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Experimental investigation of turbulent flames in uniform dispersions of ethanol droplets

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ABSTRACT

A turbulent flame in an ethanol droplet-laden uniform mixture is investigated at overall equivalence ratios (ϕ_{ov}) of 0.62, 0.72 and 0.82, using a piloted Bunsen burner. Imaging of OH* chemiluminescence and simultaneous imaging of OH PLIF and Mie scattering, both at 5 kHz, and imaging of CH_2O-fuel PLIF at 5 Hz, were used to obtain instantaneous and time-averaged images, temporal sequences and 2-D estimates of flame surface density and curvature. 1-D PDA and LDA measurements were used to obtain droplet size and velocity statistics. At $\phi_{ov} = 0.62$, the flame takes a cylindrical shape, and changes to a cone shape with increasing fuel loading to obtain higher ϕ_{ov}. Larger droplets are generally observed to have lower average and RMS axial velocities than smaller droplets. Profiles of droplet size distributions indicate a decreasing droplet number density downstream together with a shift to larger droplet diameters. The flame structure is observed to be relatively smooth at locations near the burner exit, and becomes more contorted with distance downstream. In general, droplets are observed to coincide with low-to-intermediate regions of OH. Occasionally, droplets appear to penetrate the flame front, and are detected in regions of intermediate-to-high OH. This occurs particularly at the downstream locations where the flame closes across the jet, with no significant averaged droplet penetration observed past 2 mm in the direction normal to the flame front. Measurements show a gradual reduction in flame surface density and higher flame front curvature with both distance downstream and increasing fuel loading. Estimates of the average droplet evaporation rate increase with both distance downstream and ϕ_{ov}, as droplets appear in higher mean progress variable regions. The measurements reported here are useful for model validation of flame propagation in dilute sprays.

1. Introduction

Flame propagati on in droplet-laden mixtures is of importance to a variety of practical applications, such as direct-injection IC engines and in gas turbines. A better understanding of flames in multi-phase flows is crucial to the development of more efficient combustion-based technologies, and the topic continues to be of interest. Crucially, detailed experimental measurements are required to validate advanced numerical models to facilitate the development of new technologies. Detailed reviews of the key studies in this field are available in the literature [1–4], and this section briefly summarises some key investigations pertinent to the present work, which concerns the canonical problem of a turbulent flame propagating in, or stabilised against an incoming flow of, a uniform dispersion of fuel droplets.

An early experimental study by Burgoyne and Cohen [5] investigated laminar flame propagation in monodisperse tetralin fuel droplets suspended in an air mixture confined in a combustion tube. For droplet diameters below 10 µm, the air-droplet suspension was observed to behave like a vapour and a smooth flame front was observed. For droplet diameters above 40 µm, fuel droplets were observed to burn individually in their own envelope, promoting combustion by igniting adjacent droplets. At intermediate droplet diameters, a transitional combustion regime was observed. Such studies gave a qualitative understanding of the effect of droplet size on combustion behaviour, and led researchers in search for more quantitative data, such as in the experiments by Hayashi et al. [6]. In their study, burning velocities in monodisperse ethanol-air mixtures were measured. Observations showed that for large enough droplet diameters, the burning velocity of a droplet-vapour-air mixture exceeded that of a homogeneous

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mixture of the same overall fuel-air ratio. Similar observations of the effect of droplet size on flame propagation were reported in [5], where the rugged and thickened flame structure observed for large droplet size conditions was suggested to result from incomplete droplet evaporation in the preheat zone, with droplet evaporation continuing into the hot products region of the flame. The resulting increase in the effective volume of the thickened flame structure was then suggested to promote combustion and lead to the higher burning velocities measured.

Further experimental studies expanded knowledge of the effect of droplet size on flame propagation, such as that by Myers and Lefebvre [7]. Using different fuels to also study the influence of fuel chemistry, their measurements showed flame speeds for the fuels investigated to be inversely proportional to the Sauter Mean Diameter (SMD) for droplet diameters above a critical value. This led to the conclusion that for large droplet sizes, evaporation rates are controlling to the fraction of fuel vapourised and consequently the flame speed. Furthermore, an increase in the amount of fuel vapour present in the inter-droplet space was observed to promote flame propagation. For low fuel vapour fractions, the inter-droplet distance was observed to be controlling to the survival of burning individual droplets within diffusion flame envelopes, necessary to sustain flame propagation at these limiting conditions. These and similar studies [8–10] with DNS and experiments in other configurations showed the intricate effects of droplet size and evaporation (and consequently overall fuel-air and liquid-air ratios) on flame propagation in multi-phase flows.

In practical spray systems, the spray is not monodisperse and the diameter of the droplets varies. For simplicity, a polydisperse spray is often characterised by a single value, such as the SMD, based on which the propagation behaviour is described. However, the polydispersity of a spray has been shown to influence the flame location, flame temperature and combustion behaviour. In this analytical study of a polydisperse laminar opposed flow spray diffusion flame, a characteristic droplet size was shown to be insufficient to accurately describe flame propagation [11]. This was particularly significant at limiting conditions such as flame extinction where significant errors were shown to arise.

With the development of computational models for spray combustion, detailed numerical studies have provided useful information on spray flame propagation. One such study is that of Neophytou and Mastorakos [9] where simulations of laminar planar one-dimensional freely-propagating flames in spray mists with detailed chemistry were performed. Their results showed the equivalence ratio at the reaction zone, denoted as the effective equivalence ratio (ϕ_{eff}), to be less than the overall equivalence ratio (ϕ_{ov}), due to a delay associated with droplet evaporation. This led to a reduction in flame speed in the case of overall lean mixtures, whilst increasing the flame speed for overall rich mixtures and large droplets as ϕ_{eff} approaches stoichiometry. For the latter case, evaporation of droplets which survive past the flame front into the hot products region resulted in pyrolysis and the production of hydrogen and acetylene, which by diffusing upstream to the reaction zone would result in an increase in flame speed of the propagating front. This showed that locally rich regions in reacting sprays can be associated with higher flame speeds which promote global flame propagation. Further work by Neophytou et al. [12] investigating spark ignition in a uniform monodisperse turbulent spray with complex chemistry Direct Numerical Simulations showed the flame propagation mechanism to consist of the reacting front jumping between igniting droplet-scale flames, detail not easily observed from experiments.

More recent numerical studies continue to provide closer examination of flame-droplet interaction and flame propagation in droplet-laden mixtures in the presence of turbulence, such as in the studies by Wacks et al. [13,14]. Using Direct Numerical Simulations to study flame propagation in n-heptane droplet-air mixtures, both premixed and non-premixed modes were observed to occur simultaneously but in different locations in mixture fraction space. Increasing the droplet size and turbulence intensity increased the relative contribution of non-premixed combustion to the overall heat release. A thicker flame was observed in droplet-laden mixtures compared to the corresponding stoichiometric gaseous mixture. Droplets were reported to evaporate predominantly in the preheat zone, with some droplets penetrating the flame front and continue to evaporate in the burnt gas region, resulting in fuel vapour diffusing back towards the flame front. The combustion process in the gaseous phase was observed to occur predominantly in locally fuel-lean regions, with significant equivalence ratio fluctuations arising along the flame front. From investigating the flame displacement speed and its correlation with curvature and strain rate, similarities in the local flame propagation behaviour in droplet-laden and gaseous premixed flames were observed. These similarities were suggested to indicate the suitability of applying turbulent premixed combustion modelling techniques in describing flame propagation in droplet-laden mixtures.

Of particular relevance to the present work is the experimental study by Pichard et al. [15] investigating the evaporation behaviour of n-heptane droplets in a low turbulence carrier air flow using a piloted burner. The investigation studied the effects of (i) the overall equivalence ratio (ϕ_{ov} = 0.72, 0.79 and 0.87), (ii) droplet residence time in a prevaporization tube (t_{res} = 21 and 49 ms) and (iii) the initial spray droplet Sauter Mean Diameter (SMD = 10, 20 and 25 µm) on the average droplet vaporization rate (K). Droplet velocity and size information was obtained from PDA measurements, with mean progress variable ($\langle c \rangle$) data of the spray flame obtained using OH PLIF. Their observations showed K to increase with $\langle c \rangle$, and consequently with ϕ_{ov} at a given axial location due to a shorter flame, with K also increasing with SMD. An increase in t_{res}, for which the turbulence intensity of the reactants stream decreased, led to a reduction in K as the degree of premixing increased to achieve a globally leaner and longer flame. These results are particularly relevant to many practical applications employing spray flames, where some degree of prevaporization, and consequently premixing, generally occurs and for which the effects of droplet vaporization on the global flame behaviour are important. The use of their experimental results as validation data for computational simulations by [16], which showed good agreement of the general droplet and flame behaviour, further emphasises the necessity of such detailed experimental studies in the development of advanced spray combustion models.

The application of well developed turbulent premixed flame analysis methods to study spray combustion in these recent studies motivates the present work, where the focus is on partially prevaporized ethanol spray flames. In comparison to the field of turbulent premixed flames where a larger collection of data measuring parameters pertinent to flame structure and propagation (such as burning rates, displacement speeds, surface density, curvature statistics) are widely available [17], such information is not readily available for turbulent spray flames [18]. Additionally, the majority of the detailed work on flame structure and propagation in droplet-laden mixtures has focused on laminar flows, with few studies investigating turbulence effects in detail available in the literature [19–22]. The lack of data on the canonical problem of turbulent planar flame propagating in a uniform dispersion of droplets, which is fundamental to understanding spray flame stabilisation and important applications such as gas turbine relight, has been highlighted in a recent review article [23]. The application of laser diagnostics to obtain detailed measurements of spray flames in simple burner configurations, such as in [10,15,24], are crucial to better understanding flame structure and propagation in droplet-laden mixtures through providing new insights and