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13. ABSTRACT *(Maximum 200 words)*

We examine the geometry of diffusion flames generated by the burning of a heterogeneous solid propellant, using a simple model designed to provide qualitative insights. In the fast chemistry limit a strategy is used which has its roots in Burke and Schumann's 1928 study of diffusion flames, albeit with different boundary conditions. This shows that the stoichiometric level surface (SLX) intersects the propellant surface at a point displaced from th efuel/oxidizer interface, and the variations of this displacement with Peclet number are discussed We show that for model sandwich propellants, or their axisymmetric counterpart, the geometry of the $LS when the core is oxidizer is quite different for the geometry of the SLX when the core is fi ~ el. Also, it is much easier to quench the flame on an oxidizer core, by reducing the Peclet number, than it is to quench the flame on a fuel core. When finite chemistry effects are accounted for, the flame only occupies a portion of the SLS, and there is a leading edge structure in which premixing plays a role. Enhancement of the burning rate due to premixing is identified, but a well-defined tribrachial structure is not observed We show how a sharp reduction in pressure can lead to a detachment of the flame from the SLS, with subsequent quenching as it is swept down stream.

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Objectives

This research is concerned with theoretical studies of combustion and related flow problems that are relevant to the Air Force mission. Recent topics that have been examined include premixed edge flames, heterogeneous propellant flame modeling, and rotational flows interior to solid rocket chambers.

Status of Effort

[1] The paper 'An elementary discussion of propellant flame geometry' by J.Buckmaster, T.L.Jackson and J.Yao was completed at the beginning of the period and submitted to Combustion and Flame. It has been accepted for publication in that journal. J. Yao was supported as a post-doctoral student by the grant. The abstract of the paper reads:

We examine the geometry of diffusion flames generated by the burning of a heterogeneous solid propellant, using a simple model designed to provide qualitative insights. In the fast chemistry limit a strategy is used which has its roots in Burke and Schumann's 1928 study of diffusion flames, albeit with different boundary conditions. This shows that the stoichiometric level surface (SLS) intersects the propellant surface at a point displaced from the fuel/oxidizer interface, and the variations of this displacement with Peclet number are discussed. We show that for model sandwich propellants, or their axisymmetric counterpart, the geometry of the SLS when the core is oxidizer is quite different for the geometry of the SLS when the core is fuel. Also, it is much easier to quench the flame on an oxidizer core, by reducing the Peclet number, than it is to quench the flame on a fuel core. When finite chemistry effects are accounted for, the flame only occupies a portion of the SLS, and there is a leading edge structure in which premixing plays a role. Enhancement of the burning rate due to premixing is identified, but a well-defined tribrachial structure is not observed. We show how a sharp reduction in pressure can lead to a detachment of the flame from the SLS, with subsequent quenching as it is swept down stream.

[2] A second paper, related in some ways to [1], was completed and submitted to Combustion and Flame. Its title is 'The effects of a time-periodic shear on a diffusion flame anchored to a propellant' by J.Buckmaster and T.L.Jackson. Its abstract reads:

We examine a single diffusion flame anchored to 1/4-spaces of solid fuel and oxidizer, a configuration relevant to the combustion of heterogeneous solid propellants. A time-periodic shear flow is applied, to model the shear that can be generated by the interaction of acoustic waves and the rotational base flow in a rocket chamber. The response of the flame, the heat flux to the surface, etc., to this shear, is calculated numerically. Significant enhancement of the maximum temperature and the time averaged total heat flux to the surface are found. These enhancements are essentially maximized at zero frequency, and at low frequencies the response when the the shear is directed from the fuel to the oxidizer is markedly different from the response when the shear is reversed.

[3] A third paper, a sequel to [2] is almost complete. All the work has been done, it is presently being written, and we will shortly submit it to Combustion and Flame. It deals with a periodic propellant configuration. We show that when the propellant distribution is close to stoichiometric, the SLS ([1], above) plays little role in defining the flame structure, which, instead, is dominated by a premixed flame. This flame sits over the fuel portion of the propellant surface, and there are gaps between each flame in the periodic array, gaps that are located over the oxidizer. Consequently, the heat flux from the flame will be greater

to the fuel than to the oxidizer, and this will have a proportional effect on the gasification rate of the two materials.

[4] The work in [2] was presented as a 'Work-in-progress' poster at the 27th International Symposium on Combustion held in Boulder, CO in August. A short abstract appears in the WIP Abstract Book of that meeting.

[5] The work in [2] and [3] will be presented at the 37th AIAA Aerospace Sciences Meeting in Reno, Nevada, January 1999. It is paper 99-0323, to be presented in the session P&C-03, and is titled 'Response of propellant flames to unsteady flows and related questions'.

[6] We have initiated a study of non-axisymmetric flows in solid propellant rocket motors. It appears that no such study has been performed before, despite the fact that most large rockets have non-cylindrical grain configurations. A paper is presently being typed, and figures are being prepared, for submission to the Journal of Fluid Mechanics. Its title is 'The generation of axial vorticity in solid-propellant rocket-motor flows' by S.Balachandar, J.Buckmaster, and M.Short.

This work will be presented at the annual Division of Fluid Dynamics meeting of the American Physics Society, in November.

[7] Following on the work of [6] we have devised a strategy for numerically calculating the flow in rocket chambers with star-shaped grains, 'slot-and-tube' grains, and the like. This uses asymptotics to describe the flows in the slots, a description that provides boundary conditions for the flow in the tube, which has circular cross-section. In short, computations need only be done on a circular cross-section, a dramatic simplification. This work is being done in collaboration with S.Balachandar, a professor in the department of Theoretical and Applied Mechanics at the University of Illinois, and a major figure in CFD (winner of the APS Francois Frenkiel prize in 1996). We expect to make more progress during the next quarter.

[8] In previous years we examined edge flames that arise in non-premixed combustion and are of vital importance in many flame configurations, including turbulent combustion where edges are created when holes are torn in the flame. Most recently we have successfully described, for the first time, edge flames in configurations in which the reactants are supplied as a homogeneous mixture. These novel structures are likely to be of importance in our understanding of turbulent premixed flames. A first paper has recently been published in Combustion and Flame: 'Edge-flames in homogeneous mixtures' by T.G.Vedarajan and J.Buckmaster, Combustion and Flame, 114:267-273 (1998). Its abstract reads:

We examine a premixed flame located in a plane counterflow of fresh cold mixture and hot inert. The temperature of the inert is significantly less than the adiabatic flame temperature, so that the flame response to strain-rate variations is multivalued for a finite interval of strain rates. In this interval there are two stable one-dimensional solutions, one characterized by vigorous combustion, the other by weak combustion. Numerical solutions are constructed that describe an unsteady two-dimensional evolution between the two solutions in the direction normal to the straining-flow plane. Following an initial transient, this evolution consists of a wave of permanent form, traveling at constant speed in the out-of-plane direction. This wave is an edge-flame whose speed is positive or negative, depending on the value of the strain rate. The role of edge-flames in the failure of upward rising methane/air flames in sublimit mixtures in briefly discussed.

Vedarajan was supported as a post-doctoral student for a period of six months.

[9] A second paper on premixed edge flames was completed in November 1997 and submitted for presentation at the 27th International Symposium on Combustion, the world's most prestigious forum for combustion work. It was accepted and presented at the Symposium in August 1998. It will appear in the Proceedings. It is: 'Two-Dimensional Failure Waves and Ignition Fronts in Premixed Combustion', by T. G. Vedarajan, J. Buckmaster, and P. Ronney. Its abstract reads:

This paper is a continuation of our work on edge-flames in premixed combustion. And edge-flame is a two-dimensional structure constructed from a one-dimensional configuration that has two stable solutions (bi-stable equilibrium). Edge-flames can display wave-like behavior, advancing as ignition fronts or retreating as failure waves. Here we consider two one-dimensional configurations: twin deflagrations in a straining flow generated by the counterflow of fresh streams of mixture; and a single deflagration subject to radiation losses. The edge-flames constructed from the first configuration have positive or negative speeds, according to the value of the strain rate. But our numerical solutions strongly suggest that only positive speeds (corresponding to ignition fronts) can exist for the second configuration. We show that this phenomenon can also occur in diffusion flames when the Lewis numbers are small. And we discuss the asymptotics of the one-dimensional twin deflagration configuration, an overlooked problem from the 70s.

[10] Following on the work of [8], [9] we have examined premixed edge-flames for small values of the Lewis number, and a paper was submitted to the journal Combustion Theory and Modeling in August 1998. It is: 'Cellular instabilities, sub-limit structures and edge-flames in premixed counterflows' by J.Buckmaster and M.Short . Its abstract reads:

We examine twin premixed flames in a plane counterflow and uncover, in the parameter space, a hitherto unknown domain of cellular instability. This leads us to hypothesize that when the Lewis number is small, a 2D steady solution branch bifurcates from the 1D solution branch at a neutral stability point located near the strain-induced quenching point. Solutions on this 2D branch are constructed indirectly by solving an initial value problem in the edge-flame context defined by the multiple-valued bistable 1D solution. Three kinds of solution are found: a periodic array of flame-strings; a single isolated flame-string; and a pair of interacting flame-strings. These structures can exist for values of strain greater than the 1D quenching value, corresponding to sublimit solutions.

This work will also be presented at the Eurotherm seminar "Detailed studies of combustion phenomena" to be held in October 1998 in the Netherlands.

Also, along with related work presently underway, it will be reported at the 37th AIAA Aerospace Sciences Meeting, Reno, Nevada, January 1999. It is paper 99-0701, in session MSSP-6, and its title is 'Sublimit Combustion'.

[11] We have been engaged for some years in the study of microgravity combustion, primarily funded by the NASA-Lewis Research Center. The work on near-limit hydrogen combustion done in this context is relevant to the Air Force mission, and this work is reported here:

The paper 'Flame-Ball Drift' by J.Buckmaster and P. Ronney was presented at the Eastern States Section Meeting of the Combustion Institute in October 1997, and an extended abstract published in the Proceedings. It is a preliminary report on work published under the same title, identified below. The short abstract of the paper reads:

Flame-balls are stationary spherical premixed flames that have been observed in near-lean-limit mixtures of small Lewis number under microgravity conditions. They are the subject of the SOFBALL experimental program, with space-flight studies on the STS-83 mission and the re-flight STS-94 mission. During these studies, flame-balls were observed for up to 9 minutes, some 40 times longer than the earlier KC-135 observation periods. In some of the Shuttle tests in which more than 1 ball was present, the balls were seen to drift relative to one another. The displacement was of the order 10cms in 9 minutes. This has motivated a theoretical study to understand in what circumstances drift is possible, and we wish to report a fundamental result. Specifically we have examined, using a simple model amenable to analysis, a single flame-ball located in a weak gradient of fuel and have shown that this necessarily leads to drift.

The paper 'Flame-Ball Drift in the Presence of a Total Diffusive Heat Flux' by J. Buckmaster and P. Ronney was presented at the 27th International Symposium on Combustion in August 1998, and will be published in the Proceedings. A similar presentation was made at the 36th Aerospace Sciences Meeting of the AIAA, 1998, paper AIAA 98-1029. The abstract reads:

For a one-component reaction model, the total diffusive heat flux (TDHF) is the sum of the Newtonian flux and the diffusive flux of the reactant weighted with the heat of reaction. We show that a flame-ball exposed to a weak TDHF will drift, and we derive an explicit formula for the drift speed. The key mathematical feature is that the flux generates a flame-temperature perturbation that varies as the cosine of the polar angle measured from the axis parallel to the flux vector, and this is uacceptable as it leads to a simple boundary-value problem for a harmonic function (a temperature perturbation) that has no solution. Drift generates a like perturbation and the drift speed must be chosen so that the two cancel. If the TDHF is generated by a second flame-ball whose far-temperature field is suppressed by radiation, so that only the reactant flux contributes, the balls will drift apart with a separation distance that grows as the 1/3 power of time. Observations made during recent Space-shuttle flights are presented, and are consistent with this prediction. We also formulate the problem of drift in a weak gravitational field, and solve it in an approximate fashion.

Other activity

I have a minor role as a consultant to a BMDO/ONR MURI on rocket motors, centered in the Department of Mechanical Engineering at the University of Illinois. That part of my work on propellant flames that is relevant to the program is reported to the 'masters' of the program.

I am a participant in a DOE ASCI center, also on rocket motors, centered in the Computer Science and Engineering program of the University of Illinois, where my role is to provide guidance in the context of propellant flame physics and chemistry. My collaborative work with T.L.Jackson, a senior research scientist in the center, comes about because of this. This work is reported to the 'masters' of the program .

Personnel

Faculty: John Buckmaster, PI.
Post-doctoral students: Jin Yao followed by T.G.Vedarajan. A replacement for Vedarajan will join my program in January 1999.

Honors.

Senior U.S. Scientist Award (Humboldt Prize), 1985, 1986
Buckmaster, J.
Alexander von Humboldt Foundation, Germany

JSPS Fellow, 1986
Buckmaster, J.
Japan Society for the Promotion of Science, Japan

Fellow, American Physical Society, 1986
Buckmaster, J.
American Physical Society, USA

Guggenheim Fellowship, 1990
Buckmaster, J.
Guggenheim Foundation, USA