

STUDIES OF PREMIXED LAMINAR AND TURBULENT FLAMES AT MICROGRAVITY (NASA Grant No. NAG3-2124)

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INTRODUCTION

Several topics relating to combustion limits in premixed flames at reduced gravity have been studied. These topics include: (1) flame balls; (2) numerical simulation of flame ball and planar flame structure and stability; (3) experimental simulation of buoyancy effects in premixed flames using aqueous autocatalytic reactions; and (4) premixed flame propagation in Hele-Shaw cells.

STRUCTURE OF FLAME BALLS AT LOW LEWIS-NUMBER (SOFBALL)

Successful flame ball experiments were conducted on the STS-83 and STS-94 Space Shuttle missions in 1997. Among the unexpected results were (1) flame balls survived much longer than expected based on pre-flight estimates – in most cases the entire 500 second test duration; (2) when multiple flame balls were present, they drifted apart from each other (although their “center of mass” was nearly motionless in many cases); (3) flame balls were very sensitive to small accelerations (typically $100 \mu\text{g}$ for 1 second) resulting from Orbiter vernier reaction control system (VRCS) thruster firings; and (4) remarkably, all flame balls in all mixtures tested produced between 1 and 2 Watts per ball of radiant power per ball.

The drift of adjacent flame balls was attributed to the enthalpy gradient each ball imposes on its neighbors. A model was developed by the PI in conjunction with J. D. Buckmaster. The slope of separation vs. time plots (e.g. Fig. 1), are close to the theoretically prediction of $1/3$, and the quantitative agreement is reasonable considering the simplicity of the model. The mean and standard deviation of the slope for all relevant tests is 0.334 with a standard deviation of 0.060.

The flame balls were found to respond ballistically to VRCS impulses (Fig. 2). The impulse (change in velocity) imparted to the ball is about the same as the acceleration impulse (integral of acceleration over time). The ball velocity change is somewhat greater (by a factor of about 2) than the acceleration impulse. The maximum possible factor for a spherical bubble of fluid having very low density compared to the surrounding fluid is 2 because of the “added mass” effect. This change in velocity then decays on a time scale of tens of seconds, which is comparable to the viscous time scale associated with the flame ball and its surrounding hot gas field.

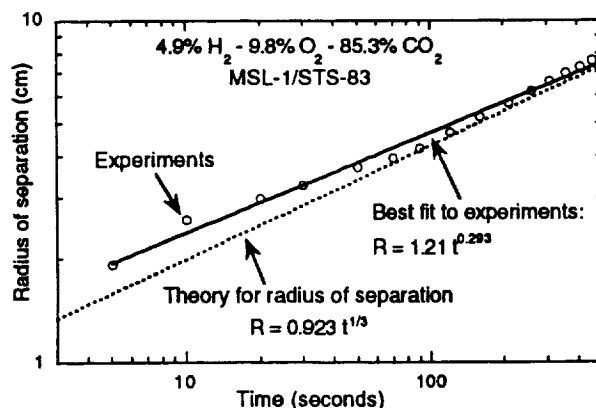


Figure 1. Examples of flame ball interactions resulting in mutual repulsion.

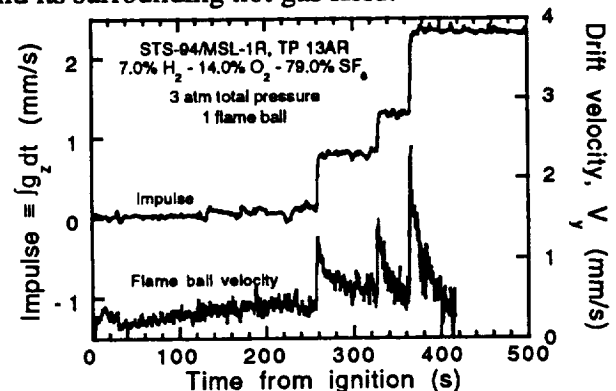


Figure 2. Effect of impulsive orbiter accelerations on flame ball drift velocity.

NUMERICAL SIMULATION OF FLAME BALL AND PLANAR FLAMES

In order to predict the properties of flame balls, a one dimensional, time-dependent flame code with detailed chemical and transport sub-models was employed to solve the usual

nonsteady equations for energy and species conservation in spherical geometry at constant pressure. It was found that the predicted flame ball radii using different chemical models vary widely, even though all of these models predict the burning velocities of steady plane flames quite accurately. Also, reabsorption of emitted radiation was found to be a dominant effect in mixtures diluted with CO_2 or SF_6 , in that calculations assuming infinite absorption coefficient for the diluent showed much better agreement with experiment than calculations assuming optically-thin diluent radiation (Fig. 3).

A numerical study of premixed-gas flames in mixtures of CH_4 , O_2 , N_2 and CO_2 using detailed chemical and radiative emission-absorption models was conducted in conjunction with Prof. Yiguang Ju of Tohoku University in Sendai, Japan. It was found that reabsorption of emitted radiation led to substantially higher burning velocities and wider extinction limits than calculations using optically-thin radiation models, particularly when CO_2 , a strong absorber, is present in the unburned gas (Fig. 4). Two heat loss mechanisms that lead to flammability limits even with reabsorption were identified: (1) differences in the absorption spectra of the reactant and product molecules and (2) the broadening of emission spectra at flame temperatures compared to ambient temperature. Via both mechanisms some net upstream heat loss due to radiation will always occur, leading to extinction of sufficiently weak mixtures. It is concluded that fundamental flammability limits can exist due to radiative heat loss, but these limits are strongly dependent on the emission-absorption spectra of the reactant and product gases and their temperature dependence, and cannot be predicted using gray-gas or optically-thin models.

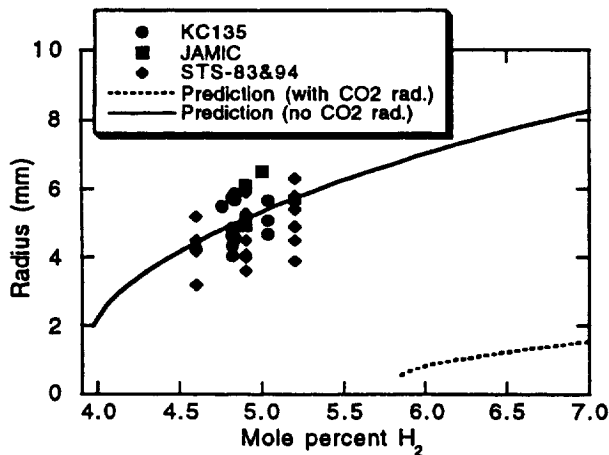


Figure 3. Predicted flame ball radii in H_2 - O_2 - CO_2 mixtures ($\text{H}_2:\text{O}_2 = 1:2$) including and excluding CO_2 radiation, along with measured flame ball radii from aircraft μg experiments, JAMIC drop-tower experiments, and the STS-83/94 space experiments.

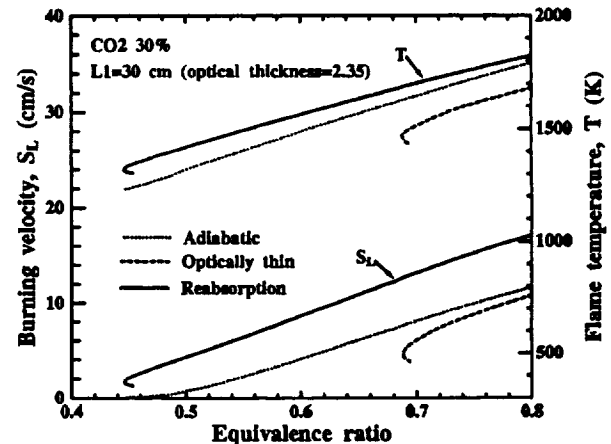


Figure 4. Predicted values of burning velocity and peak flame temperature in CH_4 - ($0.21 \text{ O}_2 + 0.49 \text{ N}_2 + 0.30 \text{ CO}_2$) mixtures under adiabatic conditions, with optically-thin radiative losses, and including reabsorption effects.

“LIQUID FLAMES”

With NASA Code UG support, the PI has introduced the use of aqueous autocatalytic chemical reaction fronts for the experimental simulation of combustion processes. These fronts exhibit very little density change across the front, have simple chemistry, are unaffected by heat losses (since the front is nearly isothermal) and have high Schmidt numbers, allowing the front to remain “flamelet-like” even in the presence of very strong flow disturbances or turbulence. Thus, such fronts are very useful for experimental study of combustion under conditions far more readily simulated by available theoretical and numerical models.

Hele-Shaw cells are frequently employed to study buoyancy effects in fluid systems in a simple quasi two-dimensional geometry where the flow is governed by a linear equation (Darcy’s law). Thus, autocatalytic reactions in Hele-Shaw cells represent the simplest possible

experimental realization of the interaction of a propagating front with buoyancy-induced convection. Fingering-type instabilities were observed (Fig. 5), which is very surprising since the classical Saffman-Taylor mechanism is not present (since there is no viscosity difference across the front). The fingering wavelength is independent of the front propagation rate (S_L) and the cell thickness (w) and is inversely proportional to the square root of the cosine of the angle of the cell from vertical. The only viable explanation of this behavior is a surface tension at the interface whose magnitude is about 0.005 dyne/cm – about 14,000 times smaller than a water-air interface.

An estimate of the magnitude of the buoyancy-induced flow disturbances was derived based on the Saffman-Taylor model, resulting in $u'/S_L \approx (\pi/12)g\delta w^2/\nu S_L$ where u' is the effective “turbulence intensity”, g the gravitational acceleration, δ the fractional density change, and ν the kinematic viscosity. The “turbulent burning velocity” (S_T) is plotted as a function of U in Fig. 6. These results show that the Yakhot model $S_T/S_L = \exp((u'/S_L)/(S_T/S_L))^2$ fit the experimental data for this experiment, as it did our previous results from several different forced-turbulence flows. These results suggest a rather simple description of the role of buoyancy on the front propagation in this simple chemical and hydrodynamic system.

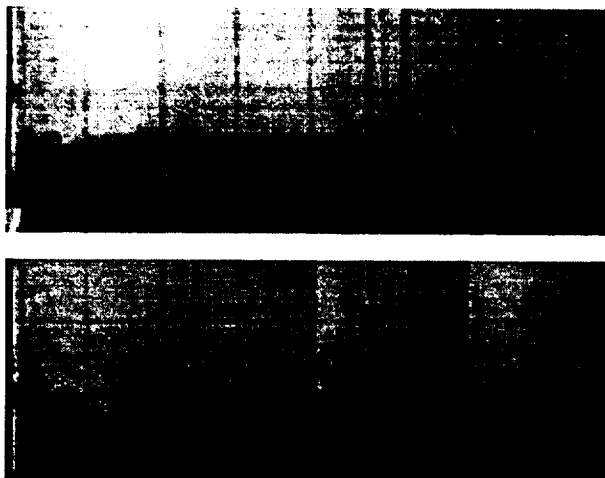


Figure 5. Upward propagating autocatalytic front in a Hele-Shaw cell. Cell thickness (w) = 1.0 mm, S_L = 0.17 mm/s. Upper image: 10 seconds after initiation; lower image: after reaching quasi-steady propagation condition. Width of cell is 200 mm.

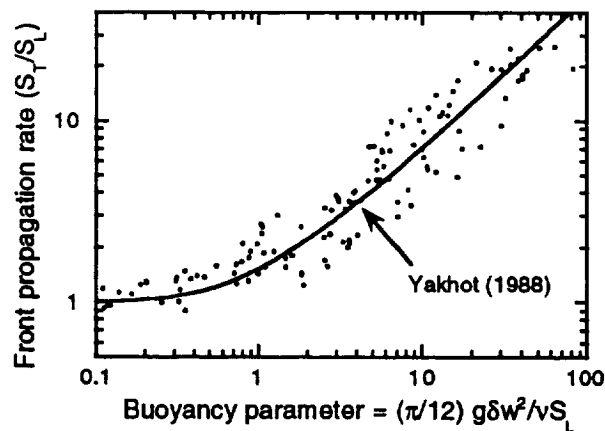


Figure 6. Correlation of wrinkled front speed (U_T) with buoyancy parameter (U_B).

PREMIXED-GAS FLAME PROPAGATION IN HELE-SHAW CELLS

As a complement to the experiments on chemical fronts in Hele-Shaw cells, premixed-gas flames in Hele-Shaw cells were also examined. Significantly, wrinkling was observed even for downward propagating (buoyantly stable) flames and flames having high Lewis number (diffusively-thermally stable) (Fig. 7a). The burning rates (S_T) of these flames are quite different from their laminar, unwrinkled values (S_L). Values of S_T/S_L in the quasi-steady stage were higher for upward vs. downward propagation, but only weakly dependent on Lewis and Peclet numbers (Fig. 7b). The first of these effects is consistent with the Joulin-Sivashinsky (JS) model, whereas the last is contrary to the JS predictions concerning the effects of heat losses. These results show that even for diffusively stable mixtures, at microgravity thermal expansion and viscosity changes across the front will lead to flame instabilities. These results also indicate that the behavior of flame propagation in narrow channels such as crevice volumes in premixed-charge internal combustion engines (the source of most unburned hydrocarbon emissions) may be quite different from that inferred from simple laminar flame experiments.

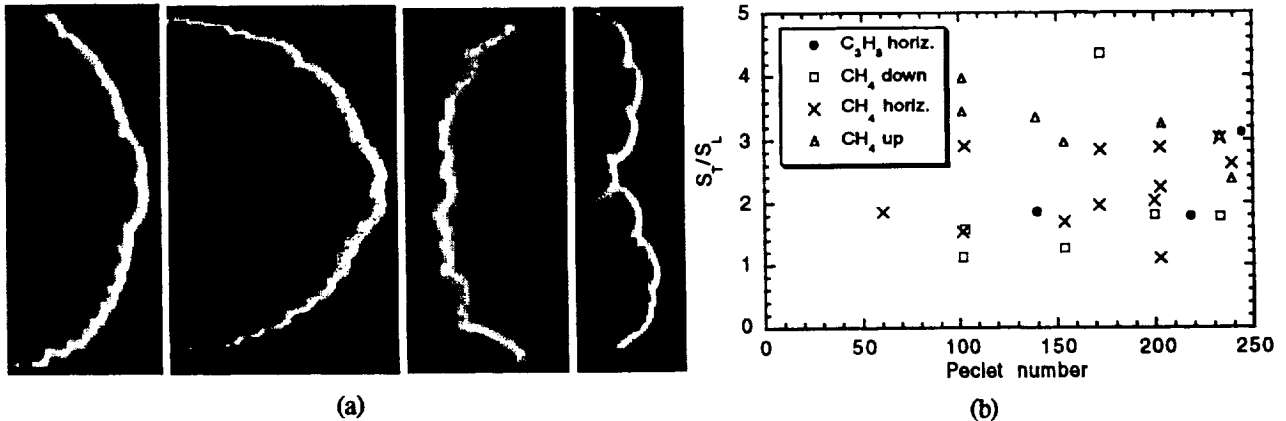


Figure 7. Characteristics of flames in Hele-Shaw cells. (a) direct images (flames propagate from left to right.) Cell width (vertical direction in these images) 39 cm. Cell length (horizontal direction in these images) 60 cm, but images are cropped to show only flame front. Images from left to right: 7.2% CH₄ in air, horizontal propagation; 7.1% CH₄ in air, upward propagation; 7.1% CH₄ in air, downward propagation; 3.0% C₃H₈ in air, horizontal propagation. (b) Correlation of wrinkled front speed (S_T/S_L) with Peclet number.

PUBLICATIONS 1997-98

Liu, J.-B. and Ronney, P. D., "Premixed Edge-Flames in Spatially Varying Straining Flows," to appear in *Combustion Science and Technology* (1999).

Vedarajan, T. G., Buckmaster, J. D. and Ronney, P. D., "Two-dimensional Failure Waves and Ignition Fronts in Premixed Combustion," to appear in the *Twenty-Seventh International Symposium on Combustion* (1998).

Wu, M.-S., Liu, J. B. and Ronney, P. D., "Numerical Simulation of Diluent Effects on Flame Ball Structure and Dynamics," to appear in the *Twenty-Seventh International Symposium on Combustion* (1998).

Ju, Y., Masuya, G. and Ronney, P. D., "Effects of Radiative Emission and Absorption on the Propagation and Extinction of Premixed Gas Flames" to appear in the *Twenty-Seventh International Symposium on Combustion* (1998).

Buckmaster, J. D. and Ronney, P. D., "Flame Ball Drift in the Presence of a Total Diffusive Heat Flux," to appear in the *Twenty-Seventh International Symposium on Combustion* (1998).

Ronney, P. D., "Understanding Combustion Processes Through Microgravity Research," to appear in *Twenty-Seventh International Symposium on Combustion*, Combustion Institute, Pittsburgh, 1998 (plenary paper).

Ronney, P. D., "Premixed Laminar and Turbulent Flames at Microgravity," to appear in *Space Forum* (1998).

Ronney, P. D., "Flame Structure Modification and Quenching By Turbulence," *Combustion Science and Technology* (Japanese edition), Vol. 6 (Supplement), pp. 53-76, 1999.

Wu, M. S., Ronney, P. D., Colantonio, R., VanZandt, D., "Detailed Numerical Simulation of Flame Ball Structure and Dynamics," *Combustion and Flame*, Vol. 116, pp. 387-397 (1999).

Abid, M., Wu, M. S., Liu, J. B., Ronney, P. D., Ueki, M., K. Maruta, K., Kobayashi, H., Niioka, T. and VanZandt, D. M., "Experimental and Numerical Study of Flame Ball IR and UV Emissions," *Combustion and Flame*, Vol. 116, pp. 348-359 (1999).

Ronney, P. D., Wu, M. S., Pearlman, H. G. and Weiland, K. J., "Experimental Study of Flame Balls in Space: Results from STS-83," *AIAA Journal*, Vol. 36, pp. 1361-1368 (1998).

Aldredge, R. C., Vaezi, V. and Ronney, P. D., "Premixed-Gas Flame Propagation in Turbulent Taylor-Couette Flow," *Combustion and Flame*, Vol. 115, pp. 395-405 (1998).

