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Experimental Investigation of Slowly Propagating Flames in Microgravity

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Abstract: Accurate measurements of the laminar flame speed are useful to constrain the uncertainty of chemical models. However, for slowly propagating flames, buoyancy distorts the flame and measuring flame speeds accurately becomes challenging. This is relevant for novel hydrofluorocarbon refrigerants, preventing an accurate assessment of their flammability. Additionally, nitrogenated chemistry could be investigated by measurements of ammonia/air flames but the low laminar flame speeds also lead to similar issues. The only way to circumvent buoyancy-induced effects is to gather measurements in microgravity. In this study, an image processing technique was developed to accurately extract the radius of the spherical flame. This is required as the projection of a sphere on a plane leads to measurement error. A lab-scale drop tower was designed and built to achieve approximately 500 ms of free fall time. The direct imaging technique was combined with the drop tower to gather flame measurements in free fall. The methodology was applied to obtain the laminar flame speed of a lean, high-pressure methane/air flame.
Keywords: Spherical Flame, Microgravity, Buoyancy, Laminar Flames

1. Introduction

Laminar premixed flames contribute in many ways, from validation targets for chemical models to developing flamelet models for turbulent combustion [1,11]. To study flames accurately with numerical simulations requires models that collate the chemical kinetics, transport, and thermodynamic properties of hundreds of species and reactions within a flame. Chemical kinetic models, if appropriately constrained, are valuable predictive tools in the design of combustion devices, assessment of explosion risk, etc. Individual reaction parameters can be theoretically estimated or experimentally measured under precise conditions, but as flames consist of hundreds of species, the model must be validated against experimental results. Thus, an iterative cycle exists of constraining the model uncertainty using a wide range of experimental data [2]. In theory, a robust model can predict any experimental data within an acceptable tolerance. Prototypically, the validation target is the flame propagation speed relative to the unburnt reactants, the laminar flame speed (S_u^o) under the stipulations of being planar, 1-dimensional, and adiabatic. S_u^o is a fundamental property of the mixture that characterizes the chemical kinetics, transport processes, and heat release. However, if the experimental uncertainty is on the order of the parameter uncertainty it provides little value in constraining the kinetic model [2].

The constant-pressure, spherically expanding flame experiment (CON-P SEF) is a widely used methodology to quantify S_u^o. However, gathering accurate measurements, in this configuration, poses a significant challenge for mixtures with a burned flame speed (S_b) of less than 100 cm/s [3]. As the LFS becomes smaller, the time scales of buoyant convection become comparable to the flame propagation [3]. By a similar argument, radiation becomes significantly more relevant for slowly propagating flames [4]. This study is largely focused on the mitigation of buoyancy effects as radiation models have been developed and validated in literature [5]

Buoyant convection has ramifications for accurate S_u^o measurements for zero-carbon fuels such as ammonia and novel low global warming potential (GWP), hydrofluorocarbon (HFC) refrigerants; both of which show strong buoyant behavior when burned with air at standard temperature and pressure [6-7]. Without accurate S_u^o measurements, the models are unable to predict the emissions characteristics of nitrogenated fuels or investigate the flammability concern associated with the low-GWP fluorinated refrigerants [8-9]. The issue of buoyant convection is quite evident as the flame morphology is heavily distorted as a result. Consequently, the strain rate and curvature vary along the flame [10]. The relationship between the burned flame speed, the measured quantity, and stretch becomes multivariate and varies as a function of time and space [10]. Any approximate method used to extract S_u^o results in significant error [10]. The only way to accurately quantify S_u^o is through microgravity measurements. However, toxic reactants or products limit options in aircraft or spacecraft. Terrestrial drop towers are a reliable way to achieve free fall. However, constraints on size and free fall time leave the CON-P SEF as the only viable experiment as it offers optical access and uses early flame evolution. High-speed shadowgraph or Schlieren systems are the conventional optical diagnostic but add significant complexity to a drop setup. In this work, a lab-scale drop tower is utilized with direct imaging to gather accurate S_u^o measurements. This method offers low-cost and high throughput tests of low-S_u^o mixtures with accuracies relevant to constraining chemical models.

2. Methods / Experimental

The primary method used in this work is the spherical, outwardly expanding flame (SEF). This approach is desirable as it has a well-defined stretch rate, is low dimensional, confined, needs relatively simple diagnostics, and can probe a broad pressure range [1]. The CON-P SEF is characterized by a negligible pressure rise and high stretch rate corresponding to small flame radii that correspond to negligible pressure rise [13]. The primary diagnostic is direct imaging which measures the flame radius as a function of time in addition to revealing any flame instabilities. The static experimental configuration is similar to other examples in literature [11-12].

The mixture is prepared using Dalton's principle of partial pressures with high-accuracy Omega PX409 absolute pressure transducers. For this work, high-purity methane and desiccated/filtered air are used. The chamber and lines are vacuumed between the fillings of fuel and air and the mixture is allowed to settle for a minimum of 10 minutes to ensure thorough mixing and quiescence. The mixtures are centrally ignited using stainless steel electrodes with a 2 mm spark gap. The breakdown is initiated by a 30 kV trigger transformer which can be further sustained by a 2 kV capacitor bank. The ignition energy can be tuned using both the discharge duration and the resistance of the capacitor bank which is minimized to avoid excessive wrinkling. The experiment was validated using 1 atm methane/air S_u^o measurements over a range of equivalence ratios, which is not shown due to space limitation.

The direct imaging process is very similar to the Schlieren and Shadowgraph optical method. An in-house radius extraction algorithm was developed to process the images. However, a correlation has to be developed to accurately measure the 3-D projection of a sphere onto a plane. This is achieved by imaging high-tolerance aluminum cylinders and developing a correlation between the seen radius in pixels to the known dimension. This correction is applied to the output of the radius extraction algorithm.

A local polynomial fit of the radius data is applied, typically with a 2nd order polynomial fit, to smooth the data and eliminate any non-physical noise. The local polynomials are differentiated to get dR_f/dt as a function of time. Assuming the burned gas is quiescent, the flame speed relative to the burned gas is $S_b = dR_f/dt$. However, if there is an inward flow associated with radiative cooling, then $S_b \neq dR_f/dt$ [13]. The relationship between the burned flame speed and stretch is given by $S_u = S_u^o - L_b K$, where K is the flame stretch and L_b is the burned Markstein length [14]. This relationship can be used to extrapolate to zero flame stretch and arrive at the theoretical S_u^o through continuity. Through asymptotic analysis, it was found that linear extrapolation to zero stretch was inaccurate, however, this is largely applicable to nonequidiffusive mixtures, and as such, only linear extrapolations are used in this work [1].

For the second aspect of this study, a drop tower was designed and built to minimize buoyancy-induced flow distortions. The drop tower was designed to achieve a free fall time of about 500 ms before it is arrested by foam cubes to minimize the impact and rebound. The drop tower has dimensions of 1.16m x 1.16m x 2.65m and accommodates the chamber, high-speed camera, and wiring. An in-house LabVIEW script simultaneously initiates recording, ignition, and the release of the combustion assembly.

3. Results and Discussion

The effect of buoyancy was illustrated by choosing a lean methane/air (ϕ = 0.65, P_i = 2 atm) flame. As shown in Figure 1, at the same stages of flame evolution, the buoyant convection carries the flame upward, significantly distorting the surface. In contrast, the same mixture in free fall retains its sphericity throughout the flame propagation.

The radius of the mixture in free fall was processed and linearly extrapolated to find S_u^o, as shown in Figure 2, however, it should be noted that the flame is affected by radiation heat loss which will lead to an underprediction in S_b. This is evident as the extrapolated S_u^o is 4.4 cm/s whereas the FFCM model, in a 1-D flame simulation with radiation, predicts an S_u^o of 7.5 cm/s [16]. The correction for radiation, for this methodology, will be incorporated in a future study.

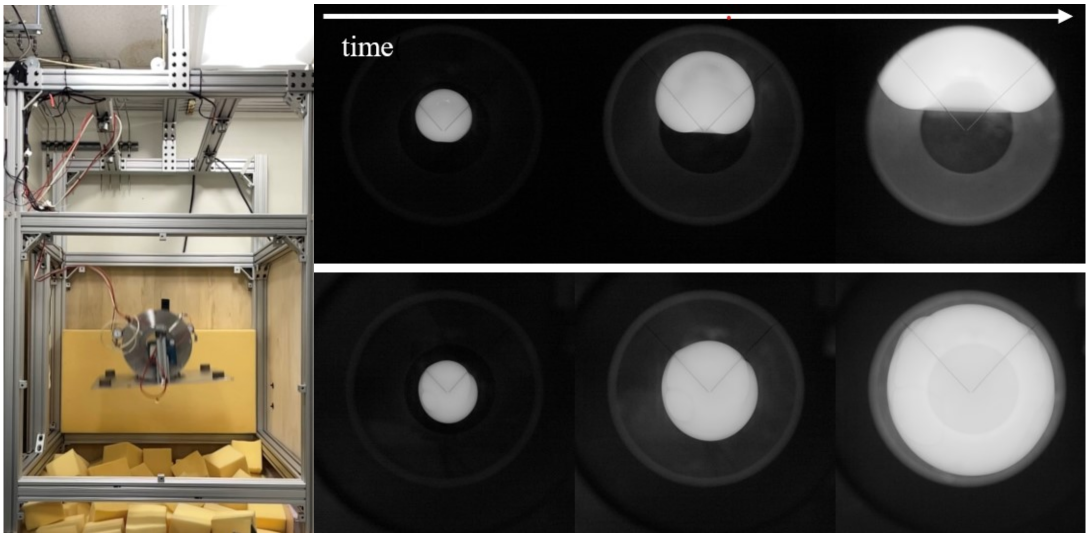

Figure 1. Evolution of a CH_4/Air (ϕ = 0.65, P_i = 2 atm) flame in a static (top) versus a microgravity setup (bottom) at the same time instants with an image of the experiment during free fall (left)

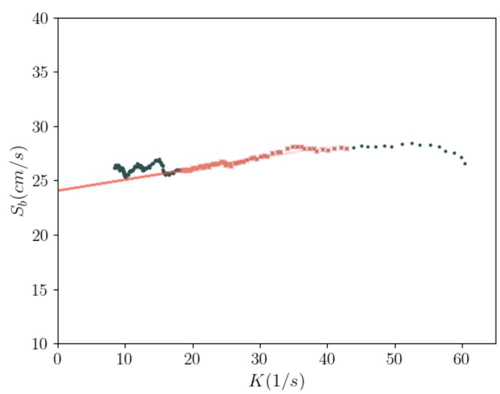

Figure 2. Burned flame speed versus (S_b) vs. Stretch (K) for the CH_4/Air (ϕ = 0.65, P_i = 2 atm) flame in microgravity (S_u^o = 4.41 cm/s). The data used for extrapolation is highlighted in the lighter color.

4. Conclusions

A free fall spherically expanding flame experiment was developed to investigate slowly propagating flames while minimizing the effect of buoyancy-induced flows. An image processing technique was developed to accurately extract the radius of the spherical flame from direct images taken from a close distance. Flame speed measurements were taken for a lean methane/air flame (ϕ = 0.65, P_i = 2 atm) in a static configuration and a microgravity configuration. The results confirmed that the fall experiment is able to minimize buoyancy-induced flows and enable the study of spherical slowly propagating flame. Further work is necessary to incorporate the radiation heat loss that can lead to systematic errors in flame speeds measured from slowly propagating spherically expanding flames.

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6. References

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