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Structure of Flame Balls at Low Lewis-number (SOFBALL)

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Objective

The work of the PI supported by NASA Grant No. NAG3-1523, starting date 9/9/93, has encompassed several topics related to the experimental and theoretical study of combustion limits in premixed flames at microgravity. These topics include: (1) flame structure and stability at low Lewis number (which is the basis for the SOFBALL space flight experiment), (2) flame propagation and extinction in cylindrical tubes, and (3) experimental simulation of combustion processes using autocatalytic chemical reactions. Progress on each of these topics is outlined below.

Progress

1. Flame structure and stability at low Lewis number

In support of several unresolved engineering issues concerning the CM-1/SOFBALL space flight experiment, scheduled for an April 1997 launch, five weeks of low-gravity flight tests were performed on NASA's KC-135 research aircraft. A brief overview is given here.

The KC-135 flights have led to a better understanding of many aspects of flight-like hardware and operational procedures. The most important lessons learned include:

- The possibility of the etching of chamber windows during flight experiments due to corrosive combustion by-products, probably from the SF_6-diluted mixtures.
- It has not been possible to obtain agreement between calculated (based on partial pressures) and measured (by gas chromatography) gas compositions
- The radiometers work as expected, but for H_2-air mixtures their signal is too weak to resolve without some pre-amplification
- Operational confidence in the flight hardware can be significantly enhanced by checking operation of diagnostics during pump-down and filling of the chamber, along with judicious use of chamber lighting

- The Xybion cameras work well, but can be damaged by intense chamber lighting

The most significant problem found with the KC135 hardware was that the transparency of the chamber windows may deteriorate significantly, apparently due to chemical etching by the combustion products of SF_6-diluted mixtures. However, many of the mixtures tested burned more strongly than those contemplated for space flight, because problems with the KC135 gas mixing and ignition systems prevented us from burning more dilute, weaker burning mixtures. Furthermore, the accuracy of the gas mixing process makes it uncertain what the actual burned compositions were.

Concerning the gas mixing issues, the following actions were recommended: test partial pressure accuracy for lower total pressure filling, evaluate automated gas mixing system, maintain constant-temperature environment during filling and evaluate a mass-based (gravimetric) gas mixing system

A radiometer preamplifier circuit has been designed, built, and evaluated on real gaseous flames. It has been agreed to use this system on the next set of KC-135 flights in conjunction with software enabling auto-ranging of the radiometer signals. These tests are particularly important for the H_2-air flames which emit only weak (but fundamentally important) thermal radiation that is difficult to detect without preamplification of the radiometer signal.

The PI has implemented a computerized IBM-PC based image processing system for use in his laboratory. One finding to date is that many of the tests run in CM-1 KC135 tests have resulted in saturated (i.e. overexposed) images. This may indicate a need for a new criterion for determining the optimal gain setting based on visual interpretation of video images.

A Hewlett-Packard workstation for conducting flame ball modeling calculations has been delivered and configured. A one-dimensional, unsteady flame code employing detailed chemical and transport sub-models, developed by B. Rogg at Cambridge University, has been obtained and is being installed on the HP workstation. This system forms the basis of ongoing flame ball modeling calculations to be used for comparison with the SOFBALL experimental results.

Several flight PI's have considered the use of some alternative to electric sparks for flame ignition because of the potential difficulties with high voltages and electromagnetic interference. The PI had evaluated the use of heated wire sources and found them to be inadequate for some cases, particularly very lean or dilute mixtures, because of limitations on the amount of energy that could be deposition in the gas in a short period of time without melting the wire. Recently, the PI has initiated a small effort to study flame ignition by laser sources and evaluate their viability for future ground-based and space-flight based μg experiments. The USC portion of this effort consists of one undergraduate student and is performed in collaboration with The Aerospace Corporation (El Segundo, CA), who provides the equipment and facilities along with pulsed laser expertise. To date, we have tested the minimum ignition energies of methane-air mixtures at one atmosphere initial pressure as a function of fuel-air ratio and compared these results to prior spark ignition experiments and numerical modeling (Fig. 1). The results suggest a critical role of the size of the energy deposition region, and the potential for significantly reduced minimum ignition energies compared to classical experiments if the size of the deposition region is made small enough.

2. Flame propagation and extinction in cylindrical tubes

The emphasis of the SOFBALL project is, as the title indicates on combustible mixtures with low Lewis number. As a complement to this study, the PI has participated in a study of flame propagation at high Lewis number. The PI suggested this study to Dr. Howard Pearlman, an NRC postdoctoral research associate at NASA-Lewis. Dr. Pearlman has conducted all of the experiments, both at low gravity and at earth gravity; the PI has provided guidance and contributed to the writing of the manuscripts based on this work. Theory predicts at high Lewis number, pulsating and traveling-wave instabilities should occur. The experiments have shown, in addition to these modes, spiral-wave flame fronts (Fig. 2). None of these modes had been conclusively observed experimentally in previous works, probably because Dr. Pearlman's experiments employed more advanced diagnostics and mixtures with higher Lewis numbers than any previous work of its type.

3. Experimental simulation of combustion processes using autocatalytic chemical reactions

In prior work, in order to study the behavior of propagating flames at high turbulence levels, without the complications of density changes or heat losses, the PI introduced the use of an aqueous autocatalytic reaction, which produces propagating fronts, as a paradigm for turbulent premixed combustion. These experiments suggested that heat losses or initiation conditions are probably responsible for the observed quenching in gaseous combustion experiments. Comparison of these results to theory suggested that Yakhot's Renormalization Group (RNG) theory provides the best description of turbulent flame propagation (Fig. 3) for large Damköhler number (Da) (ratio of mean chemical reaction rate to mean turbulent strain rate). At lower Da, Damköhler's original (1940) hypothesis (not shown) fits these data well. The fractal dimensions of these fronts compare favorably with Kerstein's heuristic model. The PI and his collaborators have also developed an extension of Yakhot's model to consider the effect of turbulence scales which are smaller than the flame thickness, and find that this model provides very good predictions of the propagation rates under these conditions.

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 (g_o) because of their very low S_L. Only when $u' >> S_L$ is this limitation unimportant. Gaseous flames with $u' >> S_L$ 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 results of aqueous and gaseous front experiments at the same U, and thereby assess the role of density changes. Quenching is not a problem in the aqueous fronts because of their high Schmidt number (Sc) (ratio of kinematic viscosity (ν) to mass diffusivity (D)) which reduces the effect of hydrodynamic strain. 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.

An ideal flow for studying the interaction of propagating fronts with flow disturbances, and one which suffers from these buoyancy influences, is the Taylor-Couette flow in the annulus between two rotating concentric cylinders. When only the inner cylinder is rotated, pairs of counter-rotating toroidal vortex pairs (Taylor vortices) fill the annulus. To obtain these vortices, the Reynolds number $Re \equiv \omega d r_i/\nu$, where ω is the angular rotation rate of the inner cylinder, d the cylinder gap and r_i is the inner cylinder radius, must be larger than about 75. Using known properties of the Taylor vortex flow and the effect of buoyancy on the autocatalytic fronts, along with representative values for the relevant parameters, we find that to avoid buoyant convection, we require $d < 0.1$ cm at $g = g_o$ and $d < 2.0$ cm at $g = 10^{-4} g_o$. (The latter g is a typical figure in space flight experiments.)

Our scaling analysis has shown that in a space experiment, it is possible to study aqueous fronts with $U \approx 7$ at $g = 10^{-4} g_o$ without buoyant convection, whereas $U \approx 140$ is the lowest possible U at $g = g_o$ 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.** Consequently, the PI has proposed the Front Interaction with Vortex Experiment (FIVE) as a space shuttle glovebox experiment.

One open issue concerning the aqueous autocatalytic chemically reacting fronts is the response of these fronts to hydrodynamic strain. This response is well established for gaseous flames, and while there is no obvious reason why the same physical mechanisms would not apply to the aqueous system as well, there is no experimental proof of this suggestion. Conventional apparatuses for studying strained flames, e.g. the opposed-jet configuration, are not suitable for such experiments because of the much slower flows required in the aqueous case. Consequently, a Taylor four-roll mill, where the strain rate is determined by the rate of rotation of the rollers, has been constructed and will be employed. To avoid buoyancy-induced flow, the upper flow region will be heated electrically to a temperature a few °C above ambient. Again, laser-induced fluorescence will be used to image the fronts and determine their propagation rate.

Refereed Journal Publications

Ronney, P. D., Haslam, B. D., Rhys, N. O., "Front Propagation Rates in Randomly Stirred Media," to appear in *Physical Review Letters* (1995).

Lim, E. H., McIlroy, A., Ronney, P. D., Syage, J. A., "Detailed Characterization of Minimum Ignition Energies of Combustible Gases Using Laser Ignition Sources," to appear in: *Proceedings of the 8th International Symposium on Transport Phenomena in Combustion*, Taylor and Francis, 1995.

Haslam, B. D., Ronney, P. D., "Fractal Properties of Propagating Fronts in a Strongly Stirred Fluid," to appear in *Physics of Fluids* (1995).

Ronney, P. D., "Some Open Issues in Premixed Turbulent Combustion," to appear in Modeling in Combustion Science (J. D. Buckmaster and T. Takeno, Eds.), Lecture Notes In Physics Series, Springer-Verlag (1995).

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Abbud-Madrid, A., Ronney, P. D., "Premixed Flame Propagation in an Optically-Thick Gas," *AIAA Journal* Vol. 31, pp. 2179-2181 (1993).

Sloane, T. M., Ronney, P. D., "A Comparison of Ignition Phenomena Modeled with Detailed and Simplified Kinetics," *Combustion Science and Technology*, Vol. 88, pp. 1-13 (1993).

Work presented but not yet published

Wu, M.-S., Ronney, P. D., "Numerical Simulation of Flame Ball Structure and Stability," Joint Technical Meeting, Combustion Institute, Central States/Western States/Mexican Sections, April 23-26, 1995, San Antonio, TX (to be presented).

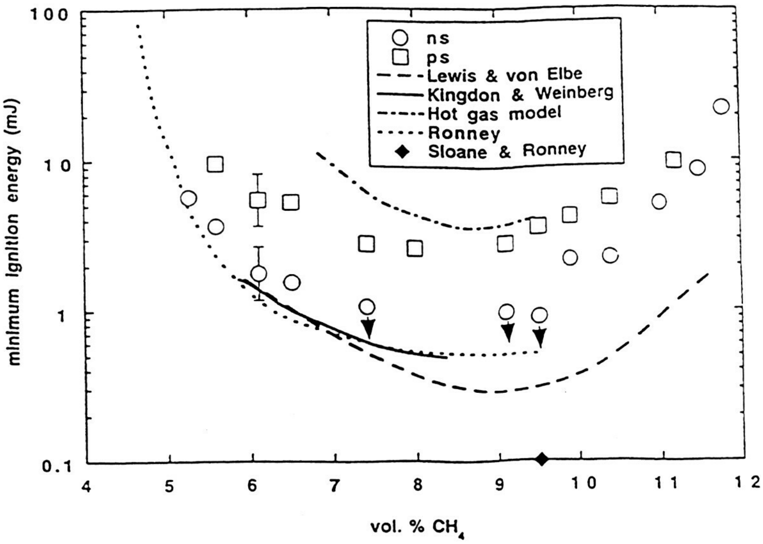

Figure 1. Measured and calculated minimum ignition energies of CH_4-air mixtures at 1 atm. Downward pointing arrows at near-stoichiometric conditions indicate conditions for which it was not possible to form sufficiently small spark energies to observe non-ignitions. For comparison, also shown are results from electric spark ignition experiments by Lewis and von Elbe and Ronney, laser spark ignition experiments by Kingdon and Weinberg, a detailed numerical computation by Sloane and Ronney and a simple hot gas model by Syage *et al.*

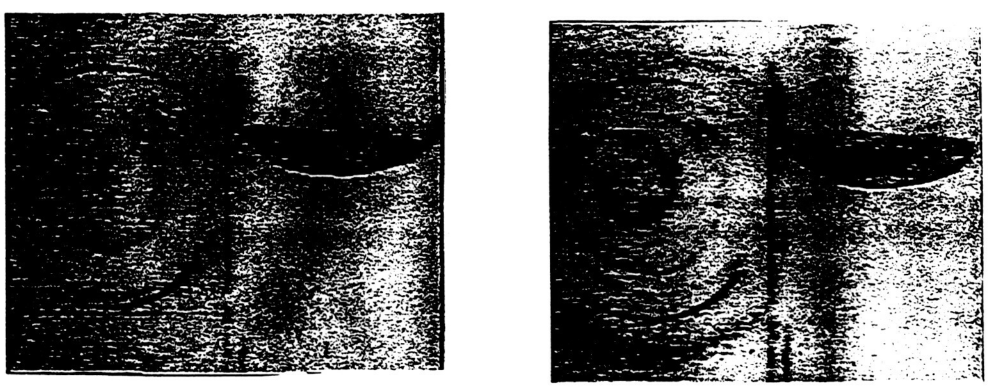

Figure 2. Images of spiral-shaped flames in a lean, near-limit C_3H_8-O_2-He mixture propagating down a 15 cm diameter tube. In each image pair, the left image is the axial view and the right image is the radial view. The second group of images was taken 0.004 sec after the first.

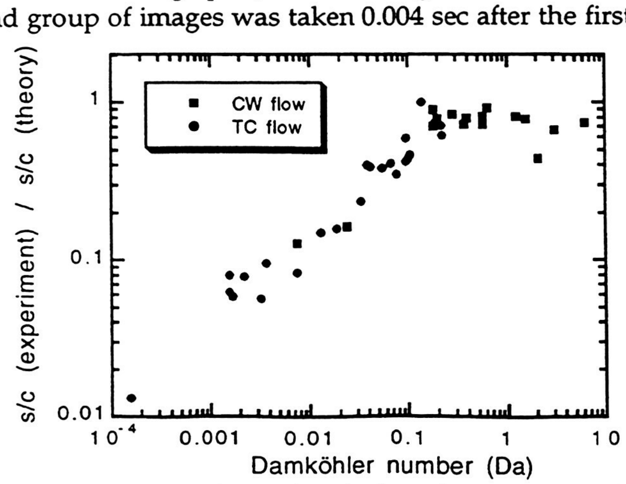

Figure 3. Comparison of measured values of turbulent front propagation rate (s) normalized by the laminar, undisturbed propagation rate (s) to the values of s/c predicted by Yakhot's renormalization group model, for fronts in a Taylor-Couette (TC) and capillary wave (CW) flow. The Damköhler number (Da) indicates the ratio of mean chemical reaction rate to mean turbulent strain rate.