STUDIES OF PREMIXED LAMINAR AND TURBULENT FLAMES AT MICROGRAVITY

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Introduction

The work of the Principal Investigator (PI) has encompassed four topics related to the experimental and theoretical study of combustion limits in premixed flames at microgravity, as discussed in the following sections. These topics include:

- Radiation effects on premixed gas flames
- Flame structure and stability at low Lewis number
- Flame propagation and extinction in cylindrical tubes
- Experimental simulation of combustion processes using autocatalytic chemical reactions

Radiation effects on premixed gas flames

Our previous work has demonstrated the importance of gas radiation in the propagation and extinguishment of premixed gas flames [1, 2]. However, gas radiation is a weak effect and is only a significant influence for very slowly burning flames. These flames can only be observed at μg due to buoyancy effects at one-g. Furthermore, it is not clear whether radiation is a fundamental limit because in very large systems (say, tens of meters) emitted radiation could be reabsorbed within the gas and thus not lost from the system. In this case the propagation rate could actually increase because radiation would augment the usual transport by conduction of heat from the flame front to the unburned gas [3].

To test these hypotheses, we have examined radiation effects by studying flames at μg in gas mixtures to which small quantities of inert, radiant particles have been added. Solid particles emit and absorb radiation across a broad spectrum, unlike gas molecules which are active only in narrow spectral bands. Thus, appreciably more radiation and absorption can be expected in particle-laden gases. Our preliminary experiments [4] have shown that at small particle loadings, burning rates are reduced (Fig. 1), peak pressures in constant-volume combustion are lower (Fig. 1) and thermal decay rates in the burned gases are increased (Fig. 2). This indicates that the significance of radiative loss is enhanced by the addition of particles to the gas. With sufficient seeding, the burning rates are practically the same as those found in particle-free mixtures (Fig. 1), the peak pressures are comparable (Fig. 1) and the thermal decay rate is smaller than particle-free mixtures (Fig. 2). All of these observations are consistent with the hypothesis that at sufficiently high particle loadings, radiation is reabsorbed within the combustible medium, and thus may not constitute a fundamental limit in very large systems. In essence, the presence of particles has made the system "larger" in that the ratio of the system size to mean absorption length of radiation is increased.

Future work will focus on methods of quantifying the particle density, mixture optical thickness, and obtaining results for a variety of mixtures and particle loadings to compare with theory and to determine if flammability limits can be entirely suppressed when radiation losses are eliminated.

Flame structure and stability at low Lewis number

We have found in previous work that the tendency of flames in mixtures with low Lewis numbers, e.g. hydrogen-air, to break up into cells affects the near-limit behavior dramatically [5]. In some cases flame *propagation* ceases entirely without flame *extinction* occurring. In these cases *stable, stationary* spherical flames ("flame balls") seem to exist. Stationary spherical flames have been predicted previously but are predicted to be unstable. Further work has showed that such phenomena seem to occur in all mixtures with sufficiently low Lewis number and near flammability limits, independent of the chemical mechanism [6]. Experiments on the KC-135A aircraft showed that these structures are stable for at least the 20 seconds of low-g available [6]. By comparison with analytical models [7, 8], it has been concluded that radiation from the combustion products, along with diffusive-thermal effects in low-Le mixtures, is probably the stabilization mechanism which allows flame balls to exist at µg.

At one-g, these flames are entirely buoyancy-dominated. Consequently, the flammability limits are much leaner at µg than one-g, for example 3.35% vs. 4.0% H_2 for H_2-air mixtures [6]. This result is in very good agreement with a computational study of flame balls employing detailed chemistry and transport models [9] in which a limit of 3.5% H_2 was predicted.

The g-jitter in the KC-135A experiments ($\approx$ 0.02g) caused substantial motion of flame balls. The drift velocity was found [6] to be proportional to $g^{1/2}$, consistent with bubble theory. This drift also led to the formation of two types of quasi-cylindrical flame structures which we have termed "flame strings" (Fig. 3) [6]. These strings are unstable, in that they eventually break into flame balls, but live much longer than would be expected based on thermal diffusion time scales alone. Consequently, they are almost certainly being supported by chemical reaction. Their existence is curious, because no *steady* solution is possible for cylindrical flames (unlike spherical flames). It seems then that they would evolve radially given sufficient time, but the axial instability which leads to their breakup manifests itself before radial evolution occurs. Recent theory [10] supports this suggestion.

Another type of flame string, not directly related to that discussed above, has been observed in H_2-O_2-SF_6 and CH_4-O_2-SF_6 mixtures, particularly at high pressures [6]. These strings are different in that they are uncorrelated with buoyancy effects and seem to form much faster than any conventional diffusional or hydrodynamic timescale would allow. We conjecture that these are a result of reabsorption of emitted radiation, which is most likely to occur in SF_6-diluted mixtures and at high pressures because the Planck mean absorption length (L_p) is much shorter in SF_6 than CO_2 or H_2O and is inversely proportional to pressure; at 300K and 2 atm, L_p for SF_6 is only 0.13 cm!.

A flight experiment is under development to determine if the apparent stability of flame balls can be confirmed in experiments where both the duration of µg is long (unlike drop-tower experiments) and the quality is significantly better than that in aircraft tests. Also, the presence or absence of flame strings will be studied to determine the role buoyancy plays in their formation. In addition to addressing development issues in support of the development of flight hardware, future work will stress the role of reabsorption of emitted radiation on these flame structures using high-pressure tests and particle-laden mixtures. It is possible that the presence of particles will influence transport of thermal energy (see above) but should not influence mass transport, leading to a radiation-influenced Lewis number which may be higher than the particle-free value, thereby inhibiting the cellular instability.

Flame propagation and extinction in cylindrical tubes

The standard apparatus for measuring flammability limits of premixed gases at earth gravity is the Standard Flammability Limit Tube, or SFLT. This is a tube 5 cm diameter and 200 cm long which is filled with combustible gas and ignited at one end. The mixture is defined to be flammable if it supports propagation throughout the tube. Despite many years of study, the mechanisms of flame extinction in the SFLT is not well understood. The relative importance of buoyancy, flame stretch, heat loss to the tube wall, radiation loss, etc. have not been assessed.

Most theories of flammability limits predict the flame propagation rate at the limit ($S_{b,lim}$). Hence, measurement of $S_{b,lim}$ enables comparison with theories. We have conducted such experiments at earth gravity in tubes of varying diameter, at varying pressures and with mixtures having varying fuels, inerts, and Lewis numbers (Le). We have found that the characteristics of the limits can be described in terms of the effect of the Grashof number $Gr \equiv gd^3/\alpha^2$ on the limit Peclet number $Pe \equiv S_{b,lim}d/\alpha$, where g is gravity, d the tube diameter and α the thermal diffusivity at room temperature. Figures 4 and 5 show the results for upward and downward propagation, respectively. In each case, at low Gr the results are consistent with theoretical predictions [11] for flame extinguishment by conduction loss to the tube walls, namely $Pe \approx$ constant ≈ 40. At higher Gr, results are consistent with buoyancy-induced extinction mechanisms, in the upward propagating case $Pe \sim Gr^{1/2}$ [12] and in the downward case $Pe \sim Gr^{1/3}$. Because of the difference in extinction mechanisms, we have found that the flammability limit can actually be wider for downward propagation than upward propagation (though for most commonly-studied values of Gr and Le, this is not the case).

In the upward case, at $Gr > 2.0 \times 10^8$ (corresponding to a pipe-flow Reynolds number of 2000) turbulent flow is exhibited; the flame behavior can be either flamelet-like or distributed-like depending on Gr and Le. Downward turbulent propagation at the limit is also possible, but would require $Gr \approx 40 \times 10^9$ according to our scaling analysis, and is beyond the limits of our apparatus.

Our scaling analyses indicate that radiation losses cannot be significant at earth gravity for any experimentally realizable conditions; either conduction losses or buoyancy effects will dominate. Of course, radiation can be the dominant extinction mechanism in large tubes at μg. We are initiating a study of this extinction process for comparison to our previous results in a constant-volume chamber with central ignition (which produces spherically expanding flames.)

Experimental simulation of premixed flames using autocatalytic chemical reactions

The PI has introduced the use of aqueous autocatalytic propagating chemical fronts (in particular, the arsenous acid-iodate system) for the experimental simulation of premixed combustion in nonuniform and unsteady flows [13]. These fronts more nearly match the assumptions made by most relevant theoretical models that do gaseous flames. These assumptions include that of constant density. The role of density change (due to heat release) in gaseous premixed flame propagation has been a continuing source of controversy, especially in turbulent flows. It has not even been established whether density changes result in an increase or decrease in the turbulent flame propagation rate (S_T) [13]. Consequently, it is desirable to compare front propagation in gaseous flames and aqueous autocatalytic fronts to study effects of density change.

A limitation on the utility of aqueous fronts is that even the small fractional density change across the aqueous front leads to significant buoyancy influences at one-g because of the very low planar front propagation rate (S_L). Only when the imposed disturbance intensity (u') is much greater than buoyancy-induced flow velocities can buoyant effects be neglected. Gaseous flames with $u' \gg S_L$ cannot be observed because of quenching which results from the hydrodynamic strain at high $U \equiv u'/S_L$; this makes it impossible to compare the aqueous and gaseous front propagation at the same U, and thereby assess the role of density changes. High U is also inaccessible to computational studies because of numerical difficulties, especially when density changes are included.

This discussion indicates the need for studying aqueous fronts at μg to eliminate buoyancy influences, enabling the study of front propagation at low U and thereby allowing comparison of front propagation in aqueous and gaseous fronts at the same u'/S_L.

We have studied these autocatalytic propagating fronts in a Taylor-Couette flow, i.e. in the annulus between two rotating concentric cylinders. This flow was chosen because (1) the flow is homogeneous in the direction of front propagation (axially), so that a quasi-steadily propagating front can be studied, and (2) well-characterized disturbances are generated even at very low Reynolds numbers (and thus low u'). When only the inner cylinder is rotated, pairs of counter-rotating toroidal vortex pair (Taylor vortices) fill the annulus. Fig. 4 shows the measured [13] effect of u'/S_L on S_T/S_L in the Taylor-vortex regime and the predictions of a theoretical model [13]; agreement is good. (Data were taken up to $u'/S_L \approx 10{,}000$, but only the lower values of u'/S_L are of interest to this study in that they may be affected by buoyancy).

Our scaling analysis has shown that in a space experiment, it is possible to study aqueous fronts with $U \approx 7$ at $g \approx 10^{-4}g_o$ (a typical figure for space experiments) without buoyant convection, whereas $U \approx 140$ is the lowest possible U at $g \approx g_o$ without buoyant convection. It is possible to study $U = 7$ in gas combustion without quenching, whereas $U = 140$ is not possible. Thus, space experiments would enable us to study the aqueous fronts at values of U accessible to gas combustion experiments and numerical simulations, enabling us to create a "bridge" between studies of fronts with and without substantial density changes.

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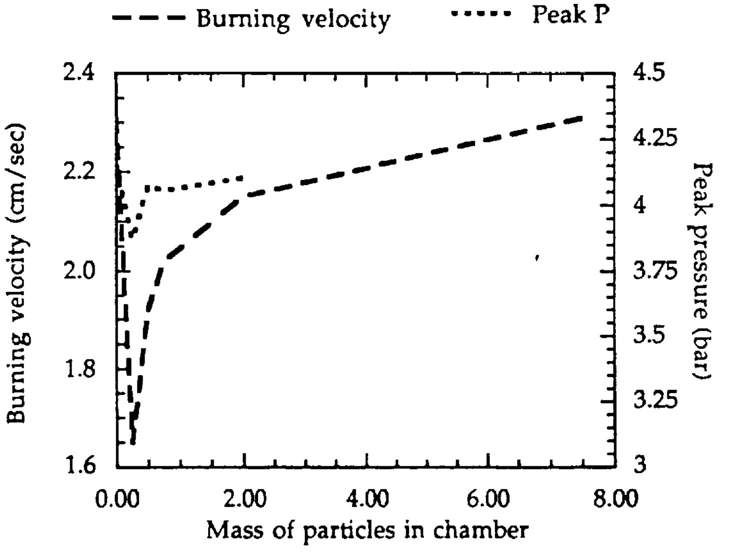

Figure 1. Propagation rates and peak pressures of particle-laden flames. Mixture: 5.25% CH_4 in air.

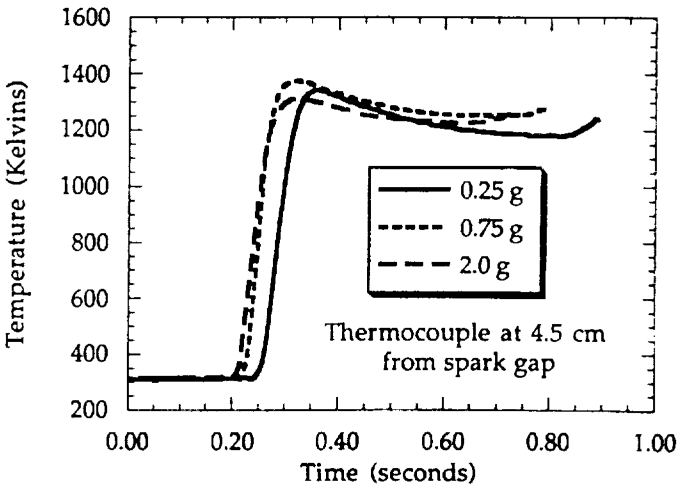

Figure 2. Thermal characteristics of flames in particle-laden mixtures. Mixture: 5.25% CH_4 in air.

Figure 3. IR image of "flame string" at μg. Mixture: 5.5% H_2 in air.

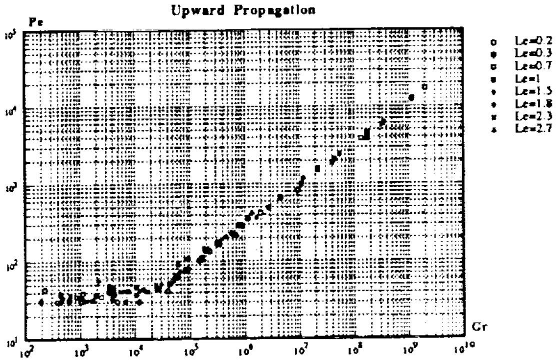

Figure 4. Limit Peclet number versus Grashof number for upward-propagating flames in tubes.

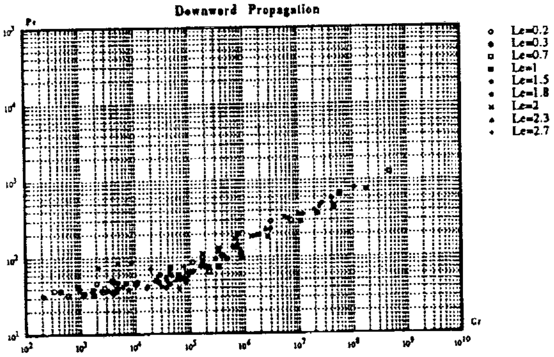

Figure 5. Limit Peclet number versus Grashof number for downward-propagating flames in tubes.

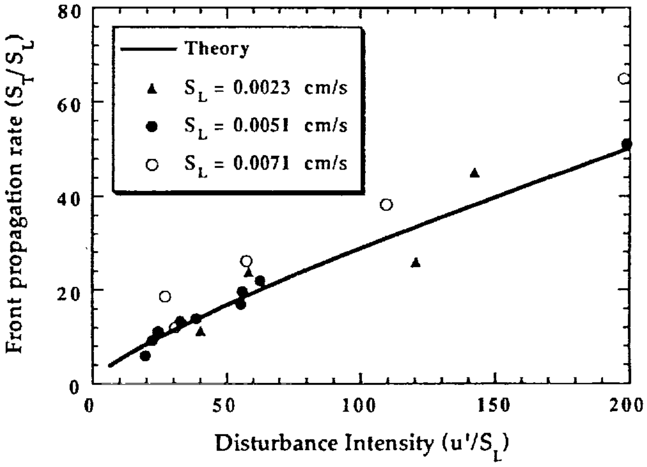

Figure 6. Effect of disturbance intensity on front propagation rate in aqueous autocatalytic system.