Simultaneous Mist and Flame Propagation Characterisation Studies in a Fully-Confined Bomb

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1 Introduction

Two-phase, or mist, incidents represent a complex potential risk for process industries [1], and are not well understood when compared to more common gaseous or liquid releases. Research is complicated not only by the understanding of multifaceted reaction chemistry, but also the development of intricate and robust experimental facilities that characterise droplet formation, in addition to the propagation of flames through turbulent flow fields. Development of such systems enables comprehensive investigation of the underlying mechanisms that contribute to two-phase explosions and in particular the potential for acceleration of the flame [2].

Cardiff's large (34 L) Constant-Volume Combustion Bomb (CVCB) has previously been used to investigate flame propagation with both gaseous and pre-vaporised reactants [3, 4, 5], and has now been modified to generate and burn two-phase mixtures. The presented work outlines changes made to the vessel (based on a previous, smaller cloud chamber design [6]) to develop the Dynamic-Volume Combustion Bomb (DVCB), which utilises rapid decompression to cool reactants, and form quasi-homogenous mists. Some of the challenges encountered when developing the facility are discussed, in addition to the presentation and discussion of preliminary commissioning results.

2 Original CVCB Configuration

A diagrammatic layout of the initial CVCB is shown with ancillary components in Figure 1. Constructed from stainless steel, the cylindrical bomb has a working volume of approximately 34 L, an internal diameter of 260 mm, and was designed to allow for a longer measurement window in the unaffected pressure region of flame expansion [7]. Eight external band-heaters and four thermocouples are employed in a PID control system to regulate ambient reactant temperature. Larger bands are used to heat the bulk of the chamber mass, with localised smaller heaters employed to avoid cold-spot formation. This is particularly important when forming two-phase mixtures, as the partial pressure of pre-vaporised reactants must approximate the equilibrium vapour pressure at any specified temperature. Cold-spots would lead to condensate formation and therefore change the designated global equivalence ratio. Four diametrically opposed 100 mm quartz viewing windows facilitate high-speed capture of flame propagation by employing a widely used Schlieren optical technique [3-5, 8-10].

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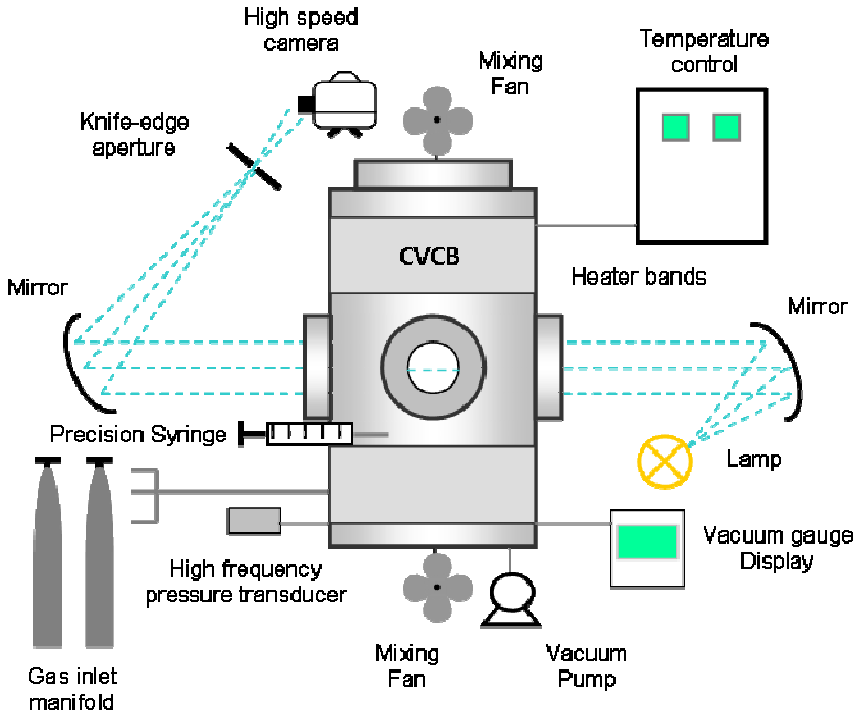

Figure 1. CVCB configuration, with additional experimental components

The Schlieren method generates an image of the effective working area in a collimated light beam, and utilises the change in refractive index resulting from variation in fluid density. A converging mirror is initially used to collimate a light source through the windows, with a secondary reflection then employed to focus light on to a knife-edge aperture. The refracted portion of the beam unblocked by the edge focuses imperfectly, thereby generating intensity gradients which are used to identify the isotherm representative of the flame front boundary. The light is captured by a charge-coupled device used in a Photron FASTCAM APX-RS high-speed camera. The system allows for a spatial resolution of approximately 0.14 mm per pixel, with diametric propagation rates calculated by bespoke software employing commercially available edge-detection algorithms. In addition a 0-12 bar GE Unik-5000 transducer is also employed in the system to capture the pressure transients resulting from combustion, acquiring data at a rate of 2 kHz.

Gas is introduced to the system through a manifold with batched mass-flow control (Bronkhorst Cori-flow). Alternatively liquid reactants are injected through a self-sealing septa, sealed in the chamber wall. The level of contamination error and equivalence ratio are regulated by monitoring changes in predetermined values of partial-pressure. This is enabled though the use of an ASG 0-2000 mbar sensor, with a resolution of 0.1 mbar and a real-time TIC 3 instrument controller readout. The system also controls and normalises chamber vacuum levels between tests, with set minimum pressures achieved following multiple evacuations. Adjacent internal fans are used to blend reactants after filling, and capacitor discharge ignition is achieved through the use of a variable voltage supply and fine electrodes introduced at 45° to the plane of measurement (to minimise any influence on propagation). Experiments are sequenced using bespoke code written using National Instruments LabVIEW, with individual components triggered by simultaneous TTL discharge from a pulse generator, feeding the ignition supply and data acquisition systems.

3 Modifications to the Experimental Setup

As previously stated, the mechanism used to form two-phase mixtures was rapid decompression: Pistons were used within the chamber to expand the pre-vaporised reactants (at near the equilibrium vapour pressure) provoking a drop in temperature, forcing the saturated vapour out of the gas phase and forming a quasi-homogenous mist. Comprehensive modifications were required to facilitate mist formation, with the major engineering components shown schematically for the upper half of the rig in Figure 2. First, a pneumatic control system was required to enable the sequenced actuation of two opposing pistons at each end of the chamber. Double-acting linear actuators (NORGREN type PRA/182063/M/180) were employed to move each piston, with quick release exhaust vents fitted on one side to accelerate retraction. Independent 5/2 solenoid spool valves utilised an 8 bar pneumatic supply to position each piston in accordance with control software demands (an updated version of the LabVIEW code mentioned in section 2). This was sequenced with a configurable offset between retraction and ignition time to ensure full formation of the flammable mist. In addition, mixing fans were repositioned to sit in the piston face, as opposed to the cylinder end. The prominent challenge associated with piston actuation was achieving an adequate seal against the polished inner-chamber face (to precisely control equivalence ratio), balanced against ensuring that retraction speed was rapid enough to enable mist formation.

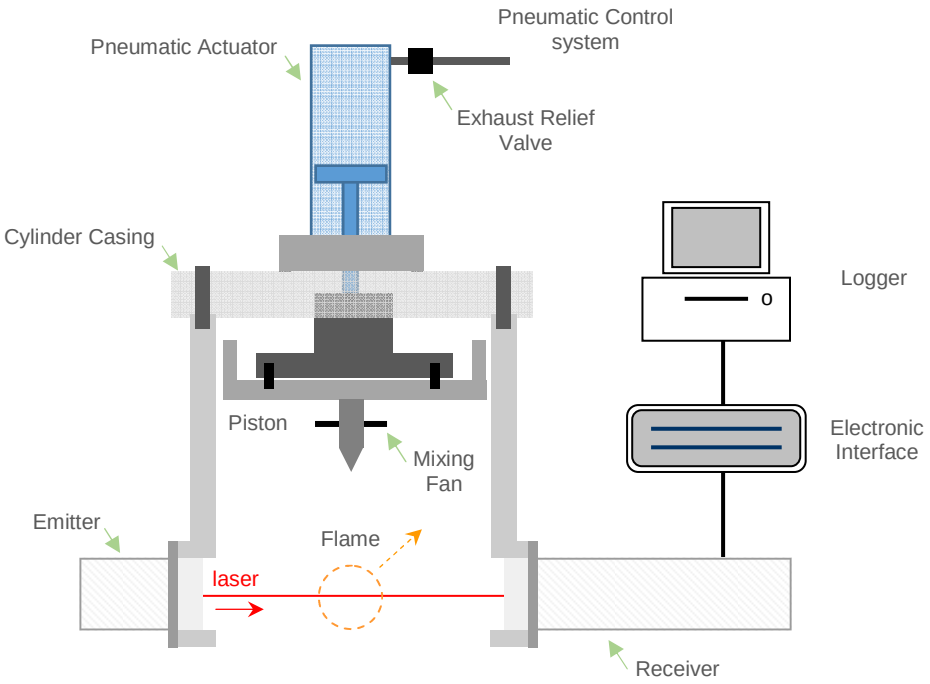

Figure 2. Schematic of system components added to facilitate mist formation

Droplet size distribution is subsequently measured by a Malvern Instruments Spraytec, with the laser crossing the internal span between the emitter and receiving optics through two additional 100 mm quartz windows, perpendicular to the Schlieren line-of-sight. The system is capable of continuous measurement using a diffractive logic technique (further information in [11]). The associated optics enable measurement in the range from 0.5 to 1000 microns, at up to 2.5 kHz. This was deemed suitable with expected Sauter mean diameters in the 5-25 micron range. The Spraytec measurement region is located at a higher position to the ignition electrodes, ensuring they do not obstruct the 10 mm diameter beam. This represents a significant limitation for the system; inasmuch that a static

laser position means the measured range must be assumed homogenous, with droplets outside the beam not measured. Raw scattering data is acquired and transmitted to the computer interface card, with results processed using RTSizer software [12].

The operational methodology requires a precise mass of liquid fuel to be introduced to the rig under vacuum, which is then allowed to fully vaporise, prior to the introduction of air for the specified pressure and equivalence ratio. The system operates with a potentially variable expansion ratio of up to 1.8-1, when running both pistons. However, it is limited by the pressure rating of the control pneumatics, so that if the test specification requires atmospheric combustion, the maximum expansion ratio is limited 1.4-1 (due to the force required to hold the large piston in position, when the system is over-pressurised prior to expansion).

4 Preliminary Commissioning Results

Initial commissioning tests were undertaken with Ethanol for combustion at atmospheric pressure. In order for the system to operate with the fuel at an equilibrium vapour pressure, variation in equivalence ratio necessitates a change in the specified rig temperature. In the equivalent flammable range, vapour pressure is sensitive to small changes in temperature, meaning fluctuations of only ±2 K can provide a significant difference in the achieved droplet distribution, or equivalence ratio. This means control of the system is complex, with real-time and precise readout of the system pressure essential, to ensure full fuel vaporisation (or conversely no condensation) prior to the introduction of air. Figure 3 below emphasises this, showing the change in size distribution for an increase in temperature from 306 K (◊) to 307.3 K (∆) for the first 2 seconds after the formation of an ethanol mist. This emphasises the need for a flexible experimental setup, with concurrent measurement of droplet size, in addition to characterising flame dynamics.

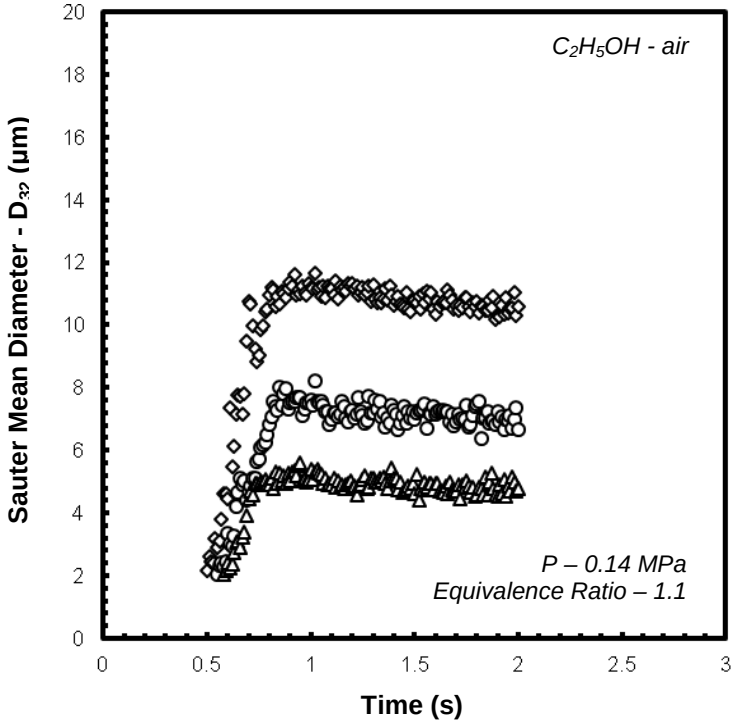

Figure 3. Change in Ethanol droplet size distribution with temperature in the range 306 K (◊) to 307.3 K (∆)

When satisfied that droplets were controllably and repeatedly produced, combustion trials were initiated (2 seconds after start of expansion) for investigation of two-phase ethanol flames at different ambient conditions of temperature and equivalence ratio (Ø). Three such mixtures and their propagation development (captured as a series of Schlieren images) are displayed in columns from top to bottom, showing their respective growth, in Figure 4 below. The propagation of the lean mixture (Ø=0.8) exhibits characteristics comparable to those observed when investigating a pure vapour flame, with a smooth and non-cellular surface area. However, even though measured droplet diameters are of a similar order, when the overall mixture becomes richer, the onset of cellularity is increasingly observed, appearing earlier as the mixture becomes progressively richer. These tendencies suggest increased thermo-diffusive instability, and agree with Lawes et al. [13] and Bradley et al. [14].

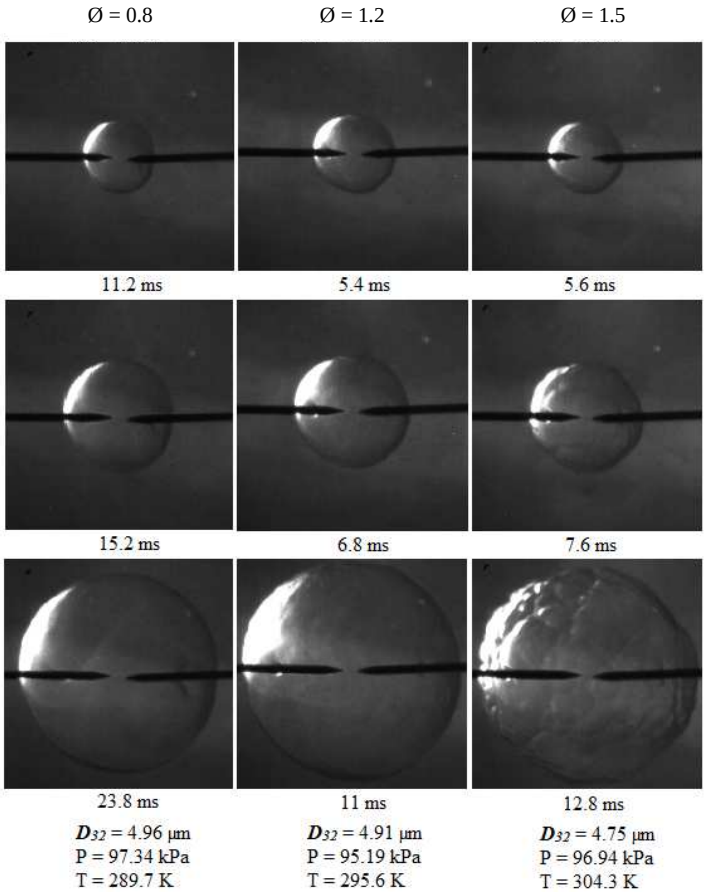

Figure 4. Observed variation in ethanol flame propagation with droplets, and an increase in equivalence ratio

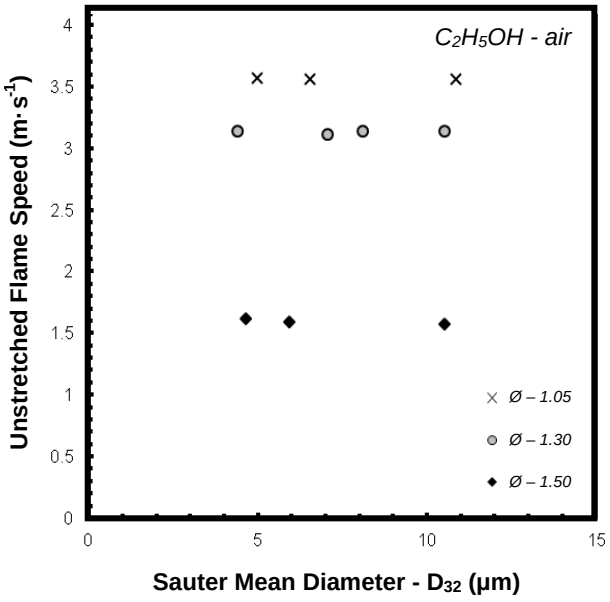

Figure 5. Change in observed unstretched flame speed with increase in mean droplet diameter

If apparent unstretched flame speed is quantified using the traditional methodology [2-10], correlating stretch rate against stretched flame speed, an increase in droplet size does not appear to yield a strong change in the measured value under these conditions (as shown in Figure 5). This possibly results from vaporisation of the fine ethanol droplets ahead of the flame, with a denser mist, or larger droplets, and more comprehensive analysis required to observe the effective inertia witnessed by other authors [15]. The work is ongoing, with a methodology modified to form larger droplets currently under investigation, in addition to burning an alternative fuel (CH_3OH).

Summary

A new optical bomb with integrated diagnostics, which extends the unaffected pressure region for two-phase flame propagation studies, has been designed and commissioned. Simultaneous mist and flame-speed characterisation has been achieved reducing uncertainty over initial pre-ignition droplet size, which is shown to be sensitive to starting temperature specification. In the droplet size range 4-12 μm and equivalence ratio 1.05-1.50, no discernible enhancement effects have been observed. However, the study is ongoing, with further work undertaken to improve the experimental and analytical technique.

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