2004

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Recommended Citation

Foster, Michael R., "The Cool Flames Experiment: Recent Results at Reduced and Partial Gravity" (2004).
Faculty Publications - Biomedical, Mechanical, and Civil Engineering. 30.
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THE COOL FLAMES EXPERIMENT: RECENT RESULTS AT REDUCED AND PARTIAL GRAVITY

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ABSTRACT

Cool flames at Earth (1g), Martian (0.38g), Lunar (0.18g) and reduced-gravity (10^{-2} g) have been studied experimentally in a closed, unstirred, static reactor to better understand the role of natural convection and diffusive transport on the induction period(s), flame shape, flame propagation speed, pressure history and temperature profile. Natural convection is known to play an important role in all terrestrial, unstirred, static reactor cool flame and auto-ignition experiments when the Rayleigh number, $Ra = \beta g \Delta T R^3 / \nu \alpha$, exceeds 600 [2,3,6]. At 1g, typical values of the Ra are 10^4 - 10^6 .

In this paper, experimental results from static, unstirred reactor studies conducted at four different gravitational acceleration levels are reported for an equimolar propane-oxygen premixture. At 1g, the effects of natural convection dominate diffusive transport, the cool flame starts near the top of the vessel and subsequently propagates downward through the vessel. The flame is inherently two-dimensional. As the effective gravitational acceleration decreases, the associated Ra decreases linearly, convective transport weakens relative to diffusive fluxes of heat and species. At reduced-gravity, cool flames are observed to propagate radially outward from a centrally-located kernel without distortion owed to convective flow at a velocity that depends on the flame radius.

HARDWARE DESCRIPTION AND OPERATION

The static, unstirred reactor and support apparatus are described in detail in reference 5. The essential hardware components include a furnace (0-600°C), a fused-silica spherical vessel (i.d.=10.2 cm) and a premixed gas mixing and delivery system. The temperature uniformity within the furnace is $\pm 10^\circ\text{C}$. The pressure in the reaction vessel is recorded with a Setra Model 204 0-25 psia transducer (accuracy: ± 1.4 Torr) mounted on the gas inlet to the reactor. The radial gas temperature profile is measured at 5 discrete radial locations, using a horizontally-mounted, type-K thermocouple rake in the vessel. A Hamamatsu C5909 ICCD camera operating at maximum gain records the emitted light through an optical port on the side of the

furnace and a Xybion intensified camera mounted on the top of the furnace records an orthogonal view.

EXPERIMENTAL RESULTS

The slow heat release that occurs during the initial induction period is expected to induce a slow toroidal convective flow in the closed vessel for $Ra > 600$ (1g, 0.38g, and 0.18g cases) as the hot, less dense gas rises in the bulk and recirculates downward along the internal vessel wall as it cools [3,6]. The rise speed of the hot gas is expected to scale as $\sqrt{g}$ [5] and thus decrease as the effective gravitational acceleration (g) decreases. Relative to the 1g case, the manifestation of the slower convective flows at 0.38g and 0.18g on the flame shape and propagation is observed indirectly through the observed modifications in the flame shape and its evolution (see Fig. 1). To date, however, this toroidal flow field has not been quantified experimentally.

Fig.1: Intensified cool flame images in an equimolar $n\text{-C}_4\text{H}_{10}:\text{O}_2$ premixture, $T_{\text{wall}}=300^\circ\text{C}$, $P_{\text{initial}}=3.0$ psia in a 10.2cm i.d. vessel at (a) 1g, (b) 0.38g, (c) 0.18g, (d) $\sim 5 \times 10^{-2}$ g (reduced-gravity). Images taken at different instants. Fig.1d has a slight asymmetry on the left-side, presumably due to the existence of the thermocouple rake.

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Flame Shape

Figure 1 shows still images of a cool flame in an equimolar n-butane:oxygen premixture each taken from a different test at a different g -level, i.e., (a) 1g, (b) 0.38g, (c) 0.18g, (d) $5 \times 10^{-2}g$, respectively, under otherwise identical conditions.

At 1g, the cool flame starts near the top of the vessel and propagates downward. At approximately midway into the vessel, the flame is noticeably curved downward near the walls and upward in the middle. At 0.38g, the flame also starts near the top, yet no inflexion is apparent (Fig.1b). Note that at 0.38g, the convective flow is expected to be 60% slower than the 1g case based simply on the $g^{1/2}$ scaling, not considering the differences in convective heat transfer. As g decreases to 0.18g (Fig.1c), the flame front also starts near the top and propagates downward and has a larger flame curvature. At reduced-gravity ($\sim 5 \times 10^{-2}g$), the flame initiates near the center and propagates spherically outward.

Skeletal 5-Step Gray-Yang Model

A one-dimensional modified five-step, skeletal Gray-Yang model that includes diffusion of species and heat [1,7,8] has been extended to two-dimensions to include the effects of natural convection. The boundary conditions are constant wall temperature, inert boundary conditions, and no slip at the wall. The initial conditions are spatially uniform gas temperature everywhere equal to the fixed wall temperature and no initial gas velocity. Representative temperature contours at a specific instant in time are shown in Fig.2. Model details will be reported under separate cover. Qualitatively, the temperature contours are reminiscent of the spectral emission from excited formaldehyde.

Observed Cool Flame Spatio-temporal Propagation at Reduced-Gravity

Cool flame propagation speeds at reduced-gravity are experimentally investigated for a fixed temperature at different initial pressures. Preliminary results suggest a weak pressure dependence on the observed flame speed. Figure 3a shows representative plots of flame diameter (based on a prescribed threshold grayscale intensity value) normalized by the vessel diameter as a function of time for different initial vessel pressures at a fixed vessel wall temperature. In all reduced-gravity tests, the flames are observed to propagate radially outward from a centrally located kernel. As the flames approach the vessel wall, the spectral intensity (8-bit resolution) in the vessel appears to recede radially inward and as such, the reported flame diameter decreases. Figure 3c shows the variation in spectral intensity along the vertical diameter of the reactor for a multi-stage ignition at 320°C and 9.7 psia. The abscissa

ranges from zero (bottom of flask) to 10cm (top of flask). Notice that the intensity increases, then decreases, then increases again as a function of time. The initial increase and decrease are representative of nearly all cool flames observed at microgravity. The later increase in intensity is representative of the intensity increase preceding the hot ignition phase of a multi-stage ignition.

Fig.2: Temperature contours predicted using modified Gray-Yang skeletal kinetic model at different instants in time (axisymmetric model shows half sphere); Temperature scale in K.

Using the data from Fig. 3a, flame propagation speeds are calculated and reported in Fig.3b. In all cases (except for the highest pressure case tested, 4.62 psia), the flame speed is highest at early times and decreases as a function of time. For intermediate radii the flames have an observed speed of ~ 12 cm/s. Future experiments will explore the role of diffusive-thermal effects (Lewis number variation), wall (initial gas) temperature, initial gas pressure, and surface chemistry (catalytic surfaces).

Fig.3: (a) Normalized flame diameter and (b) dimensional flame propagation speed for cool flames in an equimolar $n\text{-C}_4\text{H}_{10}:\text{O}_2$ premixture for $T_{\text{wall}}=300^\circ\text{C}$ at reduced-gravity; (c) representative intensity profiles associated with a two-stage ignition (cool flame followed by hot ignition).

Ignition Diagram for a Propane: Oxygen System

Buoyant convection affects the mode of reaction that occurs at an initial pressure and temperature and therefore alters the ignition diagram. Figure 4 shows the ignition diagrams for an equimolar propane:oxygen premixture at (a) 1g and (b) reduced-gravity. In the

caption, “sr” denotes a slow reaction mode characterized by a slow pressure and temperature rise without measurable light emission. The “1cf,” “2cf,” “3cf,” “4cf,” “5+cf” modes refer to single and multiple cool flame modes where the number designates the total number of sequential cool flames observed in the closed system. The “2si” and “ssi” modes denote two-stage ignition and single-stage ignition events, respectively. When comparing the diagrams, note that the reduced-gravity data reflects the mode of reaction observed within 20s, i.e., the available test time on NASA’s KC135 aircraft. The 1g data is not subject to this time constraint and the tests are run until the final pressure and equilibrates and the temperature approaches the surface (wall) temperature. These times often range from minutes to tens of minutes.

Fig.4: Ignition diagram for an equimolar $\text{C}_3\text{H}_8:\text{O}_2$ premixture at (a) 1g and (b) reduced-gravity.

At 1g, as many as five cool flames are observed, while at reduced-gravity, a maximum of two is observed within the available 20 sec test time. Highlighting a few differences: at 320°C, 2si is observed at 1g and 11.6 psia whereas a ssi at reduced-gravity is observed at 320°C and 11.4 psia. Also, at 350°C, the transition between cool flames and 2si occurs between 5.8 and 7.7 psia at 1g, while at reduced-gravity it occurs between 8.8 and 9.3 psia. Further refinement of the ignition diagrams and detailed kinetic modeling including diffusive fluxes of heat and species is ongoing.

CONCLUSIONS

The structure and oscillatory behavior of cool flames are strongly affected by natural convection at Earth and partial-gravity. As a result, the temperature and species concentration profiles are strongly modified. Ignition diagrams are different and flame stability as well as shape are affected by the convective flows. Efforts to resolve the fine-scale stability boundaries of the ignition diagram are in-progress. These results will then be compared to detailed chemical kinetic models that include diffusive transport. Future work will also explore initial mixture compositional dependencies and non-inert surfaces (catalytic surfaces).

ACKNOWLEDGEMENTS

HP wishes to acknowledge the technical support and useful discussions with Professor John Griffiths at University of Leeds. Thanks are also extended to Mr. Rich Chapek for help conducting the microgravity experiments. This work is supported by NASA under grant NCC3-1008.

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