GRAVITY EFFECTS OBSERVED IN PARTIALLY PREMIXED FLAMES

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INTRODUCTION

Partially premixed flames (PPFs) contain a rich premixed fuel–air mixture in a pocket or stream, and, for complete combustion to occur, they require the transport of oxidizer from an appropriately oxidizer–rich (or fuel–lean) mixture that is present in another pocket or stream. Partial oxidation reactions occur in fuel–rich portions of the mixture and any remaining unburned fuel and/or intermediate species are consumed in the oxidizer–rich portions. Partial premixing, therefore, represents that condition when the equivalence ratio (φ) in one portion of the flowfield is greater than unity, and in another section its value is less than unity. In general, for combustion to occur efficiently, the global equivalence ratio is in the range fuel–lean to stoichiometric. These flames can be established by design by placing a fuel-rich mixture in contact with a fuel-lean mixture, but they also occur otherwise in many practical systems, which include nonpremixed lifted flames, turbulent nonpremixed combustion, spray flames, and unwanted fires. Other practical applications of PPFs are reported elsewhere [1, 2].

Partially premixed flames contain multiple reaction zones [3, 4, 5, 6] that have either a premixed-like structure or a transport-limited nonpremixed flame characteristics in which mixing and entrainment effects are significant. A rich premixed reaction zone is established on the fuel rich side, a lean premixed zone on the fuel lean side, with a nonpremixed zone in between these two in the case of triple flames. Double flames are established when a fuel rich mixture burns in air and have two reaction zones, rich premixed and nonpremixed.

Heat release from a flame causes flow dilatation and accelerates the gas across the flamefront. In normal gravity, free convection accelerates the heated gas due to buoyancy, which leads to air entrainment into the flame it its ambient is air rich. For low Froude numbers ($Fr=\upsilon/(gl)^{1/2}$, where υ denotes the fuel stream velocity, l the characteristic length scale and g the gravitational acceleration) flames, gravity effects on a flame can dominate the effects of other physical phenomena, e.g., radiative heat transfer and diffusive transport.

Although extensive experimental studies have been conducted on premixed and nonpremixed flames under microgravity [7, 8], there is a absence of previous experimental work on burner stabilized PPFs in this regard. Previous numerical studies by our group [9, 10] employing a detailed numerical model [11, 12, 13] showed gravity effects to be significant on the PPF structure. We report on the results of microgravity experiments conducted on two-dimensional (established on a Wolfhard-Parker slot burner) and axisymmetric flames (on a coannular burner) that were investigated in a self-contained multipurpose rig [9,14,15]. Thermocouple and radiometer data were also used to characterize the thermal transport in the flame.

RESULTS

Direct imaging techniques were used to characterize the reaction zone topology. The heat
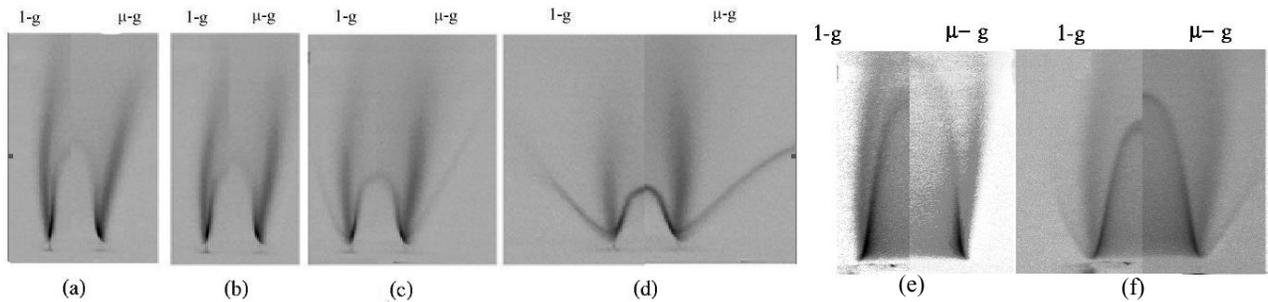
Figure 1: Direct images of the double ((a), (b) and (e)) and triple ((c) and (f))flames at 1-g and μ-g on the slot burner ((a)—(d)) and coannular burner ((e) and (f)). Conditions: (a) ϕ_{in} = 2.38, ϕ_{out} = 0, V_{in} = 21.2 cm/s, V_{out} = 32.3 cm/s; (b) ϕ_{in} = 1.68, ϕ_{out} = 0, (c) ϕ_{in} = 1.68, ϕ_{out} = 0.36;and (d) ϕ_{in} = 1.68, ϕ_{out} = 0.5; for (b), (c) and (d), V_{in} = 15.9 cm/s, V_{out} = 25.8 cm/s, (e) ϕ_{in} = 1.8, ϕ_{out} = 0, (f) ϕ_{in} = 1.8, ϕ_{out} = 0.36; for (e), and (f), V_{in} = V_{out} = 30 cm/s.

release regions of the flames were characterized with the color band associated with C_2^* chemilluminescense that was digitally isolated [14]. These images allowed us to observe the multiple reaction zones. Figure 1 presents images of double and triple flames established on both a slot burner (Figure 1 (a) – (d)) and a coannular burner (Figure 1 (e),(f)) at 1-g (left) and μ-g (right) conditions. All of these burner-stabilized microgravity flames were observed to reach a visually steady structure within 200ms of rig release from 1-g.

Figure 1(a) and (b) depict double flames with nearly identical momentum ratios between the inner and outer flows. In both cases, the outer nonpremixed reaction zone weakens towards the tip, moves outward significantly, and widens slightly in μ-g. The inner premixed reaction zone is similarly influenced by the gravity change, although to a smaller extent. The spreading and weakening of the outer reaction zones in μ-g is a result of the lower oxidizer entrainment [9, 10]. The outer nonpremixed flame depends more on advective oxidizer entrainment for larger values of φ_{in}. This advection is largely dependent on buoyancy, and, therefore, the effect of microgravity on the outer nonpremixed flame increases with increasing values of φ_{in}. This observation has been corroborated through other investigations [9, 16]. The flames established on a coannular burner, are shown in Figure 1 (d). These behave similarly to those established on a slot burner. The global effects of gravity are similar, although there are some specific configuration-dependent effects (e.g. the inner premixed flame of the axisymmetric burner elongates more in μ-g than the one of the slot burner). Figure 1 (b),(c), and (e),(f) present flame images for which the value of φ_{in} is maintained constant and that of φ_{out} is increased. The addition of the third reaction zone, and the increase in φ_{out} were observed to reduce gravity related effects on the two inner reaction zones.

Thermocouple measurements were taken at 50Hz and corrected for radiation losses. The processed data for a characteristic flame is presented in Figure 2. It presents the temperature at a specific spatial location for a double flame as it transitions from 1-g to μ-g. The high temperature region lies in the nonpremixed reaction zone, which slightly differs from previous numerical simulations [9, 10]. These differences may arise due to the model approximations or thermocouple measurement errors and will be further investigated, e.g., with more accurate nonintrusive measurement techniques. As evident from the direct images, the reaction region spreads out over a larger volume in μ-g, leading to a reduction in local heat release rate. Moreover, radiative heat transfer from the flame increases under microgravity. Consequently, the average flame temperature is observed to drop by ~17% in μ-g. Numerical predictions by our group, which included an optically thin thermal radiation model, also predicted similar temperature drop [17].
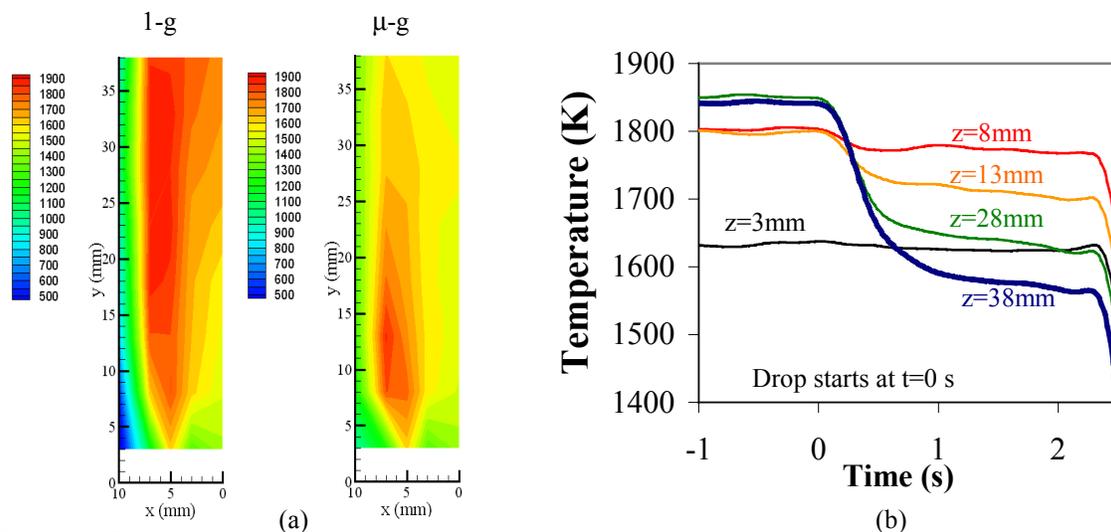
Figure 2: Temperature (a)contours and (b)transient of a double flame: $\phi_{in}=1.8$, $\phi_{out}=0$; $V_{in}=V_{out}=30cm/s$

Figure 2 (b) presents the transient response of the thermocouples for a single lateral position along a slot burner flame. Transients with two different time scales are observed as the rig is dropped. A phenomenological analysis [14] illustrates the phenomena responsible for these different responses. The first transient diminishes within the first 200 ms occurs due to the sudden change in the advection associated the flame. The second transient that persists until the end of the drop is attributed to the diffusive transport. Although the flame temperature is lower under microgravity, the total radiative heat loss from the flame increases due to the larger flame volume. Figure 3 presents data obtained from a radiation pyrometer that retains the entire axisymmetric flame in its field of view at both 1-g and μ-g. Although the time constant of the air-cooled pyrometer is too large to obtain quantitative transient data, the qualitative trend clearly shows an increase in radiative heat transfer form the flame under microgravity.
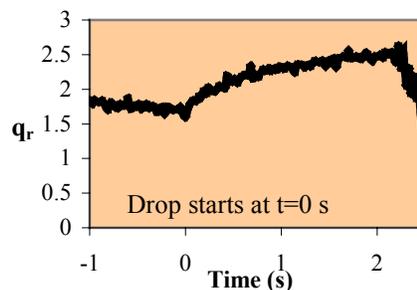
Figure 3: Radiation flux transient.

Lifted flames were observed for very rich φ_{in} and a correspondingly high reactant stream velocity. Figure 4 presents an image of a nitrogen diluted lifted double flame under 1-g and μ-g. In general, the flames were observed to oscillate in 1-g, but became steady at μ-g. The flames moved closer to the burner during the transition to μ-g during the experiment.

CONCLUSIONS AND FUTURE WORK

Herein, some of the first experimental observations of burner-stabilized, methane-air microgravity partially premixed flames are presented. Digital color, black and white, and C_2^* imaging reveals that buoyancy changes the structure of double and triple flames in a similar manner. Buoyancy induced entrainment influences regions away from the flame centerline so that the outermost flame regions are most affected by it. Gravity effects on the rich premixed and nonpremixed zones of a triple flame are less than that for a double flame. Temperature measurements corroborated this finding by showing similar structural effects on the temperature profiles. The temperature data obtained during a show changes in the advective flow during a small initial transient period. A longer transient period is also observed that is related to changes
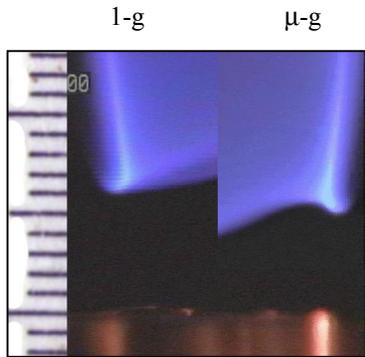
Figure 4: Lifted N$_2$-diluted flame; ϕ_{in} = 3.0, N$_2$=40%, ϕ_{out} = 0; V$_{in}$ = 30 cm/s, V$_{out}$ = 30 cm/s.
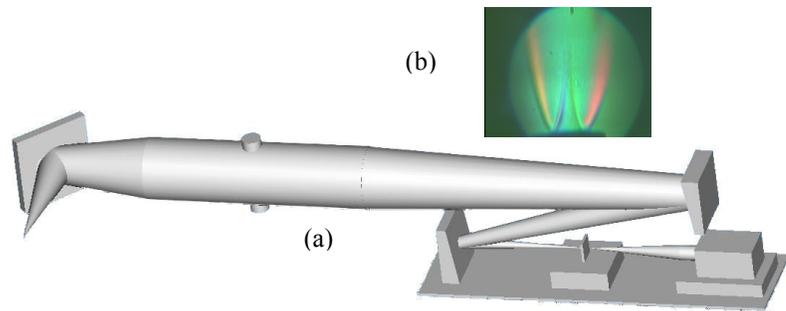
Figure 5: (a)The proposed RSD setup, and (b)image of a 1-g double f lame

in the diffusive flux, which suggests that longer μ-g times are necessary for a better understanding of microgravity effects on these flames. The average and peak temperatures of the flame were observed to decrease in μ-g due to drop in local heat release in μ-g and an increase in radiative loss. The increased radiative loss with a decreased temperature is a result of the flame radiating over a larger volume in μ-g. Nonintrusive temperature measurements involving rainbow schlieren deflectometry (RSD – Figure 5:planned setup) and holographic interferometry (DHI) have been proposed for future work.

ACKNOWLEDGEMENT

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