

Combustion of aerosols: droplet sizing study in microgravity

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Abstract

Spray and aerosol cloud combustion accounts for 25% of the world's energy use, and yet it remains poorly understood from both a fundamental and a practical perspective. Realistic sprays include a liquid breakup region, dispersed multiphase flow, turbulent mixing processes, and various levels of flame interactions through the spray. Idealization of spray configurations in a quiescent environment (the starting point for models) has been impossible in 1 g due to the settling of large droplets and buoyant pluming of post combustion gases. The objective of the present research is the experimental determination of the flame propagation velocity in aerosols. The first step of this work was to characterize experimentally the size of droplets composing the aerosol. This characterization was performed using a laser diffraction particle size analyzer "Sympatec-HELOS", using ethanol and isooctane as fuel. High pressure studies have been performed using of a high pressure combustion chamber (max pressure 12 MPa). This equipment was designed to be used aboard the Airbus A300-0g of the CNES. The interest of microgravity in this study is related to the possibility of creating aerosols without sedimentation effects. After ground tests, three parabolic flight campaigns were conducted. The results obtained allowed to determine the effects of initial temperature and pressure on the droplet diameter distribution of the aerosol. A systematic comparative analysis for identical initial conditions in normal and reduced gravity was performed, also between ethanol and isooctane droplets. During the experiments, the temporal evolution of the growth of droplet sizes was followed starting from the beginning of the condensation of expansion cooling. The durations of growth and evaporation were also measured.

1. Introduction

Automobile manufacturers are aiming to develop engines with high efficiency and specific power output while always watching the limits of the imposed emission regulations. In this context, significant achievements for the development of more efficient engines have been made over the last years. Fuel-air mixture preparation and combustion are important processes in internal combustion engines which control the engine power, efficiency and emissions. The most important features of the mixture preparation are the method of injection, spray atomization and liquid evaporation. Among these phenomena, evaporation of multi-component fuels is still not well understood despite its importance for mixture preparation at cold start operating conditions [1]. Indeed, the distribution and concentration of fuel vapor components in the combustion chamber directly affects the combustion efficiency.

Droplet vaporization has been intensively investigated experimentally and numerically during past decades. Although numerical simulation of droplet evaporation has received a considerable attention in the past, only few experimental accurate data are available for the validation of droplet evaporation models even at atmospheric pressure. Most isolated droplet evaporation experiments have been conducted with the droplet suspended on a support fiber to avoid the experimental difficulties for free-falling droplets [2]. The support fiber which has a relatively large diameter (more or less 150 μm) increases the droplet evaporation rate due to the heat transfer through the fiber to the droplet even at low ambient temperatures. Droplet vaporization models from the literature (such as [3] and [4]) have compared their numerical results mainly to experiments with large fibers sizes [5]. Consequently, these models have usually underestimated the vaporization rate. In addition, the evaporation in a combustion chamber concerns a spray, i.e. a large number of drops evaporates simultaneously; but previous models do not consider the interaction between several drops. Detailed studies of spray vaporization are therefore still necessary to obtain a better estimation of droplet evaporation rates.

Some earlier experimental studies on the combustion of droplet clouds have been reported. Wolfhard and Parker [6] studied qualitatively the evaporation of a burning kerosene spray. Burgoyne and Cohen [7], using mono-sized droplet-air mixtures of tetralin, investigated the effect of droplet size on the flame propagation. Sundukov and

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Predvoditelev [8] measured the flame speeds in two-phase mixtures of kerosene with a polydispersed droplet-size distribution. Subsequently, different authors [9-12] studied flames supported by polydispersed sprays. Hayaishi [13] characterized the propagation velocity and structure of flames in droplet-vapor-air mixtures. More recently, experimental studies were conducted by Cameron [14] and Lawes [15-17]. The main results of these studies can be summarized as follows:

- Spray flames may be slower or faster than equivalent gaseous flames; the droplet size is the determining parameter.
- Lean aerosols with large drops can still be inflammable, while the premixed gas equivalents are not.
- In aerosols the presence of a wide range of drop sizes have a strong influence on the flame structure and this will be especially important in turbulent configurations [18, 19].

Therefore, to analyse the effects of the parameters relevant for two-phase flames, it is necessary to study with details the two-phase reactive mixture (liquid fuel - gaseous oxidizer) from a granulometric point of view.

2. Experimental Methods

The experimental approach consists of introducing a fuel-oxidizer mixture (liquid / gas) in the desired proportions into the combustion chamber (10 liters). Aerosol mixtures are prepared by a condensation technique of expansion cooling (Wilson cloud chamber technique) [15]. The ignition is initiated in the center of chamber by an electric spark. This set-up allows to determine the propagation velocity of a flame in a two-phase mixture and to vary the parameters such as the nature of the fuel, the global equivalence ratio, the initial droplets size distribution and initial temperature and pressure. The experimental set-up is schematically represented in Figure (1). The pressure inside the chamber is acquired using a piezoresistive pressure sensor (100 kHz).

The aim of the current study is to characterize the cloud formation and vaporization. For safety reasons (mainly in the aircraft), air was replaced by nitrogen in the combustion chamber.

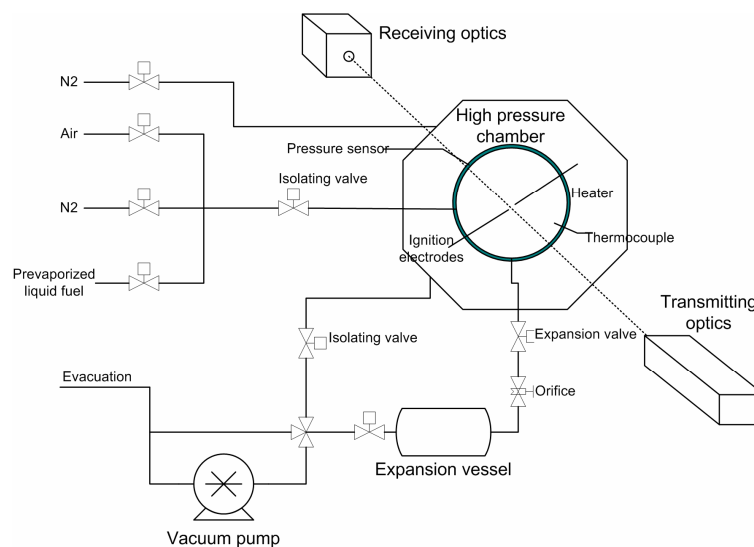


Figure1: Schematic representation of the combustion apparatus

2.1. Diffraction laser particle size analyzer

The diffraction laser size analyzer used in this study, Sympatec HELOS, offers two evaluation modes. The first solution is based on Fraunhofer diffraction and the second on precision Mie theory. The combination of measuring ranges is available for both options allowing the analysis of wide size distributions at high precision. An automatic adaptation of the beam diameter to the measuring range is allowed for largest working distances, which is important for the measurements of large aerosol volumes. HELOS system has eight measuring ranges available. Every measuring range includes 31 particle size classes. The lower limit of the lower class is the boundary of the measurement (only particles above this particle size will be analyzed). Lens R₄ was used in this study allowing measuring ranges from 0.5 μ m to 350 μ m.

2.1.1. Reference measurement and multiple light scattering

Before each measurement we perform systematically a reference measurement to measure the background level of light intensity on the laser diffraction detector in the absence of aerosol but under the same flow conditions of the dispersing medium (air). This measurement serves to compensate for possible contamination of the optical

components. An auto-alignment (autofocus) of the detector is part of the system. Besides being highly transient, the investigated sprays are dense, mainly composed of very small drops and heterogeneously distributed in space. These characteristics are a potential source of measurement bias and undesirable effects (beam steering, vignetting and multiple light scattering). Dumouchel suggests an empirical correction procedure, based on the analysis of the light intensity distribution [20], using the Malvern Spraytec instrument. We note that multiple light scattering occurs when the measuring volume contains a high number of drops either because the spray density is high or because the measuring volume is large [21]. In our case, to estimate the bias introduced by the multiple light scattering effects, we choose to validate the measure by realizing measurements with reference calibrated particles.

2.1.2. Mie or Fraunhofer ?

Laser Particle Size Analysis consists in measuring the size of particles (powders, suspensions and emulsions) using the diffraction and diffusion of a laser beam. Two theories are used depending on the size of the particles. The Fraunhofer theory is applicable for large particles compared to the wavelength (diffusion and absorption are not considered). For smaller particles, it is appropriate to use Mie Theory. The Mie model takes into account both diffraction and diffusion of light around the particle in its medium. To use the Mie model, it is necessary to know the complex refractive index of both sample and medium. This complex index has a real part, which is the standard refractive index, and an imaginary part, which represents absorption. Theoretical analysis and numerical calculations have shown that the widely used Fraunhofer diffraction based particle size analyzers may produce errors “around 35%” in small size range measurements, especially for transparent particles with a small index of refraction [22]. In order to improve the performance of our analysis, Mie scattering theory was applied.

3. Results and Discussion

3.1. Expansion:

Combustion studies require the determination of two-phase mixture composition in terms of gaseous and liquid fractions and equivalence ratios, drop size, and number density (the number of droplets per unit volume), as functions of pressure, temperature, and time during the expansion process. The evacuation of the mixture from a fixed-volume chamber (1 liter) into an expansion tank (0.5 liter) implies that the total amount of mixture in the combustion chamber decreases during the process. However, it is assumed that the overall equivalence ratio ϕ_0 in the combustion chamber, irrespective of the state of matter of the fuel, remains constant during expansion. Taking into consideration the initial pressure, we can control the expansion time. Experiments show that a reduced expansion time favors the creation of larger drops. For safety regulation reasons during parabolic flights, liquid fuel amount injected was fixed and kept constant for each experiment; therefore different equivalence ratios are obtained by varying the initial pressure. To keep the expansion time constant, the orifice size of the expansion valve was modified. Figure (2) shows the temporal evolution of temperature and pressure during the expansion. The pressure rapidly decreases when the two volumes (combustion chamber and expansion tank) are connected. Then the condensation process induces an increase of the pressure inside the whole volume.

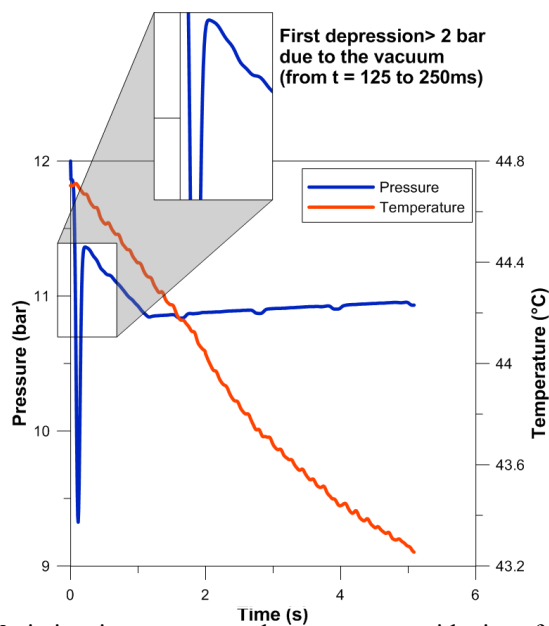


Figure 2: Variation in pressure and temperature with time for ethanol aerosol expanded from 12 bars to 11 bars at 45°C and $\phi=1.5$

Figure (3) presents a sequence of six pictures during the aerosol development from beginning to end at 4 bars, 45 °C and $\phi=1$. The first sequence between 1 and 5sec shows the expansion phase; then vaporization phase begins. The duration of these two phases depends on parameters such as initial temperature, pressure and gravity.

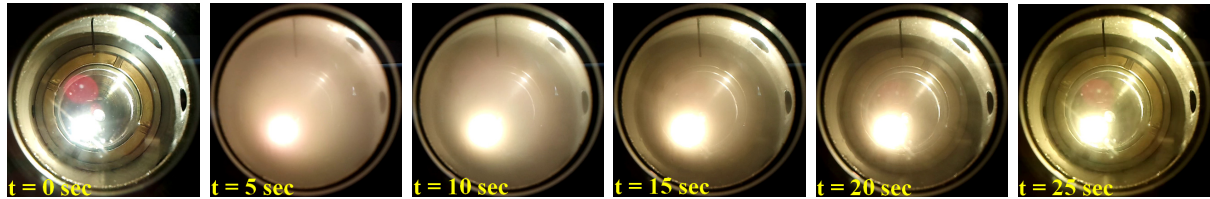


Figure 3: Sequences of ethanol aerosol at 4 bars, 45 °C and $\phi=1$

3.2. The temperature effect:

In the present study, the initial temperature of the mixture was varied from 20 to 100 °C. The results obtained (Figure 4) allow to determine the influence of initial temperature of the mixture, which is revealed by a reduction of the droplets size, noticed in particular for high temperature values (>60°C). The data also show that the vaporization rate increases with increasing initial temperature. At low temperatures (less than 60 °C), a larger equivalence ratio generates smaller droplets; the same effect of equivalence ratio on droplet diameter was remarked by Nomura [23] with methanol droplet clouds generated by the condensation method at microgravity. As seen on Figure (4), at low temperatures, a very large evaporation times (> 22sec) are obtained; for this reason these conditions were not reproduced in reduced gravity experiments (limited to 22 s).

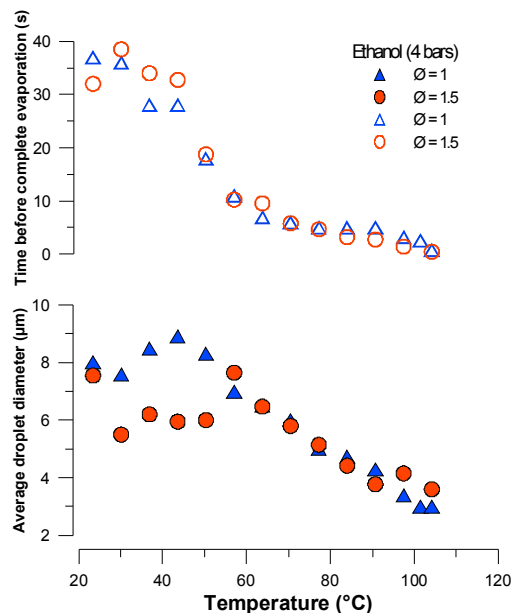


Figure 4: Variation with temperature of average droplet diameter and evaporation time for ethanol at $P = 4$ bars and $\phi=1, 1.5$

3.3. The pressure effect

We mentioned above that in our experiments, two different pressures correspond to two different equivalence ratios; in addition the equivalence ratio influences the droplet diameter at low temperatures. It is therefore complicated to determine the effect of the initial pressure. Previous experimental and theoretical results show that the average drop diameter decreases with increasing initial pressure [24], Figure (5) shows that increasing pressure reduces the vaporization time and produces a higher rate of vaporization. During the next step of our studies, we will be able to check the effect of high pressures using a new combustion chamber.

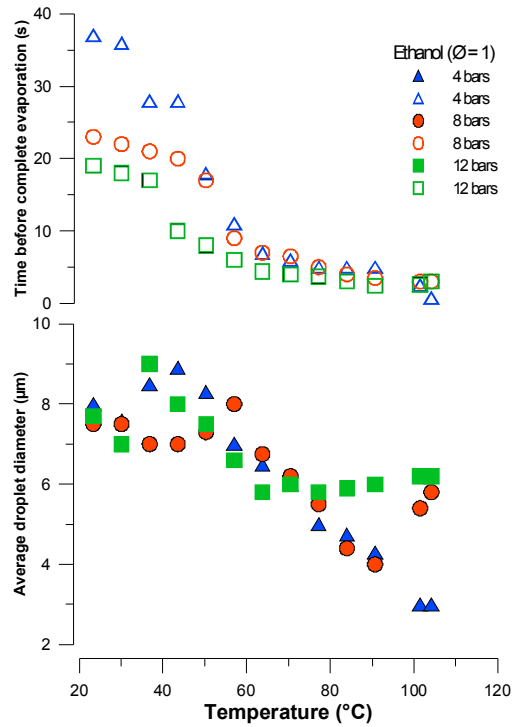


Figure 5: Variation with temperature of average droplet diameter and evaporation time for ethanol at $P = 4, 8, 12$ bars and $\text{Ø}=1$

3.4. Microgravity

Microgravity offers the possibility to simplify the investigation of spray or aerosol combustion mainly by reducing the sedimentation effects and therefore obtaining more homogeneous two-phase systems. We conducted three parabolic flight campaigns onboard of the CNES ZeroG Airbus in March and December 2010 and in May 2011. We shall summarize below the main results from these experiments.

3.4.1. Validation of the measurement system

During the first parabolic flight campaign in March 2010, three parabolic flights were performed. The goal of these flights was to test the operation of the particle size analyzer in microgravity and check the efficiency of our measuring ranges and its ability to reduce the effects of vignetting and multiple light scattering. During the first flight we used a reference powder SiC-P600 ($27\mu\text{m}$). During the second flight, another standard powder was used SiC-F1200 ($4.1\mu\text{m}$). During the third one the two powders were mixed, in order to check the results for this bi-dispersed mixture. The results obtained were always satisfactory. Figure (6) shows coherent curves corresponding to the real size of the used reference powder.

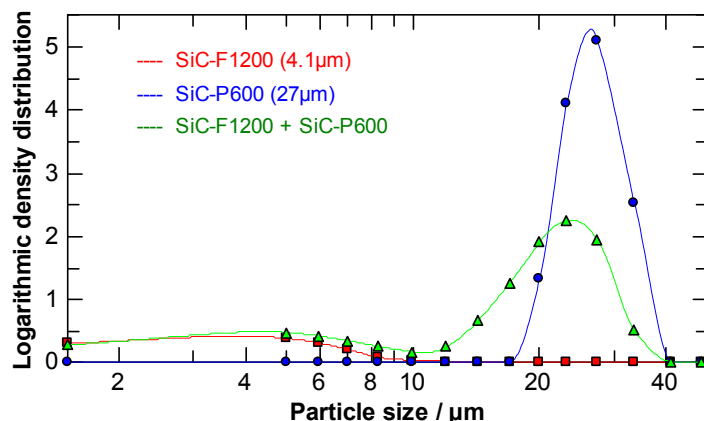


Figure 6: Particle-size distributions of SiC-P600 ($27\mu\text{m}$) and SiC-F1200 ($4.1\mu\text{m}$)

3.4.2. Droplet diameters

3.4.2.1. Average droplet diameters

For spray combustion, initial diameter is a determining parameter since it is involved in both the heating of the liquid phase and in the evaporation phase. Generally, small diameter droplets will quickly reach their saturation temperature and the evaporation rate will be high. This tendency will induce reduced ignition time and accelerate the inflammation of the aerosol. There is also some evidence to suggest that flame propagation through aerosol/vapor clouds, under certain circumstances, is faster [15]. Atzler’s study revealed that aerosol flames are, in general, more unstable than gaseous flames and become more so as the droplet size increases. The flame instabilities are manifested by a cellular surface structure which increases the surface area of the flame front and consequently increases the flame speed [25]. A comparative analysis for identical initial conditions in normal gravity and in reduced gravity shows that the reduced gravity conditions allow obtaining larger droplets sizes. Figure (7) demonstrates clearly this tendency. A comparison between ethanol and isooctane fuels shows larger droplet sizes for isooctane droplets under the same conditions.

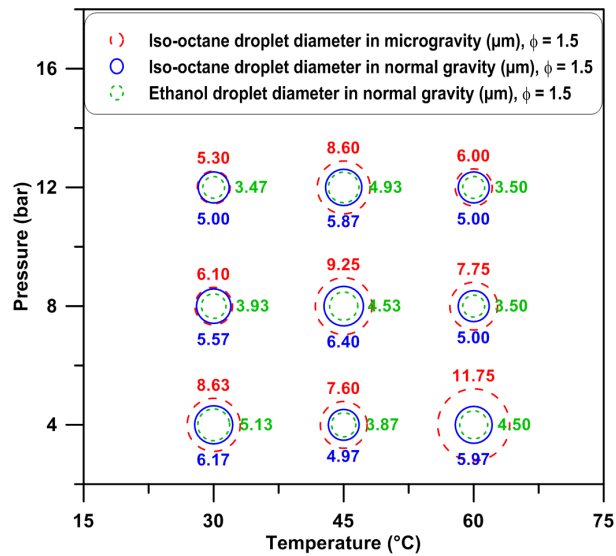


Figure 7: Variation of average droplet diameter with temperature and pressure at $\phi=1.5$ for isooctane in microgravity and normal gravity and for ethanol in normal gravity

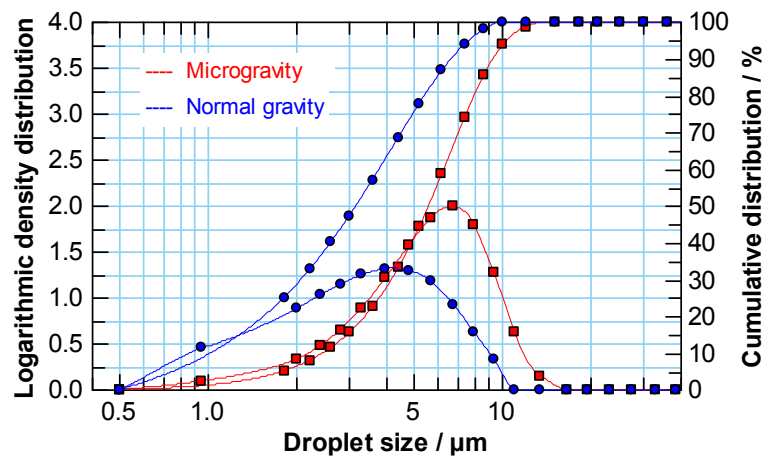


Figure 8: Ethanol droplets size distribution at 45 °C, 8 bars and $\phi=1$ in microgravity and normal gravity.

3.4.2.2. Droplets size distribution

Figure (8) shows that the cumulative curve in normal gravity covers a wider size range (between 0.5 μm and 10 μm) than the cumulative curve in microgravity (between 2 μm and 10.5 μm). We also note that the distribution curve is narrower in microgravity, showing that the aerosol is more mono-disperse in microgravity. We can also notice that the droplet sizes in microgravity are larger than the droplet size in normal gravity. The measured val-

ues of the mean density are $\rho_{\text{microgravity}} = 0.76 \text{ g/cm}^3$ and $\rho_{\text{normal gravity}} = 0.69 \text{ g/cm}^3$ respectively for microgravity and normal gravity conditions. The mean density is larger in microgravity which means that the laser beam passes through a larger quantity of liquid in microgravity, due to the larger droplet diameters and a more homogeneous distribution of the aerosol.

3.4.3. Temporal evolution

There is no fundamental difference between the combustion of gas mixtures and atomized liquids, if the droplet vaporization is completed before they reach the flame front. It is therefore important to know the droplet sizes temporal evolution before starting the combustion study. Figure (9) shows the temporal evolution of the average droplet diameter in normal gravity and in microgravity. The formation of the aerosol, from the end of the expansion, goes through three main steps: growth, coalescence and vaporization. We can note an important difference between droplet diameters evolution in microgravity and in normal gravity. In microgravity the droplets growth takes much more time giving the chance to droplets to attain larger sizes, and we also note that the droplets in microgravity have a tendency to coalesce more easily to form very large droplets. However these drops evaporate quickly. In normal gravity we see that the growth period is relatively short and coalescence is much less important; however, we note that the droplets take much longer time to vaporize. This difference can be explained by the concentration gradients which are enhanced due to the coalescence in microgravity.

To characterize completely the evaporation of droplets, we need to determine the temporal evolution of the droplet diameter. HELOS laser diffraction system allows observation of the change of diameter, but it is necessary to know exactly the value of the refractive index (n) of each product used. The refractive index also depends on the temperature of the liquid and empirical laws are also available.

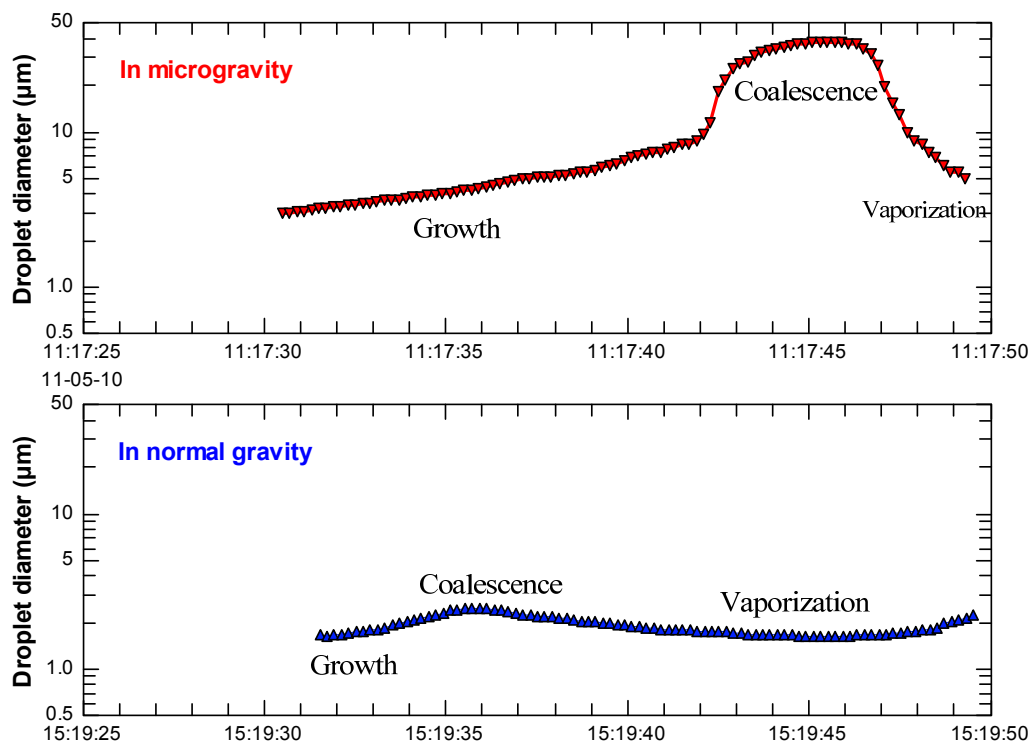


Figure 9: Temporal evolution of average droplet diameters with time for ethanol at 45 ° C, 8 bars and $\varnothing=1$ in microgravity and normal gravity

4. Conclusions

The present work was conducted to characterize the aerosol size distribution in order to prepare the combustion experiments to be conducted in the later stages of the project. Experiments in normal and microgravity conditions were conducted both for ethanol and isooctane droplets. The effects of initial temperature and global equivalence ratio were investigated. Under microgravity conditions larger droplet sizes are obtained together with more homogeneous and more mono-disperse aerosol mixtures. Isooctane droplet diameters are always larger than ethanol droplet sizes under the same conditions. The period of droplet growth was also measured and we

observed that in reduced gravity its duration is longer and the evaporation is faster. During the next step of our research, we plan to produce the aerosol at higher initial pressures and more varied equivalence ratios before moving to combustion experiments

Acknowledgements

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