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Characterization of two-phase combustible mixtures produced in a fan stirred bomb

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Abstract

The study of spray combustion is difficult due to the multiplicity of inter-dependent variables, such as pressure, temperature, droplet size, droplet size distribution, etc, especially industrial cases. Therefore, a combustion vessel developed to study the combustion of droplet clouds from a fundamental point of view has been chosen for the present work. However, it was required a full characterization of the aerosols produced before any combustion study could be undertaken. The distribution of droplets within the mixture, without combustion, was characterised using several laser diagnostics, variables such as Sauter mean diameter, number density, gas and liquid equivalence ratios were determined. Nearly mono-sized droplet clouds were obtained in this vessel and the droplet diameter was a well defined function of time.

Key words: Spray combustion, characterization.

Caracterización de mezclas combustibles de dos fases producidas en una bomba agitada por ventilador

Resumen

Estudiar la combustión de atomizados es difícil debido a la multiplicidad de variables interdependientes involucradas, tales como presión, temperatura, tamaño de gotas, distribución del tamaño de gotas, etc., especialmente en equipos industriales. Por ello, se ha seleccionado para el presente estudio un equipo para ensayos fundamentales de la combustión en nubes de gotas. Antes de efectuar un estudio de la combustión es indispensable caracterizar los aerosoles producidos en este equipo. La distribución de gotas dentro de la mezcla sin combustión se caracterizó usando varios diagnósticos con laser y se determinaron variables como diámetro medio Sauter, número densidad y relación de equivalencia gaseosa y de líquido. En este recipiente, se obtuvieron nubes de gotas prácticamente de tamaño único, siendo el tamaño de estas una función del tiempo muy bien definida.

Palabras clave: Caracterización, combustión de atomizados.

1. Introduction

The combustion of clouds of fuel droplets is of practical importance in gas turbines, diesel and spark ignition engines, furnaces and hazardous environments. So complex are the various processes of droplet formation, evaporation, mixing and chemical reaction that it is not yet possible to mathematically model them adequately.

Several works have been aimed to correlate characteristics of aerosols and their effect on burning velocity and some other properties. Exploration of important parameters affecting combustion, utilising experiments that simulate industrial applications, is difficult due to the multiplicity of dependent variables involved. Since the essential aspects of single-droplet combustion became clear, investigations on droplet clouds are necessary for a further approach to spray combustion [1]. The importance of a proper characterization of sprays in a combustion system has been stressed given the important effect that they have on pressure rise in engines, fuel economy and pollutant emissions rates [2], also the difficulty in producing sprays with precisely defined parameters (such as drop size, vapour fraction, etc.) has been recognised [3].

Several techniques have been developed for sprays characterization in the last three decades, most of them based on laser diagnostics which are preferred because are non-intrusive methods and can be used on-line, in-situ for many different purposes. By using engines equipped with optical access, the behaviour of the injected spray can be studied with laser spectroscopy and increase the understanding of the combustion process as well as supplying the CFD calculators with experimental information. For example with the Laser-Induced Exciplex Fluorescence (LIEF) method it is possible to image the liquid and the vapour phases of the injected fuel separately with two cameras. To achieve exciplex emission, two dopants are added to the fuel. At excitation of one of the dopants, these molecules can react with the other type of molecules and form an exciplex [4]. The exciplex is mainly established in the liquid, because of higher density of the two exciplex formers. The emission from the exciplex is red-shifted in wavelength compared to single-fluorescing dopants and therefore it is possible to separate fluorescence from the liquid phase and the gas phase in spray studies [4]. Other laser spectroscopic methods used, on spray studies, are Mie scattering combined with Laser Induced fluorescence and also Schlieren and Shadowgraph imaging on sprays [4]. Elastic scattering and the Lorenz-Mie (LM) theory in particular is used for the characterization of sub-micron- and micron-sized droplets of organic fuels in sprays and aerosols. Calculations on the Lorenz-Mie theory show that backward-sideward scattered visible radiation can be used for unambiguous detection of ensembles of homogeneous droplets of organic substances with diameters around 1 micrometer [5]. The LM theory has been used also to characterize different size groups in a burning spray. A 3-D technique based on a picosecond laser and a streak camera has been demonstrated for measurements of fast and turbulent biphase flows. The entire 3-D information could be obtained within a time-span of less than 15 nanoseconds [5].

The laser-extinction measurements (LEM) is another standard technique used in droplet cloud characterisation which uses a laser beam passing across the fluid and measures the residual laser light intensity at the fluid output [6]. The particle concentration is estimated from this measurement.

Other techniques also currently used in the study of the dynamics of fluid and embedded particles are the laser-induced incandescence (LII) [7], the laser-induced scattering (LIS) [7] and the standard laser Doppler anemometry (LDA) [8] frequently with the aim to determine the properties of emitted particles for in situ monitoring of combustion effluents.

Commercial equipment based on laser diffraction, such as, the Malvern Mastersizer X™, operating in transient mode, has been used to examine droplet growth, final droplet size and mono-dispersity, while Particle Image Velocimetry (PIV) has been used to confirm pre-ignition quiescence [9].

About the experimental rig, most works done during the 70's and 80's were performed on burners, for example Myers and Lefevbre (1986) correlated Sauter mean diameter data from plain-jet air blast atomizers Hayashi and Kumagai (1974) were the first to use the Wilson cloud chamber principle to produce thermodynamically sprays and use it for combustion studies, by expansion-cooling of gaseous fuel-air mixture using a cylinder-piston device, where fuel vapour becomes supersaturated and some portion condenses into droplets.

Nomura *et al.* (2000) undertook a basic study of spray combustion with a rapid expansion apparatus, similar to that of Hayashi and Kumagai (1974) that produced monodispersed fuel droplet clouds. These experiments were performed under microgravity conditions to prevent droplet falling and buoyancy.

Atzler and Lawes (1998) presented results for iso-octane in the same vessel used for the present study (a cylindrical bomb) looking for enhancement in burning velocity in aerosol-vapor clouds compared to that for gaseous mixtures.

Cameron and Bowen (2001) used a similar combustion apparatus to the present authors also based in the principle of the Wilson cloud chamber and similarly produced monodisperse droplet clouds of ethanol in the transition range from 5 to 15 μm where laminar burning velocity enhancement may occur.

Fundamental studies at The University of Leeds have been undertaken around two fan stirred bombs [12, 13]. The excellent optical access provided by these bombs facilitates the use of experimental techniques such as 4 dimensional (3 of space and 1 of time) laser sheet imaging.

The present work reports the characterization of two-phase combustible mixtures of iso-octane in one of the above mentioned fan stirred bomb, at conditions that are difficult to attain by other techniques. These include data at low temperatures, low pressure and low equivalence ratio. This study provides a wide range of laminar and some turbulent conditions at which combustion experiments might be undertaken.

2. Experimental Apparatus and Techniques

The combustion vessel and auxiliary equipment for the preparation and calibration of aerosol clouds are shown schematically in Figure 1. The combustion vessel is a development of an earlier one by Abdel-Gayed *et al.* [12] which was used only to study the burning of gases and dusts [14]. It comprised a 305 mm diameter by 305 mm long cylindrical bomb in which four fans, driven by 1.5 kW motors generated, when required, uniform and isotropic turbulence within a central region of 150 mm diameter. Windows of 150 mm diameter were installed in both end plates to provide optical access for various laser diagnostics. Elevated temperatures could be obtained by the use of two electrical heaters attached to the inside walls of the bomb.

The bomb was modified by Atzler and Lawes [11] to produce aerosol mixtures based on the Wilson cloud chamber technique [15]. This technique has been used in combustion studies by Hayashi and Kumagai [1] and Nakabe *et al.* [16], to generate well defined, near mono-dispersed, droplet suspensions in-situ by controlled expansion of a gaseous fuel-air mixture into a second vessel. For this, the combustion and expansion vessels were first evacuated to less than 1 kPa before isolating the combustion vessel from the expansion vessel with a pneumatic valve. Iso-octane was then injected into the combustion vessel, with a glass syringe, through a needle valve. Complete evaporation of the liquid was confirmed by comparing the change in pressure within the vessel during injection with the partial pressure expected for the mass of fuel injected. Agreement was, in all cases, found to be within 6%.

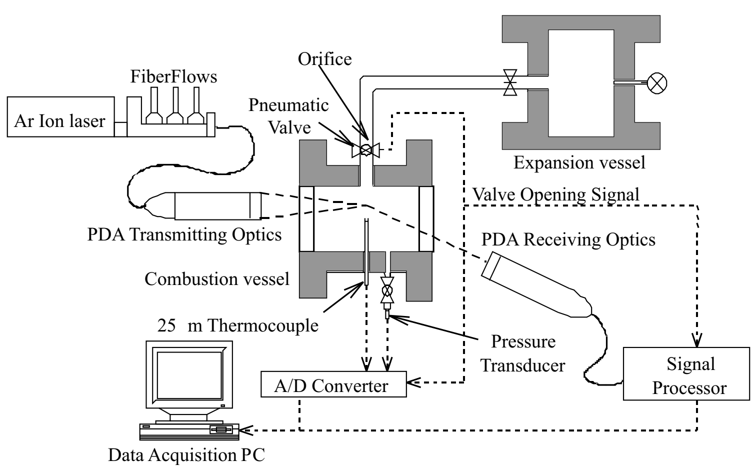

Figure 1. Experimental apparatus for droplet size measurement using Phase Doppler Anemometry (PDA) system.

Finally, dry air from a bottle was allowed into the vessel to achieve the desired equivalence ratio and initial pressure. Complete evaporation and mixing was assured by running the fans for some time before continuing. For the laminar measurements, the fans were then stopped and the gaseous pre-mixture allowed to settle for at least 10 seconds. For the turbulent measurements the fans remained running all along the experiment. Immediately prior to the measurements, the mixture in the combustion vessel was allowed to vent, at a controlled rate for up to 3 seconds, through an orifice into the expansion vessel. This caused a reduction in mixture pressure and temperature that took it into the wet regime such that droplets were formed. The relevant conditions during droplets condensation, which include pressure, temperature, liquid and gaseous phase equivalence ratio, droplet diameter distribution and number density, were functions of initial pressure, temperature and rate of expansion. To minimise fuel absorption onto the vessel walls and fans, and to minimise the effects of particulates on nucleation, the surfaces were mechanically and chemically cleaned to remove any residual deposits before the experiments.

A requirement of the present apparatus was to produce a well-defined uniform cloud of fuel droplets within a premixed fuel vapour–air mixture. The characteristics of this mixture were required to vary to cover a wide range of initial conditions for combustion studies. This required a wide range of initial conditions for mixture preparation, such as initial pressures of 150, 200, 250 y 300 kPa, at overall equivalence ratios 0.8, 1, 1.2 and 1.4, expansion rates controlled by orifices of 5, 6 and 7 mm. In the turbulent experiments orifice diameters were 20mm or more and the root mean square turbulent velocity, u´, was also varied to 0.8, 1.6 and 2.5 m/s. One of the main aspects of the droplet cloud characterisation was the measurement of the temporal variation of droplet Sauter mean diameter, D_{32}, in the rig during the expansion process, because as shown by many authors [17], burning rates on two-phase mixtures are dependent on D_{32}. Ignition conditions can be defined based on this. The droplet size measurements were performed by Phase Doppler Anemometry, PDA, the arrangement of which is shown in Figure 1. It comprised a 30 mW, LaserPhysics, Ar-ion laser, transmission and receiving optics and a signal processor, model 58N10, supplied by DANTEC. To determine the mass fraction of liquid fuel at any instant, the droplet number density (which is the amount of droplets per unit volume and also an important parameter to be defined in the characterisation), n, is required in addition to D_{32}. However, it was not possible to obtain number density measurements from PDA because of its small measurement volume and low data rate. Therefore, estimates of number density were obtained from photographs (laser sheet imaging) and from laser attenuation measurements using the Beer-Lambert Law [18] which assumes a mono-dispersed droplet cloud

$$I / I_o = \exp\left(-n \frac{\pi D_{32}^2}{4} Q_c(f, D)\right), \qquad (1)$$

where, I/I_o is the normalised laser power intensity, Q_c is the attenuation efficiency which is the function of wave frequency, f, and droplet diameter D, and is constant for visible frequencies, and L is the optical path length taken to be 305 mm which is the length of the vessel**.**

To corroborate that calculation, an experiment was attempted. During the expansion period a JVC digital colour video-camera was focused into a small volume inside the bomb, producing visible and quantifiable droplets, which were counted manually. The arrangement of apparatus for these experiments is shown in Figure 2. A pulsed *Nd-YAG* laser from *Spectron laser systems* model SL800, was chosen because of its combination of high energy and adjustable repetition rate. With pulses of 15 ns duration, it could operate at the frequency doubled wavelength 532 nm (visible, 320 mJ), chosen due to the ease of working with a visible beam. A laser sheet was formed with the present laser and appropriate optics. The framing rate for the video-camera was not known but was estimated to be 25 Hz.

For laser attenuation measurements a Uniphase 20 mW helium-neon laser with a wavelength of 632 nm was used as a light source, and a laser power meter received the beam after passing through the bomb and windows and transformed the intensity signal to produce an output in volts.

The overall equivalence ratio, $_{ov}$, of the two-phase mixture at any point before ignition is given by

$$\phi_{ov} = \phi_g + \phi_l \ , \tag{2}$$

where $_g$ and $_l$ are the equivalence ratios for the gaseous and liquid phases. The mass of liquid fuel, m_{fl}, is calculated from the volume mean diameter of droplets, D_{30}, and their number density:

$$m_{fl} = \rho_l \pi \frac{D_{30}^3}{6} nV \ , \tag{3}$$

where V represents the volume of the vessel and $_l$ is the density of liquid fuel.

The density of the liquid fraction for iso-octane, required to calculate the condensed mass was determined as a function of temperature, T, from the following expression by Yaws [19],

$$\rho_l = 239.4 * 0.266^{\left(-\left(1-\frac{T}{543.8}\right)\right)^{\frac{2}{7}}} . \tag{4}$$

The total mass of fuel, m_f, at any instant after condensation is

$$m_f = m_{fg} + m_{fl} \ , \tag{5}$$

where m_{fg} is the gaseous mass of fuel. Separating the gaseous mass of fuel and substituting for the total mass of fuel in terms of fuel partial pressure, p_f, gives

$$m_{fg} = \frac{\overline{M}_f p_f V}{RT} - m_{fl} \ , \tag{6}$$

where $\overline{M}_f$ is the molar mass of fuel, R is the universal gas constant and T is the instantaneous temperature. The partial pressure of the fuel can be expressed from the stoichiometric equation as

$$p_f = p \frac{\phi}{59.5 + \phi} \ , \tag{7}$$

where, p is the instantaneous pressure during expansion. The original equivalence ratio, , for the gaseous pre-mixture was assumed to be equal to $_{ov}$. Substituting equation (7) in (6) gives

$$m_{fg} = \frac{\overline{M}_f p \phi V}{RT(59.5 + \phi)} - m_{fl} \ . \tag{8}$$

Therefore the liquid and gaseous fraction of fuel are

$$\frac{m_{fl}}{m_f} \ , \quad \frac{m_{fg}}{m_f} . \tag{9}$$

The gaseous phase and liquid phase equivalence ratios are given by

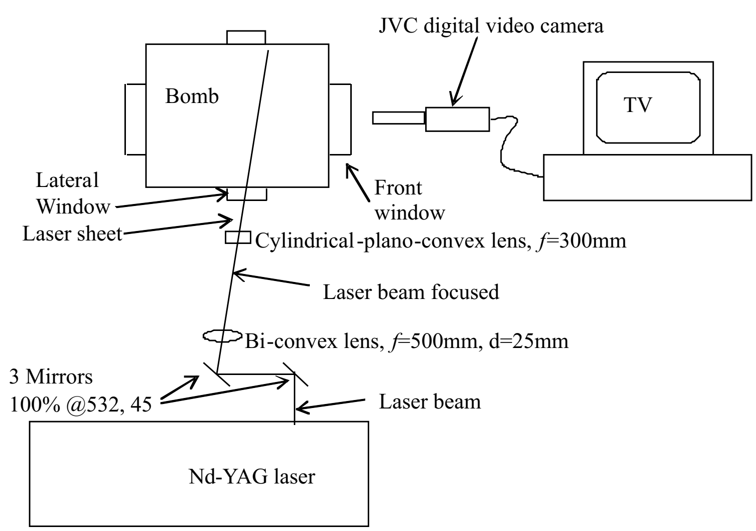

Figure 2. Apparatus arrangement of laser sheet imaging for n estimation.

$$\phi_g = \frac{\dfrac{59.5\overline{M}_a}{\overline{M}_f}}{\dfrac{m_a}{m_{fg}}} \quad , \quad \phi_l = \phi_{ov} - \phi_g \ ,$$

where $\overline{M}_a$ is the molar mass of air and m_a the mass of air.

3. Results

Results from the present research include the variation with time of pressure, temperature, droplet size, number density and equivalence ratio during the expansion process in the bomb that leads to the formation of a two-phase air-fuel mixture in it, with the purpose to establish conditions for further combustion studies (not reported here).

Shown in Figure 3 is the variation of pressure and temperature during the expansion of a stoichiometric mixture of iso-octane and air from an initial temperature and pressure of 303 K and 200 kPa. Also shown in Figure 3 is the variation of pressure gradient, dp/dt, with time, and this is discussed below. The measured temporal variation of temperature initially exhibited a polytropic relationship, as shown by the chain dashed curve in Figure 3, in which the polytropic index was found to be 1.34, indicating some heat transfer from the vessel walls. At the start of nucleation, the measured temperature departed from that of the polytropic expansion, in part, due to the latent heat of condensation. Results from turbulent measurements were very similar in trend to those for laminar. For turbulent experiments, more rapid expansion was required because the rate of droplet evaporation in the control volume was much higher than for laminar work, due to turbulent heat transfer from the wall region. The expansion time was reduced to 0.3 seconds, by removing the orifice plate from the pipeline or, in some cases, using a 20 or 25 mm diameter orifice.

For the same initial conditions as in Figure 3, Figure 4 shows the variation of Sauter mean diameter, with time for seven locations within the central region of the vessel. They were obtained by PDA and the present system could not adequately detect droplets of less than about 2 μm. Also shown in Figure 4 is the standard deviation of D_{32}, $\sigma_{D_{32}}$. Because the measurements of D_{32} at different locations were obtained from different experiments, values of $\sigma_{D_{32}}$ represent the combined effect of spatial variations and experimental repeatability. The low values of $\sigma_{D_{32}}$ indicate the near mono-dispersed distribution of droplet size that result in the present apparatus.

The solid line in Figure 4 is a curve fit through the experimental values of D_{32} and it was extrapolated to zero to yield the time of onset of nucleation. This was necessary because, as shown by [20], the rate of pressure reduction can have a significant effect on the start of nucleation. Hence, the onset of nucleation could not be

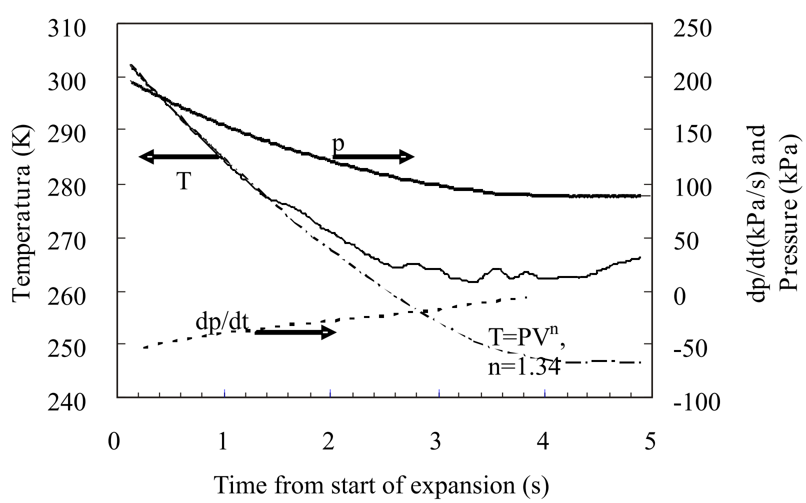

Figure 3. Variation of pressure and temperature with time after the start of expansion of a stoichiometric mixture of iso-octane-air. The initial conditions were 200 kPa and 303 K.

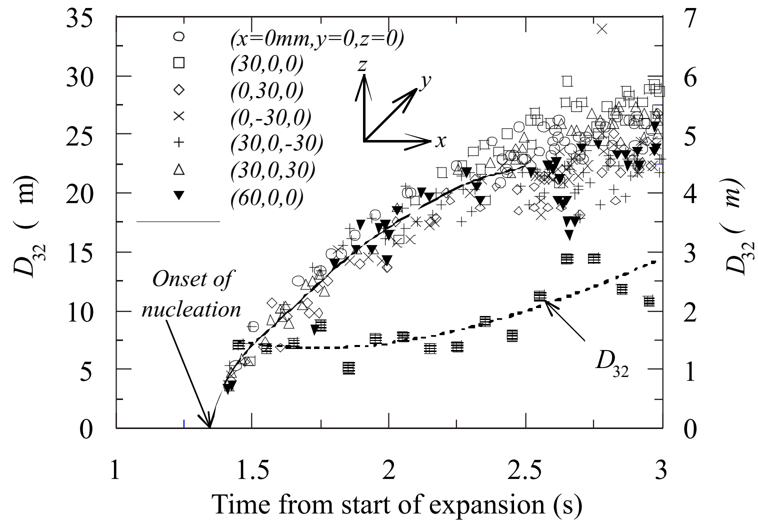

Figure 4. Droplet size variation with time and space. Conditions are the same as in Figure 3.

determined simply from measurements of pressure and temperature, nor could the subsequent liquid fraction. The results of Dobbins [20] show that with increasing values of $(1/p)(dp/dt)$, the onset of nucleation, the Wilson line, occurred further (lower pressure and/or temperature) from the saturation line.

Droplet size measurements for turbulent clouds were very similar as those for laminar, except for the droplet lifetime which was reduced by the rapid expansion process explained above.

A laser attenuation measurement to yield droplet number density in conjunction with measurements of D_{32} is shown by the dashed line in Figure 5, at the same conditions of Figure 3. The number density is shown by the solid curve in Figure 5 and was obtained from equation (1).

Shown by the circular symbols in Figure 5 is the variation of number density with time that was obtained from microscopic imaging. Because of the uncertainties due to laser sheet intensity and thickness variations, the results from the imaging were normalised to agree with that from the laser attenuation measurements at 1.4 seconds after the start of expansion. Similar trends were obtained from both techniques and they indicate that, from about 1.6 ms after the start of expansion, droplet number densities are approximately constant. This corresponds to droplet Sauter mean diameters of over 7 μm.

Shown in Figure 6 is the variation with time of T, D_{32}, p, ${}_g$, and m_{fl}/m_f. Also shown by the triangles in Figure 6 are values of D_{32} obtained with a Malvern particle size analyser by Hargrave *et al.* [4]. These values, which represent an integration of the Sauter mean diameter throughout the optically accessed region of the vessel, are in good agreement with the present PDA measurements.

Figure 6 shows that the present vessel provides a range of two phase mixtures within which combustion studies can be undertaken, such range depends on the initial gaseous conditions of pressure, temperature and equivalence ratio and on the time between the start of expansion and flame initiation. Because laminar combustion takes place within a duration of, typically, 50 ms while droplets develop during condensation relatively slowly over about one second, it can be assumed that droplet size and distribution are the same as those at ignition, and that the evaporation of droplets at or near the flame front is almost instantaneous. A similar relationship exists between the combustion time and droplet condensation time during turbulent combustion.

4. Conclusions

The present is a fundamental study of two-phase mixture characterisation at conditions pertaining to gas turbine altitude re-light. Characterisation was undertaken under laminar and turbulent conditions. The aerosols of iso-octane have been generated by condensation from an initially gaseous charge. The effects of changes in overall equivalence ratio, pressure, temperature, expan-

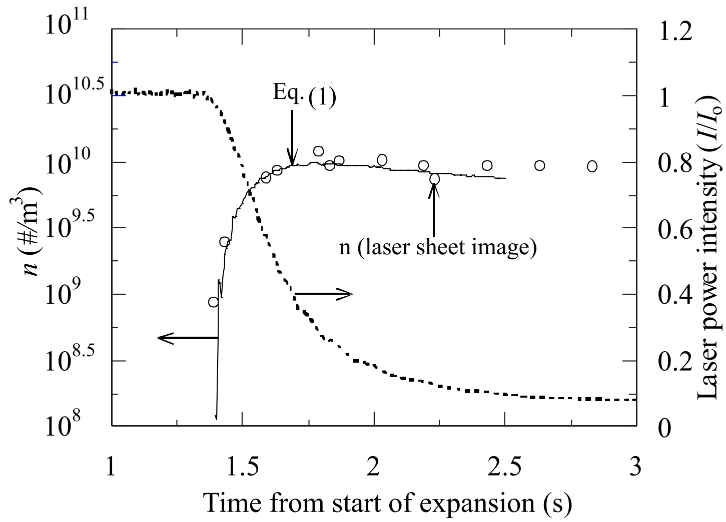

Figure 5. Variation with time of laser power attenuation and droplet number density. Conditions are the same as in Figure 3.

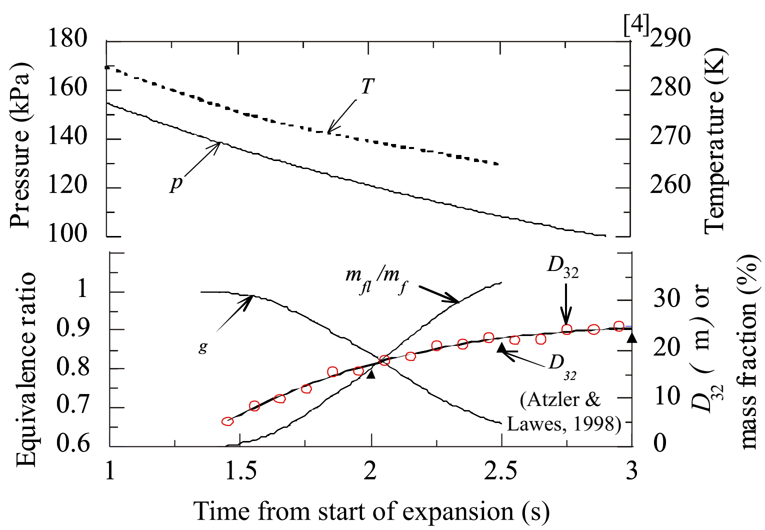

Figure 6. Variation of all relevant mixture properties with time during expansion. Conditions are the same as in Figure 3.

sion ratio and turbulence on drop diameter and number density were evaluated.

- Aerosols were generated using the Wilson cloud chamber principle. This method used the cooling of a fuel-air mixture by expansion to cause the condensation of a part of the initially evaporated fuel into a fog of droplets. Unlike aerosols produced by injection systems, these droplet clouds were homogeneously distributed in space, the droplets were of nearly equal size and the level of turbulence generated in the combustion chamber by mixture preparation was negligible. Aerosols were generated at a wide range of conditions: Sauter mean diameter from 2 to 30 μm, pressures from 90 to 258 kPa, temperatures from 266 to 293 K and overall equivalence ratios from 0.8 to 1.4.
- Although gaseous and liquid fractions of fuel in the mixture and the droplets diame-

ter were not independent of each other, the expansion method offered some flexibility through the use of different pre-expansion pressures, temperatures and equivalence ratios.

List of Symbols

D droplet diameter (μm)

f frequency

I laser intensity

L optical path length (m)

m mass (kg)

M molar mass (kmol/kg)

n number density of droplets (m^{-3})

p pressure (kPa)

Q_c attenuation efficiency

R universal gas constant (KJ/kg/K)

t time (s)

T temperature (K)

V volume (m^3)

ρ density (kg/m^3)

ϕ equivalence ratio

Subscripts:

a air

f fuel

g gas

l liquid

o original, non attenuated, reference condition

ov overall

30 volume mean diameter

32 Sauter-mean diameter

Abbreviations:

PDA phase doppler anemometer

LM Lorenz Mie

LIEF laser-induced exciplex fluorescence

LEM laser-extinction measurements

LII laser-induced incandescence

LIS laser-induced scattering

LDA laser doppler anemometry

PIV particle image velocimetry

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