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THE BEHAVIOR OF METHANE-AIR PARTIALLY PREMIXED FLAMES UNDER NORMAL- AND ZERO-G CONDITIONS

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Introduction

Partially premixed flames (PPFs) represent a class of hybrid flames containing multiple reaction zones. These flames are established when less than stoichiometric quantity of oxidizer is molecularly mixed with the fuel stream before entering the reaction zone where additional oxidizer is available for complete combustion. This mode of combustion can be used to exploit the advantages of both nonpremixed and premixed flames regarding operational safety, lower pollutant emissions and flame stabilization. A double flame containing a fuel-rich premixed reaction zone, which is anchored by a nonpremixed reaction zone, is one example of a partially premixed flame[1]. A triple flame is also a PPF that contains three reaction zones, namely, a fuel-rich premixed zone, a fuel-lean premixed zone, and a nonpremixed reaction zone [2].

Herein we focus on two aspects of our investigation, one involving the development of optical diagnostics that can be used on a microgravity rig, which has been recently fabricated, and the other on the numerically predicted differences between normal- and zero-gravity PPFs. Both the measurements and simulations examine the detailed structure of methane-air PPFs stabilized on a Wolfhard-Parker slot burner.

Experimental Results

Optical diagnostic techniques have proved very useful for nonintrusive temperature and composition measurements in flames, since they provide detailed data with high spatial and temporal resolution. Temperature measurement methods include Rayleigh and Raman scattering, laser-induced fluorescence, and higher-order light-scattering methods such as coherent anti-Stokes Raman spectroscopy. These techniques are used for both point and planar measurements, but do not readily yield quantitative information and cannot be easily used in microgravity applications due to both power and size restrictions. Alternatively, path-integrated or line-of-sight measurement techniques based on the change in the optical phase of a light beam, such as interferometry [3,4,5] and deflectometry [6], can be used to reconstruct the refractive index in flames and thereby infer the temperature distribution. These techniques are well suited to the available

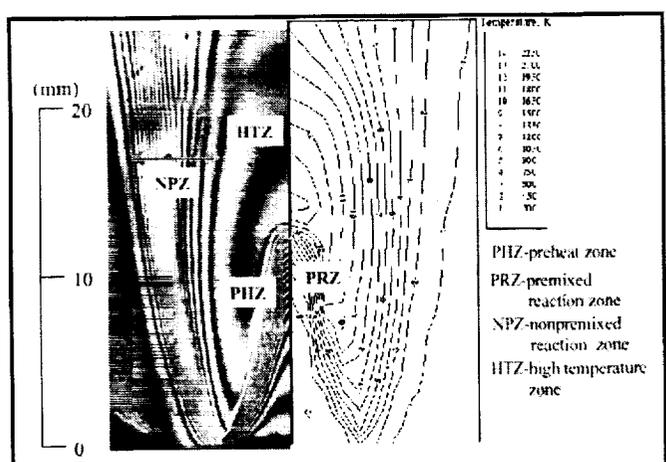


Figure 1: Comparison between a reconstructed hologram (left) and the inferred temperature distribution (right) for a partially premixed (double) methane-air flame established at $\phi_{in}=1.5$, $V_{react}=V_{air}=30 \text{ cm s}^{-1}$.

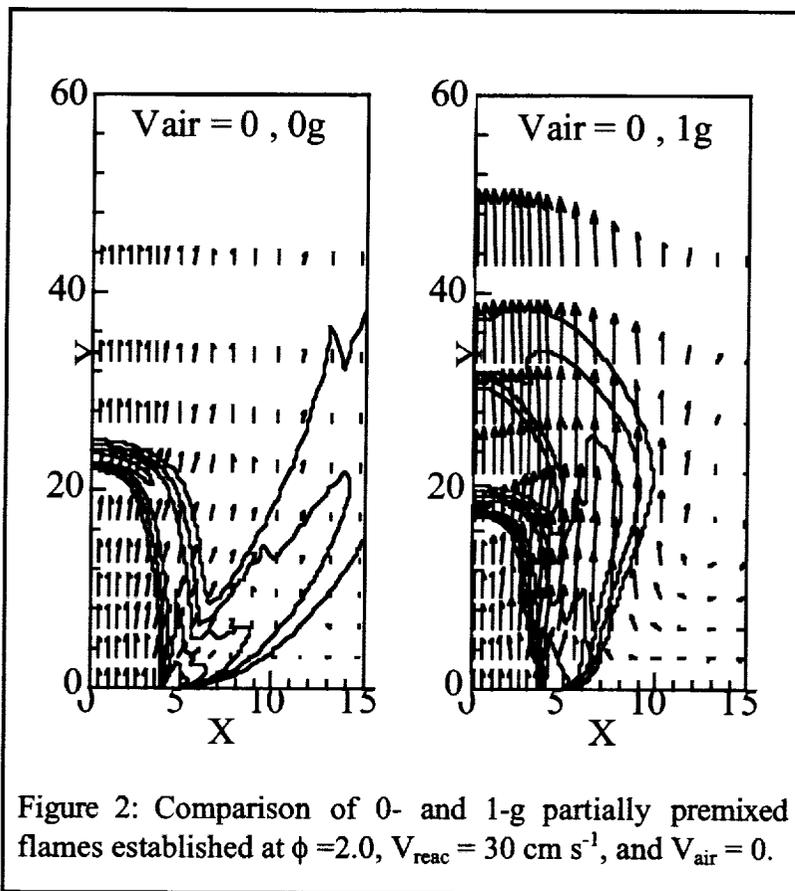


Figure 2: Comparison of 0- and 1-g partially premixed flames established at $\phi = 2.0$, $V_{\text{reac}} = 30 \text{ cm s}^{-1}$, and $V_{\text{air}} = 0$.

microgravity facilities.

We have developed an application of holographic interferometry that is appropriate for partially premixed flames. We have refined a double-exposure laser image plane holographic technique to measuring the temperature profiles of steady two-dimensional partially premixed flames [4,5]. An example of the fringe pattern that is formed is presented in Figure 1. We have shown that the refractive index in PPFs can be modeled by a relation that contains relatively minor errors, which depend upon the rich-side equivalence ratio. Larger errors arise in the case of nonpremixed flames. The maximum error in determining the local temperature lies in the range 6.3-34% (its value being $\approx 50 \text{ K}$ for

PPFs) for $1.5 \leq \phi_r \leq \infty$, while the corresponding average error lies in the range 2.4-12.3%. The temperature distributions determined by using holographic interferometry were found to correlate with the heat release in the various reaction zones.

Numerical Predictions

Although oscillating flames and flame-vortex interactions have been studied extensively, previous investigations have generally examined these phenomena in the context of either nonpremixed or premixed flames, but not with respect to a partially premixed flame (PPF) containing both premixed and nonpremixed reaction zones. Compared to either a premixed flame or a nonpremixed flame, the response of a PPF to perturbations or to a vortex may be significantly different due to thermochemical and transport interactions between the two reaction zones. We have examined the structure of unsteady partially premixed flames focusing on interactions between the two reaction zones and the existence of state relationships for oscillating partially premixed flames. Details of the computational model are to be found in the literature [2,7].

Figure 2 presents a comparison of the 0- and 1-g partially premixed flames established at $\phi = 2.0$, $V_{\text{reac}} = 30 \text{ cm s}^{-1}$, and without any coflow. The flame structure is depicted in terms of heat release rates and velocity vectors. For both cases, the flame structure is characterized by the presence of two reaction zones, one a rich premixed zone and the other a nonpremixed zone. These reaction zones are spatially separated, but involve strong interactions due to the

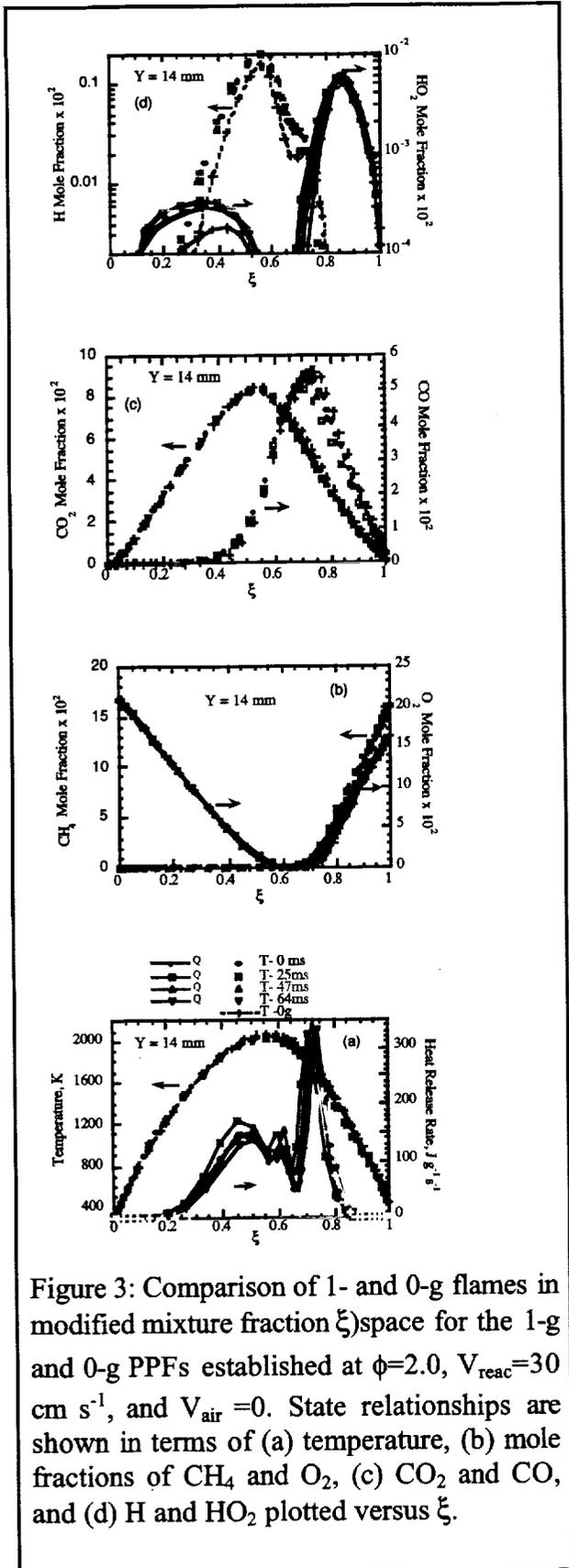


Figure 3: Comparison of 1- and 0-g flames in modified mixture fraction (ξ) space for the 1-g and 0-g PPFs established at $\phi=2.0$, $V_{\text{reac}}=30 \text{ cm s}^{-1}$, and $V_{\text{air}}=0$. State relationships are shown in terms of (a) temperature, (b) mole fractions of CH_4 and O_2 , (c) CO_2 and CO , and (d) H and HO_2 plotted versus ξ .

thermochemistry and scalar transport. The fuel is mostly consumed in the premixed zone to produce CO and H_2 , which are transported to and consumed in the nonpremixed zone. The nonpremixed zone in turn provides heat and H atoms to the premixed zone.

Under 1-g conditions, the flame heat release produces both flow dilatation and buoyant convection. Flow dilatation or gas expansion due to the heating causes downstream motion normal to the flamefront, which is quite evident in the region downstream of the inner premixed reaction zone for both 1- and 0-g flames. The buoyant gases accelerate the flow in an opposite direction to the gravity vector, causing air entrainment that enhances the fuel-air mixing and, consequently, influences the upstream region. The effect of flow dilatation is to push the outer nonpremixed reaction zone away from the central plane, while the buoyant convection has the opposite effect. For the 1-g flame, in the absence of coflow, the latter effect dominates. Consequently, the outer nonpremixed reaction zones differ distinctly for the 0- and 1-g flames. For the latter, this reaction zone is more compact and closer to the inner premixed zone, and has a closed tip. Thus, the effect of gravity on a partially premixed flame is to reduce the spatial separation, and, thereby, enhance interactions between the two reaction zones.

Figure 3 presents state relationships for the temperature and species mole fractions with respect to ξ for the 0- and 1-g flames at an axial location $Y=14 \text{ mm}$ above the burner exit. The species include the reactant species (CH_4 and O_2), an intermediate fuel species (CO), a major product species (CO_2), and two radical species (H and HO_2). In order to identify locations of the two reaction zones, the heat release rate profiles are also shown in Fig. 4a. Since the 1-g flame for these conditions is unsteady, the profiles for this flame are shown at four different times during one oscillation period. The profiles depict both the reaction zones. The rich premixed reaction zone for both 1- and 0-g flames lies between 0.72

$< \xi < 0.8$, and the nonpremixed zones between $0.47 < \xi < 0.55$. Although the 1- and 0-g flames have markedly different spatio-temporal characteristics, the temperature as well as the major and minor species profiles follow similar state relationships in terms of ξ for the two flames. Thus, an important observation is that the modified mixture fraction is effective in characterizing the structure of both steady and unsteady partially premixed flames.

The minor species (H and HO₂) profiles also exhibit remarkable similarity for the two flames in the modified mixture fraction space. The maximum in the H atom concentration occurs in the nonpremixed zone, implying that this zone represents a region of higher chemical activity from which H radicals are transported to the premixed reaction zone. HO₂ radicals are produced through the reaction $H + O_2 + M \rightleftharpoons HO_2 + M$ and mainly consumed through the reaction $HO_2 + H \rightleftharpoons OH + OH$ both in the premixed and nonpremixed reaction zones. This is confirmed by the HO₂ profiles presented in Figure 3d. These profiles also indicate that the chemical activity involving HO₂ is much higher in the premixed zone compared to that in the nonpremixed zone, and the production of HO₂ occurs upstream of the premixed reaction zone ($\xi > 0.9$), and outside of the nonpremixed reaction zone ($\xi < 0.3$).

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