhanced.

Reference [17] is a report of preliminary experimental studies of unsteady flames generated by point ignition in dusty gases, and [18] describes a preliminary theoretical treatment of this problem. A hydrodynamic description is adopted, with stretch effects accounted for using an empirical formula, and we examine the competition between the Zeldovich-Spalding effect in which radiative losses on the diffusive scale tend to quench the flame, and the Joulin effect in which radiative preheating on the scale of the Planck length tends to strengthen the flame. It is shown that, in due course, the Joulin effect should dominate and lead to super-adiabatic flame speeds. Superadiabatic flame-speeds have not been observed in the experiments, but too much should not be made of this in view of the preliminary nature of the work. In the experimental studies, actual particle loadings are not known. And although the strategy adopted in the theoretical study is both plausible and natural, it may be that it is oversimplified. More elaborate treatments will certainly be justified when the experimental record is clarified.

Smouldering combustion

A microgravity experimental program has been underway for some time, [1] page 251, and the problem has long been studied at 1g. There is interest in one-dimensional reverse (co-flow) smoulder in which the solid fuel and air enter the reaction zone from the same side, as in a premixed flame; in one-dimensional forward (counter-flow) smoulder in which the fuel and air enter the reaction zone from opposite sides, as in a diffusion flame; and in two-dimensional smoulder.

It is not difficult to construct a simple model of reverse smoulder which, with plausible choices for the several parameters, yields a structure, propagation speed, and maximum temperature which are consistent with experiment. Elaborations of the simple model are difficult to justify in the absence of some distinct qualitative behavior that remains unexplained, since detailed quantitative comparisons are meaningless in the context of simple models. Observations reported in [19] reveal an unexplained phenomenon, namely quenching at high blowing rates. As the blowing rate is increased from small values the burning rate first increases, reaches a maximum, decreases, and then quenching occurs at a non-zero burning rate. A simple analysis predicts the maximum, but not the subsequent quenching, and the addition of classical heat loss terms is no remedy. However, in [20] it is shown that endothermic pyrolysis in the oxygen-free region behind the exothermic reaction zone can lead to quenching. Responses are shown in Fig. 4 with and without pyrolysis.

The analysis of [20] assumes equilibrium between the two-phases. This assumption will first break down within the reaction zone, if this is thin, modifying the structure, an issue briefly discussed in [21].

Counter-flow smoulder is necessarily unsteady, with thermal energy accumulating within the combustion field. The first decent analysis appears to be that described in [22], and the nature of the combustion field is sketched in Fig. 5. In [23] we enlarge on the discussion of the pyrolysis wave, and examine reactant leakage through the oxidation zone. Leakage has been observed experimentally, [24].

Reference [25] describes an analysis of two-dimensional smoulder, modeled as an oxygen-limited free-boundary problem. The configuration is sketched in Fig. 6. Solutions are obtained for different air velocities under the assumption that the wave is shallow, a consequence of the large bulk solid density relative to the gas density. Results are consistent with recent simulations carried out by DiBlasi [26].

Other work

Reference [27] contains a numerical treatment of plane vapor-diffusion flames and their stability, an attempt to obtain insights into phenomena observed in annular pool fires. During the extinction phase of total pool burning, when the flame is fragmented, it is noted that the edge of a fragment can advance or retreat. The model provides an explanation of how this can come about.

References

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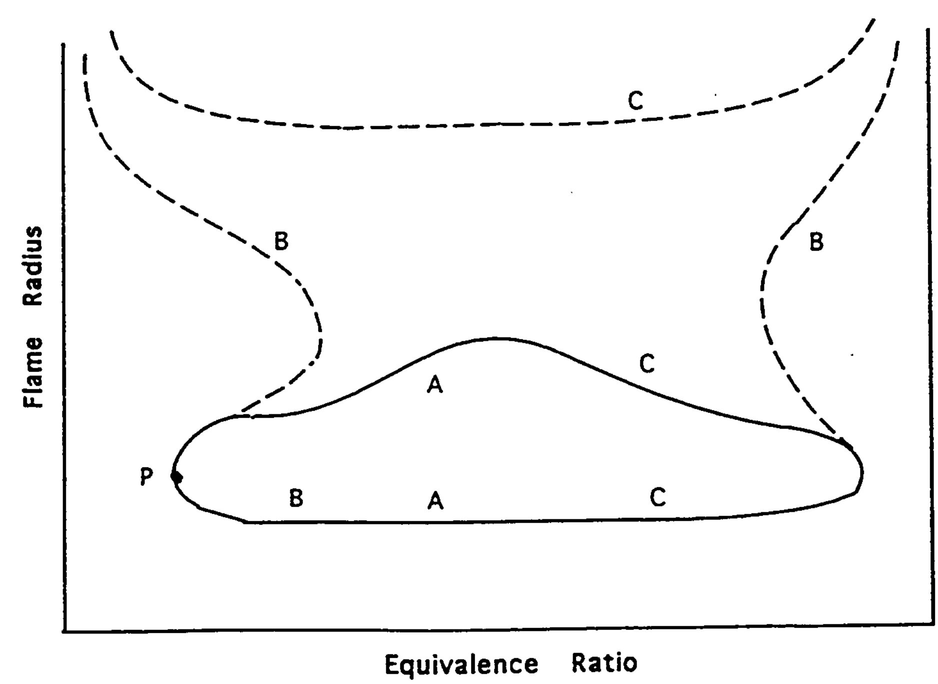

Fig. 1. Flame-ball response. A (closed curve): No absorption. B: Moderate absorption. C: Weak absorption.

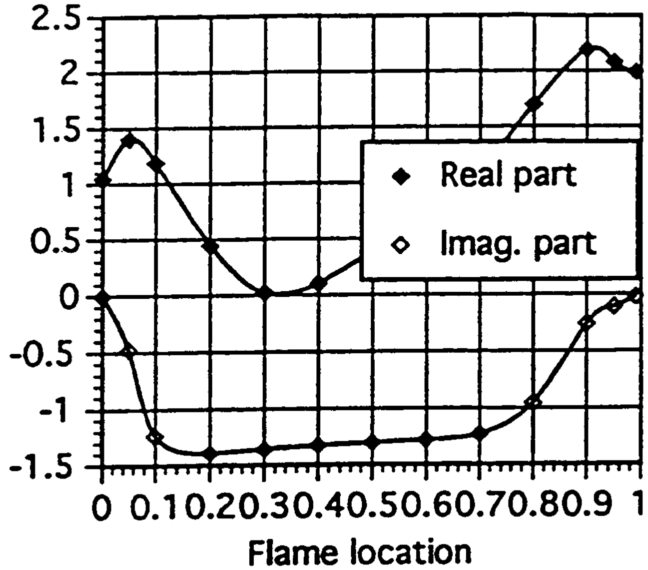

Fig. 2. Frequency of an acoustic mode that is the second harmonic at 1, the fundamental at 0. The mode is unstable when the Imag. part is negative.

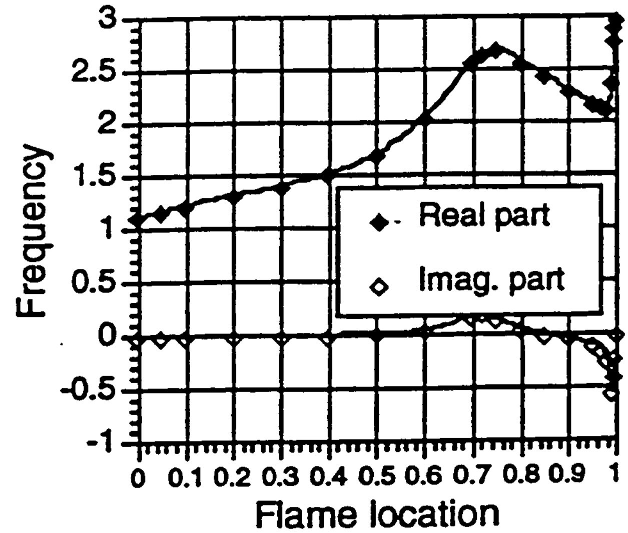

Fig. 3. An acoustic mode in a spherical vessel. Instability is only predicted for a flame radius greater than 0.83.

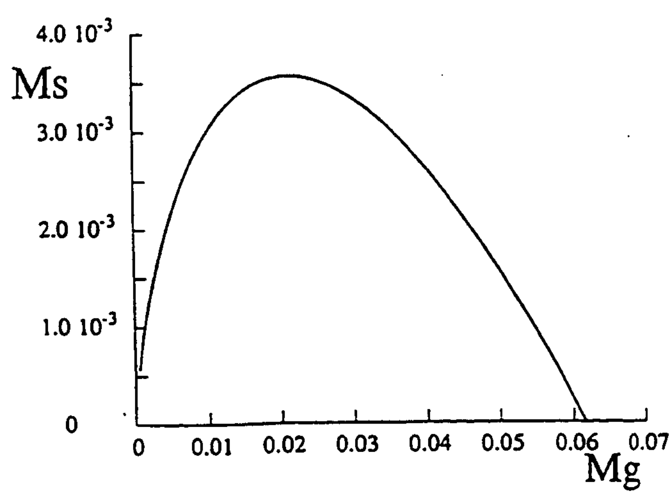

Fig. 4a. Mass flux of solid vs. blowing rate in co-flow smoulder, no pyrolysis.

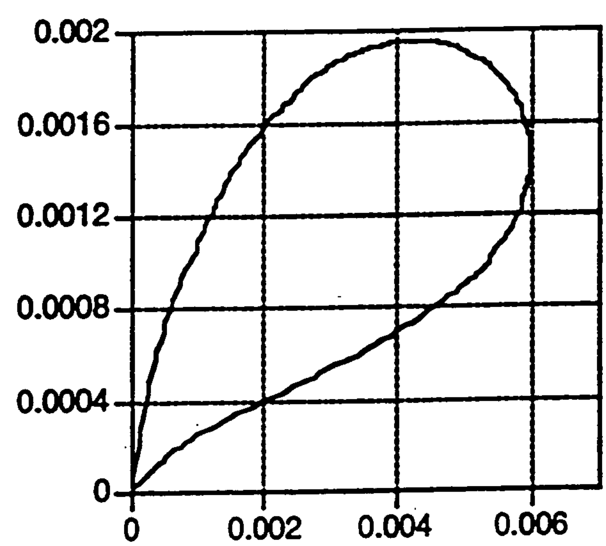

Fig. 4b. Mass flux of solid vs. blowing rate with pyrolysis.

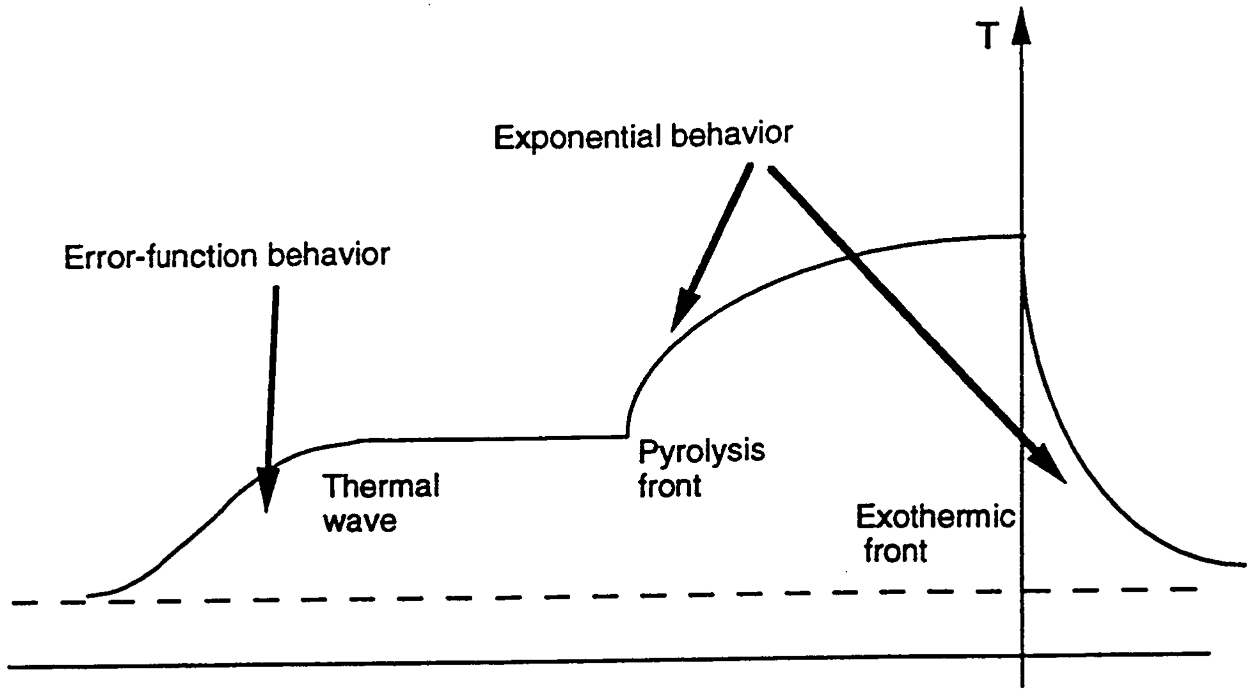

Fig. 5. Temperature profile in counter-flow smoulder. In a frame attached to the exothermic front there is an endothermic pyrolysis front moving to the left at fixed speed, and to the left of that, a convective-diffusive thermal wave.

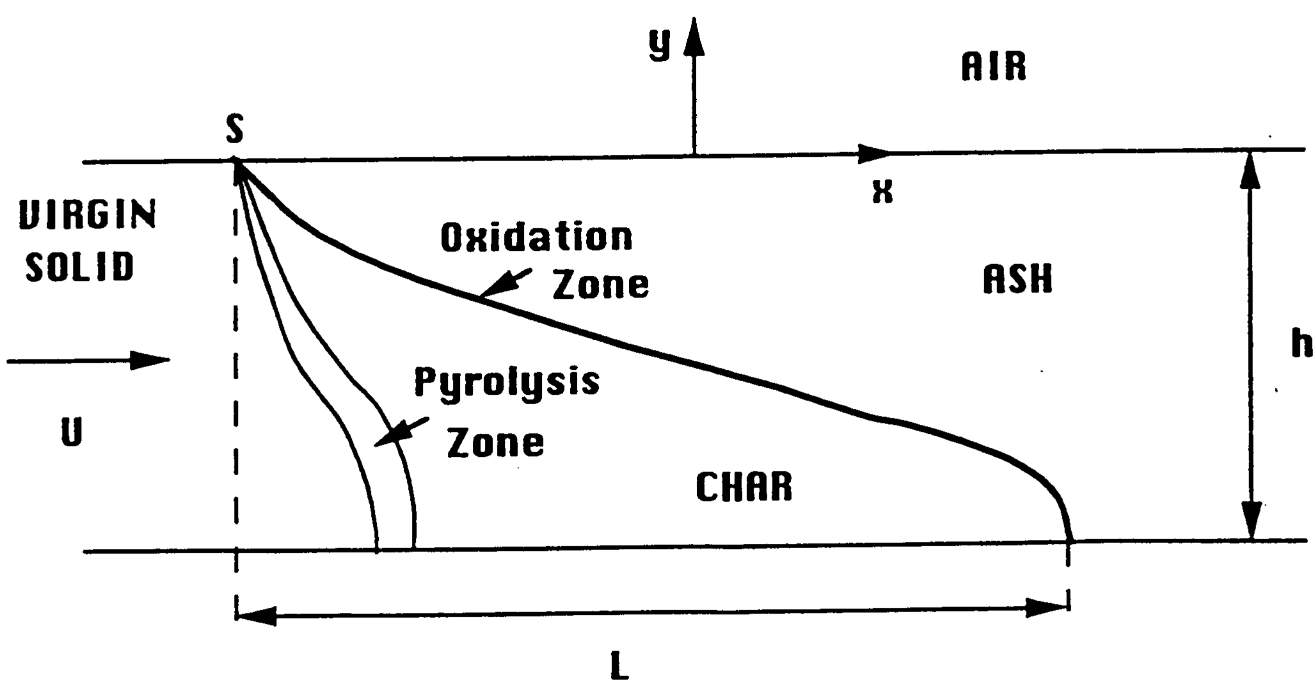

Fig. 6. The structure of a two-dimensional smoulder wave. The oxidation front is modeled as a steady two-dimensional free-boundary problem.