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STRAIN-RATE-FREE DIFFUSION FLAMES: INITIATION, PROPERTIES, AND QUENCHING*

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Introduction

For about a half century, the stabilization of a steady *planar* deflagration on a heat-sink-type flat-flame burner has been of extraordinary service for the theoretical modeling and diagnostic probing of combustions gaseous mixtures (ref. 1). However, most engineering devices and most unwanted fire involve the burning of initially unmixed reactants. The most vigorous burning of initially separated gaseous fuel and oxidizer is the diffusion flame. In this useful idealization (limiting case), the reactants are converted to product at a mathematically thin interface, so no interpenetration of fuel and oxidizer occurs. This limit is of practical importance because it often characterizes the condition of optimal performance (and sometimes environmentally objectionable operation) of a combustor. A steady *planar* diffusion flame is most closely approached in the laboratory in the counterflow apparatus (ref. 2). The utility of this simple-strain-rate flow for the modeling and probing of diffusion flames was noted by Pandya and Weinberg 35 years ago (ref. 3), though only in the last decade or so has its use become internationally commonplace. However, typically, as the strain rate a is reduced below about 20 cm^{-1} , and the diffusion-flame limit (reaction rate *much* faster than the flow rate) is approached, the burning is observed to become unstable in earth gravity. The advantageous steady planar flow is not available in the diffusion-flame limit in earth gravity. This is unfortunate because the typical spatial scale in a counterflow is $(\kappa/a)^{1/2}$, where κ denotes a characteristic diffusion coefficient; thus, the length scale becomes large, and the reacting flow is particularly amenable to diagnostic probing, as the diffusion-flame limit is approached. The disruption of *planar* symmetry is owing the fact that, as the strain rate a decreases, the residence time $(1/a)$ of the throughput in the counterflow burner increases. Observationally, when the residence time exceeds about 50 msec, the inevitably present convective (Rayleigh-Benard) instabilities, associated with hot-under-cold (flame-under-fresh-reactant) stratification of fluid in a gravitational field (refs. 4 and 5), have time to grow to finite amplitude during transit of the burner.

Can we, with access to microgravity testing, more closely achieve the vigorous, strain-rate-free diffusion-flame limit in the burning of initially separated gaseous fuel and oxidizer? In microgravity, it is not convenient to try to "turn down" a counterflow. Rather, we decide to start with static gaseous fuel occupying one half-volume, and static gaseous oxidizer the other half-volume, of an impervious noncatalytic isothermal squat rectangular-solid container, with height significantly smaller than the length of a side of the horizontal square cross section (Fig. 1a). Typically, the chamber is 25 cm x 25 cm x 9 cm, with 1.25-3.27-cm-thick stainless-steel walls. The oxidizer is separated from the fuel by a thin (but rigid) impervious planar interface. For specificity, we take the upper half-volume to be filled uniformly with oxygen diluted with helium, and the lower half-volume to be filled uniformly with hydrogen diluted with argon, such that the two half-volumes have equal pressure, temperature, density, and (hence) "average molecular weight". At time zero, with minimal disturbance and with minimal elapse of time, we seek: (1) to remove the separator, by translation at nearly uniform speed in its own plane, through a tightly fitting slit in one side wall (Fig. 1b), and (2) to create a diffusion flame at the *planar* interface between the nonhypergolic (not spontaneously reactive) constituents of the two half-volumes (Fig. 1c). Demonstration, in a ground-based microgravity testing facility, of an experimental design for achieving a planar diffusion flame at the centerplane of the container is the primary near-term goal of this project. Straightforward analysis (refs. 6-9) of a moving-boundary problem (ref. 10) indicates that, in microgravity, the flame thenceforth travels so that it is situated at an interface at which the hydrogen and oxygen meet in stoichiometric proportion. If

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(as we intend) the initial amount of hydrogen is deficient relative to the initial amount of oxygen, then eventually (if not immediately) the planar flame travels further and further into the half-volume initially containing hydrogen (Fig. 1d), until the hydrogen is (virtually) fully depleted. Of course, when the amount of residual hydrogen becomes small, and/or the diffusion flame approaches the cold end wall, the situation is inconsistent with a vigorous, thin diffusion flame. The burning is extinguished before the hydrogen is fully depleted, owing to the finite rate of the actual chemical-kinetic mechanism. However, there is an interval during which the travel of a virtually strain-rate-free, planar diffusion flame may be tracked; within the container in microgravity, we expect to achieve what is inaccessible in earth gravity, the only compromise being the introduction of time, as well as a Cartesian coordinate, as an independent variable (ref. 11). The rate of travel of the hydrogen-air diffusion flame is much slower than the rate of laminar flame propagation through a hydrogen-air mixture. This relatively slow travel facilitates diagnostic detection of the flame position as a function of time, but the slow travel also means that the time to burnout (extinction) probably exceeds the testing time (typically, a few seconds) available in earth-sited facilities for microgravity-environment conditions.

We have undertaken analyses (ref. 7) to predict: (1) the position and temperature of the diffusion flame as a function of time; (2) the time at which extinction of the diffusion flame occurs; and (3) the thickness of quench layers formed on side walls (i.e., on lateral boundaries, with normal vectors parallel to the diffusion-flame plane), and whether, prior to extinction, water vapor formed by burning condenses on these cold walls. We regard our (*generalized* Shvab-Zeldovich/Burke-Schumann) model as semi-empirical. We hope that empirical assignment of optimal values for dimensionless groups arising in simplistic statements of the transport and kinetic processes will permit us to fit some of the microgravity data (explicitly, the position and temperature at the thin flame in some of the experiments). We further hope that the guidance from that experience will permit us to assign values to these dimensionless groups to predict the corresponding observations in the remainder of the experiments. If so, the viability of the modeling to quantify, to a practically useful accuracy, key properties in a difficult-to-analyze diffusion flame, *with appreciably differing diffusivities*, will have been demonstrated.

Initiation of the Diffusion Flame

The design for the initiation of the diffusion flame between initially separated, not-spontaneously-reactive fuel vapor and oxidizer in microgravity has features in common with the evolution of burning of a stratified gaseous mixture in a gallery of a coal mine in earth gravity (refs. 12-14). For the ensuing description, we envision vertical end planes for the gallery. In such a gallery, the relatively light gas methane is concentrated near the ceiling of the gallery, and the relatively heavy air near the floor; mixture with combustible composition lies between an upper (horizontal) plane at the fuel-rich flammability limit, and a lower (horizontal) plane at the fuel-lean flammability limit. After ignition along a line near one end wall, the line ignitor being parallel to the floor and to the nearby end wall, a two-dimensional deflagration propagates, within the combustible mixture, from the nearby end wall toward the opposite end wall. In fact, the propagation speed is more rapid for near-stoichiometric strata than for strata with mixture near a limiting composition for combustion; thus, the horizontally propagating deflagration has a curved configuration, with the leading "nose" of the deflagration lying in a plane (the "centerplane") parallel to the floor, at a height roughly midway between the fuel-rich-limit plane and the fuel-lean-limit plane; the retarded end points of the propagating "deflagration arc" lie in the fuel-rich-limit and fuel-lean-limit planes. Behind the deflagration but above the centerplane, excess fuel vapor (but virtually no residual oxidizer) persists, there being less and less excess fuel vapor as the centerplane is approached from above. Behind the deflagration but below the centerplane, excess oxidizer (but virtually no residual fuel) persists, there being less and less excess oxidizer as the centerplane is approached from below. At the centerplane, where no excess fuel vapor or oxidizer persists, and where the temperature is approximately the highest of any strata, a planar (horizontal) diffusion flame persists; the residual fuel vapor and oxidizer diffuse toward this planar flame to continue the burning. The horizontal-anchor-resembling configuration formed by the curved deflagration and the planar diffusion flame is a "three-branched flame". However, the diffusion flame does not remain planar at much distance behind the propagating deflagration, owing to the previously discussed Rayleigh-Benard instability in earth gravity.

In microgravity, no stratification arises within the H_2/Ar and O_2/He contents of the half-volumes of our container. Prolonged interpenetration of the contents of the two half-volumes would result in a homogeneous mixture (in our case, fuel-lean). However, (Fig. 1b) a significant H_2/Ar and O_2/He stratification persists for a limited time after separator removal; ignition along a line in the centerplane, near to and parallel to one side wall, would result in the just-described "three-branch flame". Moreover, in microgravity, for not too tall a chamber, no Rayleigh-Benard instability would arise to disrupt the planarity of the diffusion flame engendered at the centerplane. We set off the line ignitor as soon as diffusive interpenetration of the fuel vapor and oxidizer gives a combustible layer sufficiently thick to sustain flame propagation.

One feature of the chamber in microgravity with no counterpart in the coal-mine gallery on earth is the translation of the flat separator, at moderate speed (~ 125 cm/s) in its own plane until its trailing edge clears the side wall. The moving separator entrains a laminar flow by viscous forces, both in boundary layers formed on the separator, along the portion of its top and bottom surfaces still within the chamber, and in the wake of its trailing edge (Fig. 2) (ref. 15). The flow in the narrow boundary layers and wake does induce a broad weak recirculatory "cell" in each half-volume; this organized motion could augment the

otherwise almost purely diffusional transport of fresh reactant toward the planar flame, but the organized (counterflow-like) flow decays under viscous diffusion in about a quarter second. Planar Fickian diffusion remains the mode of reactant transport throughout the overwhelming preponderance of the test duration. However, if, during the brief interval for which the flow in the wake of the trailing edge of the translating separator exists, the premixed flame is able to propagate into the wake, then the deflagration advances across the centerplane at a speed that is the sum of the wake-flow speed and the propagation speed. In such a case, the diffusion flame is entirely in place (i.e., fills the entire square centerplane of the container -- except in the immediate vicinity of the cold side walls) almost as fast as the trailing edge of the separator exits the chamber.

Separator Withdrawal and Flame Spread across the Centerplane

If a thin flat plate in the plane $z = 0$ is abruptly set in motion, at time $t = 0$, at constant speed u_o in the x direction, then there is associated motion of a viscous incompressible fluid in the half space $z > 0$ above the plate and in the half space $z < 0$ below the plate, with the velocity profile expressible in terms of the selfsimilar independent variable $[z^2/(vt)]$, where v denotes the (constant) kinematic viscosity of the gas. The trailing edge of the flat plate is taken to lie at $x = u_o t$. Behind the plate ($x < u_o t$), there is no longer any skin friction, but, in the approximation adopted here, fluid in the region behind the trailing edge is instantaneously set in motion by the movement of the plate. In the domain $x < u_o t$, if u denotes the velocity in the x direction and w in the z direction, then in the boundary-layer approximation for the Eulerian formulation of the conservation of momentum in the x direction,

$$u_t + u u_x + w u_z = v u_{zz}. \quad (1)$$

In the "modified-Oseen" approximation, in which the nonlinear convective-transport term is linearized for tractability,

$$u_t + \frac{u_o}{3} u_x - v u_{zz} \approx 0, \quad (2)$$

where the choice of the appropriate "average coefficient" as $(u_o/3)$ is anticipated to be a good approximation on the basis of past experience. Henceforth, we adopt the notation $a \equiv u_o/3$. A solution to Eq. 2 that joins, to satisfactory approximation, to the solution holding for $x > u_o t$ is given by

$$u(x, z, t) = \begin{cases} \frac{2}{\pi} u_o \left(\frac{x - a t}{2 a t} \right)^{1/2} \exp[-z^2/(4 v t)], & a t < x < 3 a t \\ 0, & 0 < x < a t. \end{cases} \quad (3)$$

Thus, when the plate has moved a distance $u_o t$, the length of the disturbed region behind the plate is $(2/3) u_o t$; the precise, finite length of the disturbed region is a consequence of the adoption of the Oseen approximation.

The net delivery of fluid at the "far" side wall $x = 2W$ (i.e., the volume delivered, per unit depth in the y direction, for a standard Cartesian coordinate system) is equal to $4[v(2W)^3/u_o]^{1/2}/\pi^{1/2}$. Since the net delivery of fluid at $x = 2W$ varies as $u_o^{-1/2}$, the delivery is minimized by increasing the speed of separator withdrawal, u_o . However, the velocity profile is Gaussian in the transverse coordinate z , and the flow is subject to the growth of instabilities. Transition to turbulence may occur if the Reynolds number becomes sufficiently large (i.e., if the speed u_o becomes sufficiently large) (ref. 15). For $u_o = 125$ cm/s, $2W = 25$ cm, and $v = 0.1$ cm²/s, the delivery is 10-12 cm², with the duration of the interval of delivery, $t_f[= 3(2W)/u_o] \approx 0.6$ s; the peak delivery rate is $2[v(2W)u_o/\pi]^{1/2} \approx 20$ cm²/s. The peak return-flow speed is 20 cm²/s divided by the height of the return-flow domain, i.e., the half-height of the container L . If $L = 4.5$ cm, then the transversely averaged peak return speed is on the order of 4-5 cm/s. If the delivery is 10-12 cm², and the height over which this delivery is distributed in a return flow is 4.5 cm, then the fluid displacement by the piston-like return flow is 2-3 cm.

At least part of the fluid entrained during withdrawal of the separator may form counterrotating corner vortices, one above the midplane in the vicinity of the side wall at $x = 2W$ and a comparable one below the midplane in the vicinity of the side wall.

We estimate that the vortices might be turbulent, with radius R at the time of separator withdrawal $t_1 (= 2W/u_o)$ of 1.25 cm (ref. 16). The inviscid interaction of the two vortices with one another and with the side wall at $x = 2W$ is such that each vortex would move toward the side wall and toward the end wall of its half-volume. The entrained fluid not entering the vortex seems likely to support the translation of each vortex toward the end wall in its half-volume, but to transport the vortex away from $x = 2W$ and into the interior of the half-volume. If each vortex at its periphery interacted strongly with a nonrotating wall, the e -folding time for viscous decay would be $R^2/(\pi^2\nu)$, or about 1.7 s for adopted parameter values. In the absence of such a peripheral constraint, the vortex could persist longer. We conjecture that the vortex continues to grow for a brief time beyond t_1 , owing to the flow entrained in the wake of the trailing edge; if so, then the vortex radius increases from $R \approx L/4$ to $R \approx L/2$, interaction with the fixed container walls increases, and the vortex decays on the order of 3.2 s.

At time $t_o(>0)$, line ignition occurs at $x = X_o(\geq 0)$ in the centerplane $z = 0$, where the length of the square cross section $2W \gg X_o$. Specifically, ten electrode pairs, located on the line $(x = X_o, z = 0)$ and approximately evenly distributed over the distance $2W > y > 0$, are simultaneously sparked at time $t = t_o$. We here track the flame position $X_f(z, t)$, only in the centerplane $z = 0$, and henceforth denote $X_f(0, t)$ as $X_f(t)$, for brevity of notation. If we adopt a fixed value v_f for the laminar flame propagation speed through the combustible mixture formed by diffusional interpenetration aft of the trailing edge of the translating splitter plate, then, in view of the flow field just examined,

$$\dot{X}_f(t) = \begin{cases} v_f + \frac{2}{\pi} u_o \left(\frac{X_f(t) - a t}{2 a t} \right)^{1/2}, & a t \leq X_f(t) < 3 a (t - t^*) \\ v_f, & X_o \leq X_f(t) < a t, \end{cases} \quad (4)$$

where $X_f(t_o) = X_o$. Ignition occurs at $t_o(>0)$ because it takes a finite time t^* for a combustible mixture to form at position x , once the splitter plate clears position x . Thus, the time t_{spread} , defined by $X_f(t_{spread}) = 2W$, is a function of the given positive parameters X_o, t_o, v_f, t^*, u_o , and $2W$. By inspection, for rapid flamespread, we seek to initiate the flame in the wake, or, if the flame is initiated behind the wake, we seek to have the flame catch up to the wake, so that convection enhances propagation for the spread of the flame across the centerplane. We have not included expansion of burned gas in the x direction as an aid to flamespread, because, from geometric considerations, the burned gas expands primarily in the z direction, and because a conservative (upper-bound) estimate on t_{spread} is sought.

To ensure the one-dimensionality of the subsequent travel of the resulting diffusion flame, we seek as rapid a propagation across the centerplane as is consistent with physical constraints (e.g., avoiding transition to turbulence in the flow induced by separator withdrawal), and with experimental procedure (e.g., limitations of pull mechanisms for separator withdrawal, in view of the size, weight, reliability, and cost constraints for microgravity testing). Otherwise, events in portions of the centerplane from which the separator is withdrawn earlier get a headstart on events in portions of the centerplane from which the separator is withdrawn later -- an anomaly for a test with purportedly planar symmetry.

Test Rigs

Three apparati have been designed, constructed, instrumented, and used for ground-based testing in earth gravity.

First, an ignition rig, of virtually the same geometric configuration as the above-described chamber (25 cm x 25 cm x 11 cm), has been used to determine the margin against detonation. The chamber dimensions exceed the critical cell size for hydrogen-oxygen detonation; this observation raises concern if a seal or other failure inadvertently allowed the fuel and oxidizer to mix prior to ignition. Thus, testing was undertaken to determine: (1) the maximum pressure to be expected in the apparatus; and (2) the minimum voltage required by the ignitor box to initiate burning of the mixed gaseous reactants -- information needed to design the power supply for the ignitor box. Testing included trials with ten stainless-steel electrode pairs, each of 0.46-mm gap, evenly spaced over a 19-cm span. Accordingly, intended combinations of hydrogen/argon and oxygen/helium, to be carefully initially segregated in the experiment, were intentionally mixed homogeneously prior to sparking in the test rig; the equivalence ratio ϕ extended from 0.15 to 1.0; the initial pressures tested were both atmospheric and subatmospheric. Two of three 13.5-MPa acoustic transducers, all specially potted against heat, were mounted in opposite corners of a square cross-section, the third being located at the center of one of the 25 x 25 cm walls. Three distinct pressure-vs.-time profiles were recorded during the series of tests. One was the smooth rapid pressure rise and fall that is characteristic of deflagration. The second was a smooth pressure rise, followed by the onset of a short period of high frequency fluctuations (similar to pressure oscillations indicative of

end-gas knock in cylinders of spark-ignition engines) at the start of pressure tail-off. The third was a smooth pressure rise for a short period, followed by a pressure spike and brief fluctuations. The corner-mounted probes often recorded the last two phenomena, while the side-wall-centered probe recorded only the first two. Some of the pressure spikes observed were sufficient to cause failure of the corner-mounted transducers, which were rated not to fail mechanically below a static pressure of 6.8 MPa. No pressure spikes or "knock" occurred for $\phi \leq 0.4$ with the ten-gap multispark ignitor, although an alternative two-spark ignitor did give a pressure spike at $\phi = 0.4$; use of the multispark ignitor significantly reduced the propensity to spike or "knock". Typical pressure rise was about four-fifths of the theoretical adiabatic pressure rise, the difference being attributable to heat loss to the walls. An input of 75 V to the ignitor box ensured ignition (of the tested mixtures) by the multispark ignitor.

Second, a pull rig (with dimensions similar to those of the planar-flame chamber) has been constructed to determine the force required to achieve splitter-plate (separator) withdrawal at a fairly uniform speed of about 125 cm/sec. The top periphery of the portion of the splitter plate in the test chamber is in contact with an O-ring; the bottom periphery is in contact with an inflatable seal, maintained at partial inflation during withdrawal to minimize leakage of contents from the chamber. Silicon-based vacuum grease, used as a chemically inert solid lubricant for the seal-separator interface, permitted more repeatable and more uniform speed (of the separator during withdrawal) than did the alternative lubricants graphite and molybdenum disulfide. Measurement of the seal leakage has not been completed.

Third, flat flames of H_2/air , H_2/O_2 , CH_4/O_2 , and other mixtures are stabilized on a water-cooled sintered-porous-disc burner to calibrate the "readings" of relatively inexpensive infrared cameras, to be used for nonintrusive temperature measurements in the experiments. The ratio of the emission intensity on the 1.45- μm and 1.94- μm lines, effectively unique to the product gas H_2O , is to be used to infer the temperature; the particular ratio indicative of a specific temperature is established by recording the ratio for each of four specific temperatures, known by a proprietary technique and well distributed over the range of 2000 K-2800 K.

Plans

A combined test chamber and auxiliary chamber (for receipt and storage of the withdrawn rigid separator) have been machined, and 2.5-cm-thick fused-quartz windows for the optical access of diagnostic instrumentation are to be installed, along with the ignition subsystem and separator-withdrawal subsystem. Space allocation on a drop rig for testing the diffusion-flame-initiation design in the 5-seconds-microgravity facility is under way. Near-term testing is limited to hydrogen-fueled diffusion flames.

However, the long residence time accessible in a strain-rate-free diffusion flame makes the apparatus highly suitable for experiments for collecting sooting-rate data over a range of pressure, for hydrocarbon-vapor-fueled burning.

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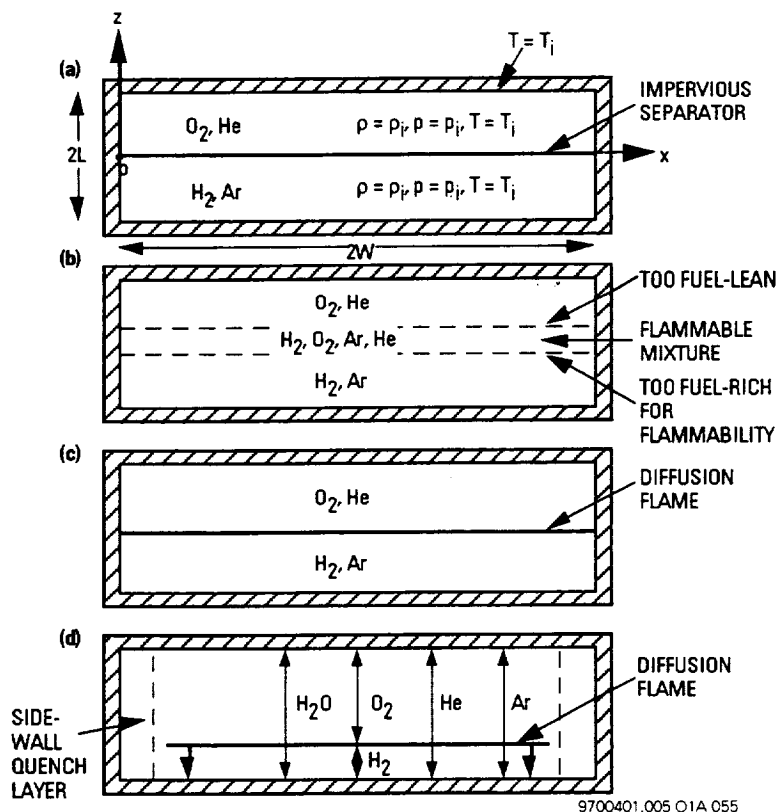


Figure 1.—A planar translating diffusion flame.

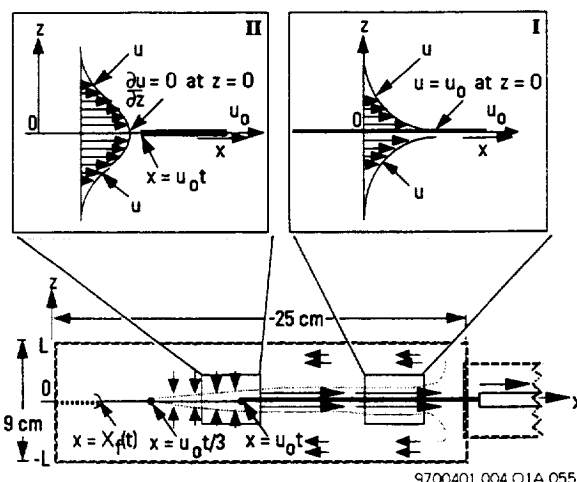


Figure 2.—Triple flame behind a moving splitter plate.