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Burning rates of turbulent iso-octane aerosol mixtures in spherical flame explosions

M. Lawes, A. Saat *

School of Mechanical Engineering, University of Leeds, Leeds LS2 9JT, UK

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Abstract

Experimental studies of aerosol combustion under quiescent and turbulence conditions have been conducted to quantify the differences in the flame structure and burning rates between aerosol and gaseous mixtures. Turbulence was generated by variable speed fans to yield rms turbulence velocities between 0.5 and 4.0 m/s and this was uniform and isotropic. Homogeneously distributed and near monodispersed iso-octane-air aerosol clouds were generated using a thermodynamic condensation method. Spherically expanding flames, following central ignition, at near atmospheric pressures were employed to quantify the flame structure and propagation rate. The effects of the diameter of fine fuel droplets on flame propagation were investigated. It is suggested that the inertia of fuel droplets is an important cause of flame enhancement during early flame development. During later stages, cellular flame instability and the effective, gaseous phase, equivalence ratio becomes important. The latter effect leads has increases the flame speed of rich mixtures, but decreases that of lean ones. Droplet enhancement of burning velocity can be significant at low turbulence but is negligible at high turbulence.

Keywords: Flame speed; Aerosol flame; Droplets; Two phase; Turbulent

1. Introduction

Spray, or aerosol, combustion is of practical importance in many applications that include automotive engines, gas turbines, furnaces, heaters and explosions. However, it is poorly understood due to the complexity of spray combustion systems, in which critical parameters such as evaporation rate, burning rate and turbulence interact. Under initially quiescent conditions, theoretical [1–3] and experimental [4–7] studies have suggested that flame propagation through aerosols can be faster than that in fully vaporized homogeneous mixtures. However, under turbulent conditions, there is little fundamental experimental data. Mizutani and Nishimoto [8] investigated the effects of turbulence on combustion of a two-phase fuel–air mixture on a burner. They found that the flame speed increased in proportion to the rms turbulence velocity, u', and inversely with droplet diameter. A similar trend was observed using various fuels; kerosene [9,10], decane and toluene [11] and propane with kerosene drops [12]. It was suggested [9,10] that droplet evaporation rate was a controlling factor in turbulent flames when the turbulence is low, at $u' < 2.0$ m/s. However, these works used large droplets of between 40 and 100 μm, at which conditions there is no comparative laminar experiments as a reference. For example, typical laminar aerosol studies have been undertaken with droplets between 10 and 40 μm [1,5–7]. Sulaiman [13] and Lawes et al. [14] suggested that the burning rate

* Corresponding author. Fax: +44 (0)113 343 2150.
E-mail address: mnas@leeds.ac.uk (A. Saat).

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of turbulent iso-octane-air aerosols with droplets of about 4–15 μm could be significantly lower than that of gaseous flames. They also performed laminar studies with similar sized droplets. However, these works were inconclusive because they were unable to maintain the same initial pressure and temperature for the aerosol and gaseous mixtures.

Contradictory evidence was provided by [15] who observed that the addition of kerosene drops into a turbulent ($u' = 0.13$ m/s) propane-air flame yielded a higher burning rate than for the propane-air flame alone. They also observed that as turbulence increased, this combustion-promoting effect became less significant until, ultimately, burning approximated that of a gaseous flame and droplet size and number density were insignificant variables. It was suggested [15] that this was because of increased evaporation and mixing and demonstrates that increased turbulence may reduce or eliminate the burning rate enhancing effect of droplets in aerosol flames that have been reported for quiescent mixtures [5–7].

In the present work, spherically expanding turbulent flames were employed to quantify the flame structure and propagation rate. Aerosols were generated by expansion of the gaseous pre-mixture to produce homogeneously distributed suspensions of fuel droplets. The effect of fine droplets, up to 14 μm diameter, on turbulent flames was examined at various values of u' between zero and 4.0 m/s. Comparisons of flame propagation were made between gaseous and aerosols mixtures at similar conditions.

2. Experimental apparatus and technique

The combustion vessel (CV) and auxiliary equipment for generation and combustion of aerosol mixtures is described in [14] and is shown schematically in Fig. 1. It resembled a Wilson cloud chamber [16] and was a 23.2 l cylinder with a diameter and length of 305 mm. Optical access was through 150 mm diameter windows in both end plates. Two electrical heaters, attached to the end plates, preheated the vessel and mixture to the desired temperature. Four identical fans, driven by independently controlled induction motors, were mounted equi-spaced around the central circumferential plane. These provided isotropic turbulence within the field of view of the windows. Turbulence was characterised by [14,17] in gaseous mixtures and, in [18], it was found to be unchanged in the presence of aerosols. Full details, including power spectra, velocity and length scales are given in [17]. For conditions reported here, $u' = 0.0016 \times$ fan speed (rpm), and the integral length scale is approximately constant at 40 mm.

Aerosol mixtures were prepared by condensation through controlled expansion of a gaseous fuel–air mixture from the combustion vessel into the expansion vessel (EV in Fig. 1), which was pre-evacuated to less than 1.0 kPa. This reduced the pressure, P, and temperature, T, of the mixture in the combustion vessel until it became lower than the saturation temperature of the fuel; at which point condensation occurred and an aerosol cloud was generated. The technique is described in [14]. The characteristics of the aerosol were calibrated, without combustion, by in-situ measurements of the temporal variation of P, T, droplet arithmetic mean diameter, D_{10}, and number density, N_D, with reference to the time from the start of expansion. Measurements of D_{10} were performed using Phase Doppler Anemometry and an estimate of N_D was calculated based on laser attenuation and droplet size measurements [14]. Shown in Fig. 2 is a typical variation of aerosol parameters during the expansion of a turbulent stoichiometric mixture of iso-octane-air at initial conditions of 200 kPa, 303 K and $u' = 1.0$ m/s. Expansion took place in approximately 500 ms

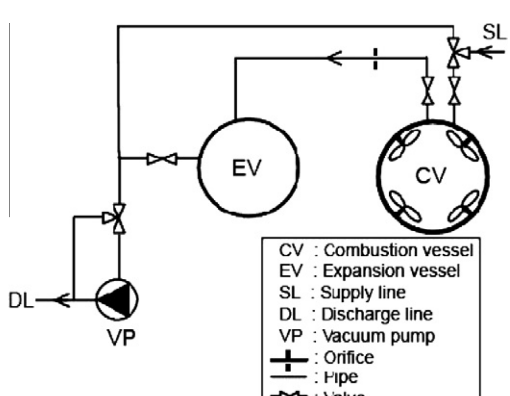

Fig. 1. Experimental apparatus.

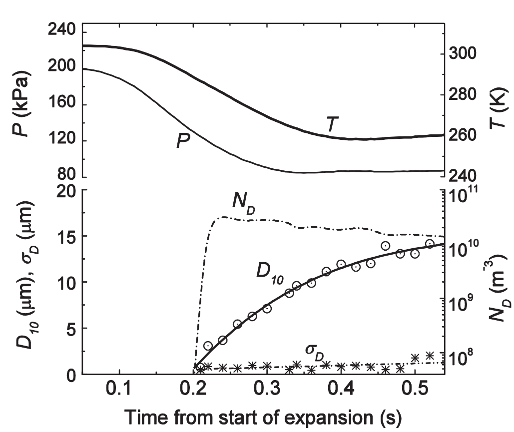

Fig. 2. Typical variation of aerosol parameters with time during the expansion of stoichiometric turbulent iso-octane-air aerosols.