



Laminar mass burning and entrainment velocities and flame instabilities of *i*-octane, ethanol and hydrous ethanol/air aerosols



Derek Bradley^{a,*}, Malcolm Lawes^a, Shiyong Liao^b, Aminuddin Saat^c

^a School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, United Kingdom

^b School of Thermal Engineering, Chongqing University, Chongqing 400044, China

^c Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 Johor, Malaysia

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ABSTRACT

The paper reports experiments employing the cloud chamber technique for creating fuel aerosols, in studies of premixed laminar flames. Spherical explosion flames were initiated at different times after the start of expansion of the original gaseous mixture to lower pressure. Flame speeds were measured close to atmospheric pressure, over a range of equivalence ratios of *iso*-octane, ethanol and hydrous ethanol with air. A methodology was developed for deriving mass burning velocities and entrainment velocities, as well as mass burning fluxes, from the measurements of aerosol number densities, droplet sizes and flame speeds. It was vital to estimate whether droplet evaporation was completed in the flame pre-heat zone. This was done by calculating the spatial progress of droplet evaporation for the different aerosols from values of the evaporation rate constants of the different fuels.

With predominantly the leaner mixtures and smaller droplet diameters, evaporation was close to completion, but the mass burning velocities of the aerosols were somewhat lower than those of the corresponding gaseous phases, because of the lower final temperatures due to the required evaporation enthalpies. However, the mass burning fluxes were higher than those for the purely gaseous flames, due to the higher two-phase reactant densities. At the higher values of the liquid phase equivalence ratio, in overall lean mixtures, the mass burning velocity could exceed that in the purely gaseous phase due to localised enrichment around the droplets.

The presence of fuel droplets is shown to enhance the generation of Darrieus–Landau, thermo-diffusive instabilities and the associated flame wrinkling. With richer mixtures and larger droplets, it is possible for droplets to enter the reaction zone and further enhance existing gaseous phase instabilities through the creation of yet further flame wrinkling. This leads to the maximum entrained fuel mass flux, in the richest mixture, being significantly higher than that occurring at the maximum burning velocity of a premixed gaseous flame.

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1. Introduction

Studies relevant to droplets and spray flames have featured in a number of experimental and numerical investigations for at least seven decades. Such combustion is of practical importance in a wide range of applications including gasoline and diesel engines, gas turbines, and furnaces. The two phase combustion of liquid sprays is usually turbulent, particularly when spray formation occurs in high pressure liquid jets. Because of its practicality, studies of the turbulent combustion of sprays have been more prevalent than those of laminar combustion. The present study concentrates on the measurements of differently defined laminar burning veloc-

ities of aerosols and the associated flame instabilities. These are also of fundamental relevance to turbulent burning.

Burgoyne and Cohen [1] generated mono-dispersed liquid aerosols of tetralin in the size range 7–55 μm by bubbling heated nitrogen through tetralin. The mixture passed to a re-heater which vaporised the tetralin, following which the mixture passed down a tube, where slow condensation formed a nearly mono-dispersed mist. This was burned in a laminar flame propagating along a tube, and also in a burner. For droplet diameters below 10 μm , combustion was as in the gas phase, while above 40 μm each droplet burned individually in their own envelope of air.

Mizutani and Nakjima [2] measured laminar burning velocities of propane-kerosene droplets-air flames on a burner with an air atomiser and in a cylindrical explosion bomb with an ultrasonic atomiser [3]. They found that both the burning and propagating velocities of propane flames were markedly accelerated by the

* Corresponding author. Fax: +44 1132 424 611.

E-mail address: d.bradley@leeds.ac.uk (D. Bradley).

Nomenclature

| | | | |
|-----------|--|----------------------|---|
| AF_s | molar ratio of air to fuel at stoichiometric condition | T_b | adiabatic flame temperature of burned gas within sphere of radius, r_c |
| B | non-evaporation mass correction factor | \bar{T}_{uo} | temperature of unburned mixture |
| D | droplet concentration factor, see Eq. (18) | \bar{T}_{ur} | mean temperature of unburned gas within sphere of radius, r_f |
| d | instantaneous droplet diameter | t | time |
| d_{ocr} | critical initial diameter of droplet for 90% evaporation | u_d | droplet velocity just ahead of the flame |
| d_o | initial droplet diameter | u_g | gas velocity just ahead of the flame |
| k | fuel evaporation rate constant | u_e | entrainment velocity at radius, r_f |
| L_b | flame speed Markstein length | u_{eg} | entrainment velocity at radius, r_f for gaseous mixture |
| m | total mass within sphere of radius r_f | u_ℓ | unstretched laminar burning velocity |
| m_b | mass of burned gas within sphere of radius r_c | u_r | mass burning velocity, see Eq. (12) |
| m_d | mass of droplets within sphere of radius r_f | u_{rg} | mass burning velocity of gaseous mixture |
| m_u | mass of unburned gas within sphere of radius r_f | | |
| M_A | molar mass of air | Greek symbols | |
| M_F | molar mass of fuel | ρ | density |
| n | number density of droplets | ρ_b | density of burned gas within sphere of radius r_c |
| P | pressure | ρ_d | density of droplets |
| P_{u0} | initial pressure of mixture | ρ_{ug} | density of original unburned gas |
| Pe_{cl} | critical Peclet number | ρ_{uo} | density of original unburned aerosol |
| R | ratio of r_c/r_f | $\bar{\rho}_{ur}$ | mean density of unburned gas within sphere of radius, r_f |
| \bar{R} | universal gas constant | ϕ | equivalence ratio |
| r_c | radius of completely burned zone | ϕ_g | equivalence ratio of gas phase |
| r_d | mean radius of droplets | ϕ_l | equivalence ratio of liquid phase |
| r_f | outer radius of preheat zone | ξ_p | thickness between start of preheat and the reaction zone, $\xi_p = r_f - r_c$ |
| r_{sch} | schlieren flame radius | ν | kinematic viscosity. |
| S | correction factor for flame thickness | | |
| S_n | flame speed | | |
| S_{no} | flame speed at zero stretch rate | | |
| S_{n48} | flame speed at flame radius of 48 mm | | |
| T | temperature | | |

addition of a very small amount of kerosene droplets. The smaller they were, the greater the effect. The combustion-promoting effects of droplets were more marked for leaner mixtures and were less so as the mixture became richer than stoichiometric. Polymeropoulos and Das [4] showed that, for kerosene spray flames, with an increasing degree of spray atomization, the flame burning velocity increased to a maximum value, and then decreased to a burning velocity that approached that of the gaseous premixture.

The smaller droplet sizes are better generated by condensation from the gaseous phase, as in a Wilson cloud chamber [5], than by atomisation of the liquid phase. The technique is capable of generating close to monosized droplets in a uniform mixture and was developed for combustion systems by Kumagai and coworkers [6,7]. Rapid expansion of gaseous ethanol–air mixtures created condensation droplets of ethanol. These might be small enough to vaporise ahead of the reaction zone in a laminar flame, with the fuels initially in a mixture of liquid and gaseous phases. With this technique, Hayashi et al. [7] measured the propagation velocities of ethanol flames through droplets and vapour–air mixtures. Their high quality measurements showed that for a high liquid phase equivalence ratio, ϕ_l , droplets of 4 and 7 μm diameter give a burning velocity less than that of the corresponding homogeneous mixture under lean mixture conditions, but this eventually increased above that of the corresponding gaseous phase mixture for rich mixtures. They also showed, under microgravity conditions, that at sufficiently large flame diameters, cellular flames developed for equivalence ratios, ϕ , >1.1 . Later experiments [8] showed a tendency of lean aerosol mixtures to burn faster than the corresponding gaseous lean mixture, but the converse occurred for rich mixtures.

Extensive numerical studies by Sirignano [9] and Aggarwal and Sirignano [10] of spray flames showed that the reaction zone does not consist of an array of flames surrounding separate vaporising

droplets, but exhibits, simultaneously, both diffusion-like and premixed-like characteristics. Vaporisation occurs from droplets both behind, and ahead, of the propagating flame. The slip velocity of droplets in the gas flow ahead of the flame causes stratification of the unburned gas mixture and this can lead to an increase in the overall local equivalence ratio ahead of the flame, with a resulting change in the flame speed [10]. Numerical studies of spherical explosive flame propagation with single step Arrhenius kinetics, showed that, as the droplet size increased there were increasing departures from the original uniform equivalence ratio, due to the relative motion of the two phases [11].

Polymeropoulos [12] employed a laminar flame aerosol model with heat release from two sources: single droplet combustion and homogeneous reaction of fuel vapour. He found a range of droplet sizes, between about 10 and 15 μm , within which the burning velocity was a maximum for both lean and rich mixtures, but there were no conclusive confirmatory experimental observations. Lin and Sheu [13] derived the changes in laminar burning velocities of near-stoichiometric sprays as a function of droplet radius and initial fuel fraction, using matched asymptotics, large activation energy, techniques. For a given droplet radius, the peak value of the burning velocity was displaced to higher values of the overall equivalence ratio by an increase in the liquid fuel fraction.

The combustion modelling of reactive spray in engines by Stapf et al. [14] showed that large droplets create a long trailing vapour cloud with “inferior” ignition and combustion, while the smaller droplet clusters evaporate very quickly generating ignitable fuel–air mixtures.

In their experimental studies of laminar explosions in lean premixed aerosols, Atzler et al. [15] explained the development of relatively low frequency oscillations, accompanied by pulsating flame cellularity, in terms of the droplet slip velocity. The linear stability

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