Characterisation of Mist Generation through Cloud Chamber Technology

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Abstract
This paper develops understanding and appropriate techniques for characterising mist generation from super-saturated liquid-air systems. Whilst the technology for this technique originates from Wilson (1897), to date mainly a qualitative understanding of the relationship between mist characteristics and initial control conditions exists. Here, an improved design of cloud chamber, which facilitates accurate control, is described, and temporal measurement techniques for thermodynamic control parameters are proposed and appraised. Mist characteristics are quantified using transient laser-diffraction measurements. Expansion is described by a polytropic thermodynamic process with appropriate coefficients, and the influence on mist generation of primary control parameters expansion rate, expansion ratio and initial temperature are quantified and analysed. Applications include fundamental studies of two-phase combustion, quenching explosions by ultra-fine water mists and well as the traditional meteorological interest.

1. Introduction

The thermodynamic processes that govern generation of clouds and mists, such as occur in the natural environment, have intrigued scientists for over a century. Wilson (1897) was so inspired that he attempted to simulate such conditions in his Cambridge laboratory; the series of experimental devices he developed became known as 'Wilson Cloud Chambers' [1]. These devices facilitated a rapid expansion of a humid environment, inducing a saturated or super-saturated atmosphere. One of Wilson's objectives was to determine the degree of super-saturation the atmosphere could sustain without mist formation for given process conditions. He showed empirically that a lower expansion ratio appeared to exist below which mists could not be formed. The primary variables for the process change are initial temperature, expansion ratio and expansion rate, and mist characteristics change in accord with changes in these variables. However, no definitive methodology for predicting cloud characteristics as a function of operating parameters is known to the authors.

Various research applications for cloud chambers have been demonstrated over the last century. Of interest to the current investigators is the application first demonstrated by Hayashi and co-workers [2], where it was shown that the cloud chamber principle may be applied to generate 'idealised' fuel mists for study of combustion fundamentals. However, none of the three chambers developed by Hayashi [2-4] allowed generation of fuel mist combustion in the most interesting, practical size of constituent droplet sizes - the so-called 'transition' droplet size, where a currently ill-defined transition occurs between mist burning in 'vapour' or 'droplet' mode.

Bowen and Cameron, [5&6] proposed and subsequently demonstrated that Hayashi's methodology could be developed to design a facility for generating mists traversing the 'transition' fuel droplet sizes (5µm<d<15µm). Moreover, they proposed that a cloud chamber suitably designed could be utilised to study the efficacy of fine water-mists in retarding, or indeed quenching, a propagating flame; confirmation of this application has yet to be published. With these applications as a focus, it becomes apparent that there is a requirement for improved understanding and predictability of mist generation utilising the cloud chamber approach, which forms the aim of this paper.

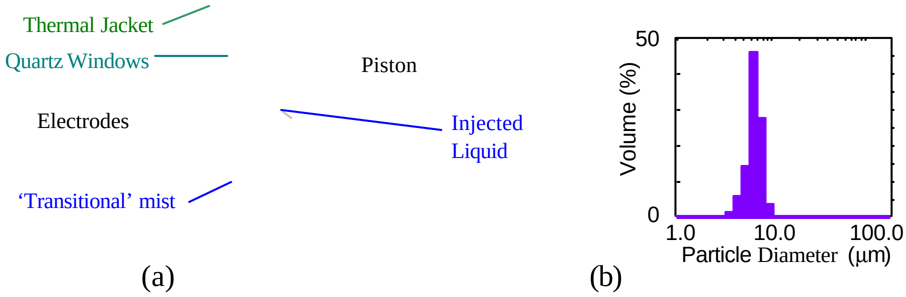
2. Experimental Facilities and Diagnostics

2.1. Cardiff Cloud Chamber Facility

The Cloud Chamber utilised in this research programme is an improved version of that originally designed and commissioned by Cameron [6]. The original chamber (Figure 1a) comprised a 120mm id steel cylinder fully enclosed by a quartz window at one end, and a piston, edged circumferentially with non-lubricated seals, at the other. The piston is pneumatically-driven such that it may be retracted from an initial position to a pre-set final position at variable speed. Hence, by varying the final piston position post-retraction, and the speed of retraction, independent control of two primary mist control variables is afforded. Temperature within the rig was varied primarily via a heated jacket, and further optical access is achieved by two diametrically-opposed quartz windows. Liquid is added into the confined rig using accurate micro-pipettes, though the rig was slightly vented to atmosphere in the original design as the liquid was added.

A number of subtle changes have been made in order to improve the reliability and accuracy of data sets obtained. An efficient system for mechanical mixing and uniform heating of the entire cloud chamber is required to ensure a homogenous mixture before expansion. This has been achieved through the addition of a re-circulation system driven by a heated-head pump, and a newly specified, fully automated heating jacket capable of heating the entire chamber body and re-circulation pipe work from ambient temperature to 120°C. The aforementioned system coupled with comprehensive insulation eliminates relative 'cold-spots' throughout the rig, which ensures there is no condensation of fluid out of the vapour phase during mixing.

Assurance of the quality of the initial contained volume of air is required to allow the precise levels of humidity to be specified within the rig. Modifying the re-circulation system, it became possible to purge the entire rig with compressed air which had been passed through a filtration system comprising both water and hydrocarbon traps. This allowed tightly controlled levels of humidity to be prepared in the chamber.



(a) (b)

Figure 1(a)&(b). Schematic of Cloud Chamber at Cardiff demonstrating Mist generation and Typical Droplet Size Distribution Created in Cardiff Cloud Chamber

For data reliability and repeatability, accurate initial pressures within the chamber are required. This is now achieved using an absolute pressure sensor, which indicates whether gas is to be added to or taken from the airspace via self-sealing septa using a gas tight syringe.

2.2. Experimental Diagnostics

One of the objectives of this programme is to establish the thermodynamic state of the environment throughout the expansion and mist generation process by recording accurate temporal measurements of pressure, temperature, and expansion rate, and for droplet cases, droplet size and growth rate.

Pressure and expansion rate could be measured using 'off the shelf' technology with pressure signals being monitored using a 0-15psi absolute pressure cell, and expansion ratio being measured using a suitable linear potentiometer coupled to the piston, this latter device facilitating quantification of both retraction rate and expansion ratio. The transient response time of both the pressure sensor (1ms for 10% to 90% of step change) and potentiometer (with instantaneous response) render them directly applicable. However, quantification of the gas/vapour temperature requires some diagnostic development.

First, 'standard' thermocouples were considered for this application, but it was found that in the quiescent gaseous medium, these did not have a fast enough response time. For this reason, a compensated circuit (Figure 2) was proposed and developed, based on similar approaches for speeding up the response rate of similar temperature measurement systems [7&8] for other applications. The compensated circuit could then be calibrated for the 200μm bead-tipped thermocouple used in this study, and an adequate time constant achieved.

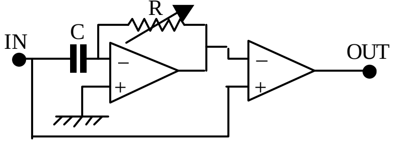


Figure 2. Thermocouple Compensated Circuit

Data capture is based around a National Instruments Data Acquisition system running 'Lab-View' software. This system allows transient recording of up to 8 channels at a recording rate of up to 10,000 samples per second, though for this programme only 3 channels acquiring at a rate of 1,000 samples per second was utilised.

The methodology used for quantification of transient droplet growth and final droplet size is laser diffraction (utilising a Malvern Mastersizerχ^{TM}) operating in 'transient' mode, such that a 'sweep' measuring droplet size is undertaken every 10ms over a 1 second period from the start of expansion. The chamber was originally designed to provide optical access for a range of laser-based measurements, and to minimise the effect of vignetting for laser-diffraction droplet sizing [6]. Furthermore, mist obscuration levels for this application are within an acceptable range for reliable characterisation of the clouds.

3. Experimental Programme and Results

The experimental programme was designed to characterise the thermodynamic characteristics of the cloud chamber, and furthermore, to gain a better qualitative understanding of the physical processes that affect the formation of mono-dispersed mists within Cardiff's cloud chamber. This facilitates better control and predictability of mist generation in the future. The expansion ratio was always chosen to be in excess of that representing Wilson's supersaturated limit for cloud-like generation (1.375) [1], to ensure repeated mist formation, which was confirmed for each experimental case. The range of expansion rate selected (0.1-0.4 m/s) facilitates generation of mists traversing the combustion ‘transition’ droplet size range, whilst the initial temperatures are suitable as representative conditions for the applications of fuel-mist combustion and ultra-fine water-mist mitigation.

For each case, three repeats were undertaken, with only the mean values presented and discussed in this paper. The initial pressure for each experiment was set at 1013 mbar before expansion, and a constant initial volume of 0.87 litres utilised throughout. As detailed in the previous section, transient measures of pressure, temperature and piston kinematics were recorded. For wet studies, droplet growth is also quantified.

3.1. Dry Cases

To develop understanding of the processes governing droplet formation, the characteristics of the expansion process of the cloud chamber first requires investigation. As a benchmark, a preliminary programme was undertaken utilising a ‘dry’ airspace within the cloud chamber, thus removing inherent complications associated with phase changes. A representative example of temporal experimental data for a dry case is presented in Figure 3:

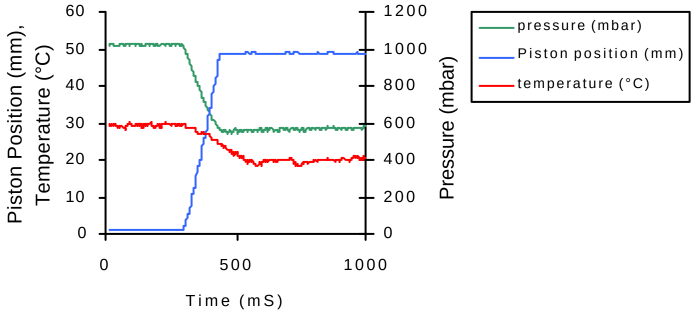


Figure 3. Transient recordings of Temperature, Pressure and Piston position against Time for a Rapid Expansion with Initial Temperature 30°C, Expansion Ratio 1.62

Electrical noise is an inherent problem for these measurements, and so a moving average line of best fit was required to facilitate a transient characterisation of the thermodynamic response of the expansion process. Table 1 specifies the ‘dry’ experimental programme. Experiments were conducted with initial temperatures of 30°C and 50°C, respectivly. 3 expansion ratios of 1.38, 1.62 and 1.87, chosen for compatibility with ongoing combustion-related research programmes utilising the cloud chamber. Expansion Rate is also systematically varied to assess its influence on mist formation [1-4&6].

Table 1. Summary of experiments conducted with 0% humidity

Initial Temp.(°C)	Expansion Ratio	Piston speed (m/S)	ΔT (°C)	ΔP (mbar)
30	1.87	0.38	11.5	545
30	1.87	0.18	9.5	545
30	1.62	0.42	10	491
30	1.62	0.16	8	491
30	1.38	0.35	7	336
30	1.38	0.16	6	336
50	1.87	0.37	9	545
50	1.87	0.19	8	545
50	1.62	0.33	10.5	491
50	1.62	0.19	9.5	491
50	1.38	0.38	7.5	336
50	1.38	0.17	6	336

Data such as those represented in Figure 3 may be used to model the thermodynamic process under dry conditions. Assuming an ideal gas and polytropic process, by presenting the thermodynamic data appropriately, it is possible to obtain the polytropic coefficient for the cloud chamber expansion process. In Wilson's seminal work, he presumed an adiabatic process with corresponding polytropic coefficient of 1.40, though no corroboration of this assumption was presented. Here, the data may be presented in several ways, and results are dependent not only on actual thermodynamic changes, but also the accuracy of the various measurement techniques proposed. Due to the inherently faster response times of the pressure sensor and linear potentiometer, pressure/volume correlations are considered the most accurate, whereas correlations involving temperature have been used for comparison, to assess the new improved methodology for temperature measurement in this challenging environment whilst also offering insights of qualitative trends.

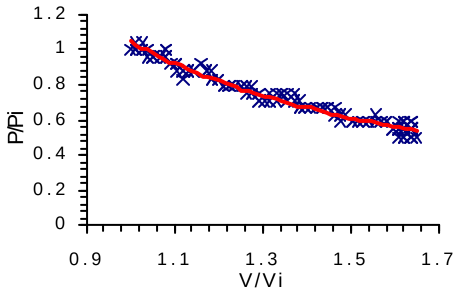


Figure 4. Pressure versus Volume Plots for a rapid expansion of the Cardiff Cloud Chamber initial temperature 50°C and Expansion Ratio 1.62

Using the pressure and volume measurements for 'fast' and 'slow' expansions, polytropic coefficients (PV) of 1.33 and 1.12 respectively are derived. By comparison, processing the temperature measurements similarly, lower polytropic coefficients (PT) of less than 1.1 were recorded for both expansion rates. These aforementioned (PV) coefficients approach the expected isothermal conditions.

3.2. Mist Generation

Similar studies to those described in section 3.1 but for 'wet' conditions have been undertaken, so that the effects of initial temperature, expansion ratio and expansion rate may be investigated with respect to droplet growth and ultimate droplet size.

It has been shown previously that the mists produced within the Cardiff cloud chamber are reasonably homogeneous and monodisperse [6]. Again reasonably mono-disperse mist were consistently measured in the new improved rig, as indicated in the representative Figure 1(b). Henceforth, mist quality is characterised by a single parameter, the Sauter Mean Diameter (SMD).

Again simultaneous temporal characterisation of temperature, pressure and piston position are recorded, but superimposed onto these plots are the additional characteristics of droplet growth from results produced by the Malvern Mastersizer χ^{TM}, run in transient mode simultaneously throughout the expansion (Figure 5). Note the relatively long quasi-steady period for mist and thermodynamic variables, lasting in excess of half a second, a very attractive feature for fundamental combustion studies and other applications.

Again a comprehensive programme was undertaken and a series of graphical representations of the format of Figure 5 were generated and analysed. A summary of all results for the mist generation programme is presented in Table 2 below.

Table 2. Summary of experiments conducted initially at 100% humidity

Initial Temp. (°C)	Expansion Ratio	Piston speed (m/s)	ΔT (°C)	ΔP (mbar)	Droplet Diameter D_{32} (μm)	$\frac{dD_{32}}{dt}$ (μm/ms)
30	1.87	0.4	7.5	502	5.4	0.1123
30	1.87	0.23	6.5	502	8.5	0.0972
30	1.62	0.33	7	419	5.1	0.0917
30	1.62	0.18	5.5	419	7.7	0.0846
30	1.38	0.38	7	336	8.4	0.124
30	1.38	0.16	6	336	12.6	0.0609
50	1.87	0.38	5.5	502	6.4	0.0933
50	1.87	0.23	5.5	502	9.9	0.0622
50	1.62	0.33	6	419	6.2	0.0954
50	1.62	0.2	5.5	419	8.6	0.0828
50	1.38	0.39	4.5	293	5.7	0.0807
50	1.38	0.18	4	293	10.4	0.0617
50	1.38	0.17	4	293	15.7	-
50	1.38	0.14	4	293	21.6	-

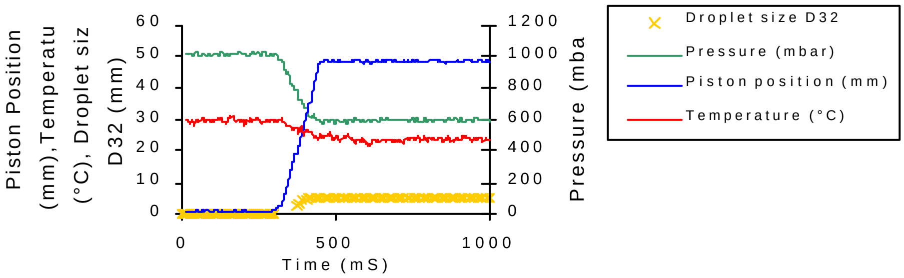


Figure 5. Transient recordings of Temperature, Pressure, Piston position and Droplet Growth for a Rapid Expansion with Initial Temperature 30°C, Expansion Ratio 1.62

4. Analysis and Discussion

First, the results of the ‘dry’ test programme are informative in characterising the thermodynamic process and assessing the applicability of the various diagnostic techniques proposed and developed for this application. Figures 3 and 5 indicate that the transient pressure and volume diagnostic techniques appear to perform well for this application, and this qualitative assessment is endorsed by the polytropic coefficients derived from Figure 4. The coefficient of 1.33 derived for the ‘fast’ expansion is less than the perfect (infinitely fast) adiabatic value of 1.40 utilised by Wilson [1] as expected,due to the occurrence of extraneous heat transfer during expansion. Furthermore, the coefficient sensibly reduces with expansion speed.

Polytropic coefficients derived similarly but utilising temperature as one of the diagnostics are unsatisfactorily low, particularly for the fast expansion, indicating that the compensated circuit (Figure 2), whilst shown to substantially reduce the time constant, alone is not sufficient to provide accurate transient temperature measurements in this quiescent environment. Since the principle and advantages of the compensated circuit has now been proven for this application, a smaller (e.g. 50μm) sheathed and grounded thermocouple should be utilised in future work to progress towards more accurate, less noisy, temperature measurements. However, for the remainder of this paper, useful qualitative trends concerning temperature measurements are discussed.

Tables 1 and 2 show that there is a smaller temperature drop observed in the wet cases compared with the corresponding dry cases; the recorded temperature drops are of the order of 30-40% less for the wet cases. This reduction in temperature drop is an indication of the influence of the latent heat of formation of the droplets. Further evidence is provided by noting that the associated reduction for the 50°C initial temperature case is smaller in comparison to that for the 30°C initial temperature, due to there being a larger volume of water changing phase as the gradient of the saturation curve for water gets steeper the higher the initial temperature.

The results presented in Table 2 can be represented to provide an insight into the influence on droplet growth of three primary control variables : initial temperature, expansion ratio and expansion rate.

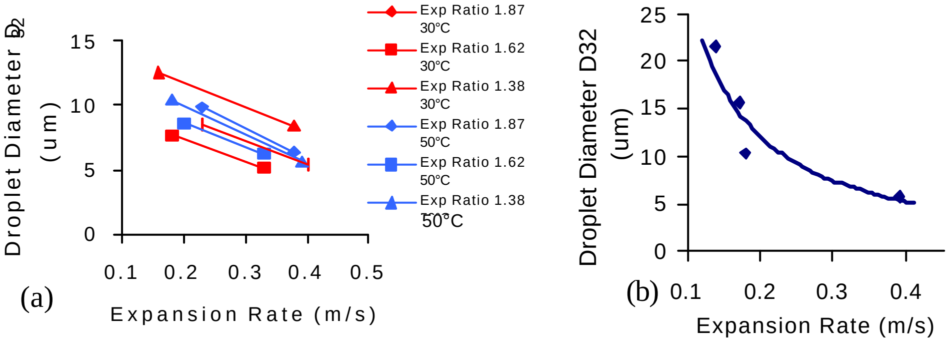


Figure 6 (a)&(b). Effect of Expansion Rate on the Final Droplet SMD for expansion rates greater than 0.2 and complete range for initial Temperature 50°C and Expansion Ratio

Figure 6(a) shows that reduction in expansion rate results in increase in SMD droplet size for all cases considered, which is in agreement with previous studies [6]. However, combined with the earlier conclusion that slower expansion rates reduce the temperature drop, this indicates that less water changes phase, leading to the conclusion that there should be fewer nucleation sites. This conclusion requires direct validation, as Malvern measurements proved inappropriate for this purpose.

The droplet growth rate has been measured from the Malvern data and recorded in Table 2. Growth rates for this experimental programme vary between 0.06-0.124 µm/ms, increasing with expansion rate. The gradients between initial and final conditions presented for all expansion rates between 0.2-0.4m/s in Figure 6(a) are very similar, ranging between –1.9 and –2.1x10^{-5} seconds, and perhaps indicating a characteristic time for the droplet growth process within this range. Further experiments to establish the extent of this range are presented in Figure 6(b), which shows that a further reduction in expansion rate below 0.2 m/s induces a significant increase in droplet growth, showing this trend to be certainly lower-bounded. It is not possible to assess the upper bound of this apparent characteristic time using the current apparatus without modification.

Figure 7 shows the influence of expansion ratio and initial temperature of the system. Reducing the expansion ratio between 1.3-1.9 has a non-linear effect on SMD droplet size. A pronounced non-linear trend indicating a droplet size minimum is evident for the lower initial temperature cases (30°C), whereas this variation diminishes for the higher initial saturated temperature condition (50°C), so that a variation of only about 2 µm or less was attainable using expansion ratio control at 50°C.

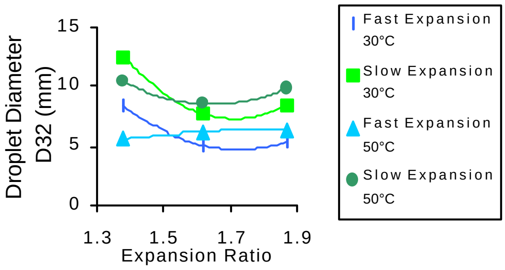


Figure 7. Effect of Expansion Ratio on Droplet Diameter for a range of Initial Conditions

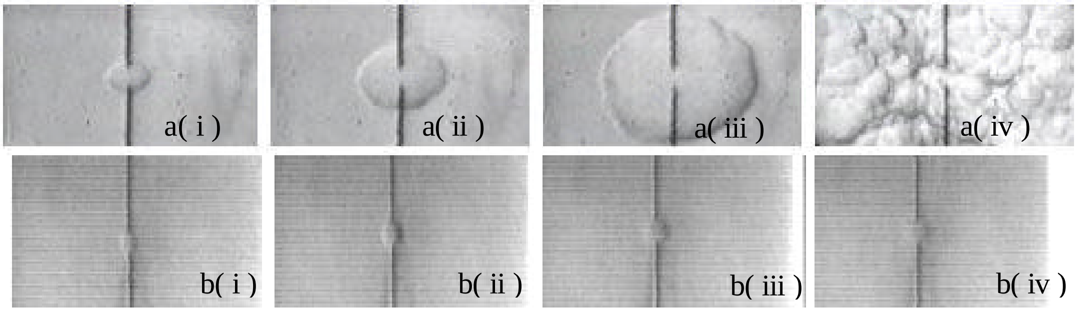


Figure 8. Combustion Applications of Cloud Chamber Technology (a) Homogeneous Mist Combustion (b) Flame Quench by Ultra-Fine Water Mists

Figure 8 shows Schlieren images representing ongoing studies for the improved Cardiff Cloud Chamber. The first sequence shows a propagating n-octane mist flame, indicating flame instabilities, which are influenced by mist characteristics, as well as initial pressure and temperature. The second image sequence demonstrates the effectiveness of ultra-fine water mists in quenching stoichiometric methane/air explosions.

5. Conclusions

- Appropriate diagnostic techniques have been developed for accurate transient quantification of chamber pressure, rate of expansion, droplet growth rate and ultimate droplet size in a novel cloud chamber/combustor facility.
- Circuit compensated electronics designed and integrated to accelerate the transient response of thermocouple temperature measurements in the rig require further development to improve on the current qualitative data.
- Polytropic thermodynamic process coefficients have been derived for the cloud chamber operation. These vary with control conditions, and approach the adiabatic index for faster expansions.
- Lower temperature drops during expansion are noted for wet cases compared with dry expansions, indicating latent heat effects during droplet formation.
- Droplet-growth rates have been quantified, increasing with expansion rate.
- In the expansion rate range 0.2-0.4 m/s, a quasi-steady characteristic time ($-2.0\text{x}10^{-5}$s) appears to exist independent of initial temperature and expansion ratio. It has been shown not to hold for expansion rate less than 0.2 m/s.
- A non-linear relationship between droplet size and expansion ratio exists, which diminishes for higher initial temperatures.

6. References

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