Experimental investigation of evaporating bi-component droplets in a turbulent channel flow

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Abstract

The reduction of the pollutant emissions and the identification of new fuels can be achieved by a better understanding of the physical phenomena like fuel droplets evaporation and heat exchange. Mathematical modelling of these phenomena will find further its applicability in the simulation of the spray evaporation inside a combustion chamber. The long term objective of this study is to experimentally investigate the influence of the turbulence on the multi-component droplets evaporation. The experimental database will be used in the future to validate the numerical simulation developed in parallel at ONERA.

The short term objective is to investigate the coupling of the Global Rainbow Thermometry (GRT) and Phase Doppler Anemometry (PDA) techniques in a highly turbulent and confined flow and to characterize the droplet size, velocity and temperature evolutions in the channel. As liquid, a mixture of n-octane and 3-pentanone is used.

The experimental setup consists in a square cross-section channel flow with a very high level of turbulence intensity. An ultrasound atomizer disposed inside the duct allows the formation of a cloud of bi-component droplets of different sizes and velocities which are quickly dispersed in the carrier flow. The measurement techniques are described and the results are presented for different measurement positions in the channel flow..

Introduction

Multiphase gas - liquid flows are widely encountered both in nature and for different engineering applications. Nowadays, all fuels are mixtures of different chemical species. For a good prediction of evaporation, a multicomponent evaporation model has been developed at ONERA For the validation of this model a detailed data base must be built.

This study focuses on the experimental investigation of the bi-component droplet evaporation and transport through a duct of square cross-section. The influence of the heated turbulent flow on the droplet dispersion and evaporation is examined.

Droplets behavior inside a turbulent flow is strongly dependent of the flow characteristics. The droplets dispersion, accumulation and evaporation are highly dependent to the sensitivity of each droplet to the turbulent structures in the flow. The volume fraction of the dispersed phase also plays an important role.

The literature concerning the spray behavior in a highly turbulent heated flow is distributed across different disciplines: measurement techniques, fluid dynamics, sprays, heat and mass transfer. The turbulent flow through a duct of square cross section was largely investigated up to now, both experimentally [1] and numerically [2]. Nevertheless, there are limited data regarding the liquid phase temperature in this configuration.

Concerning the experimental investigation techniques, the Rainbow Thermometry was initially developed as an optical non-intrusive technique used for individual droplet temperature and size measurement. Later it was extended for measurements inside polydisperse sprays and nowadays it is recognized as Global Rainbow Refractometry (GRR) or Global Rainbow Thermometry (GRT) technique. The basic principle of the GRT is the summation of the rainbows signals corresponding to the droplets of different shapes, dimensions and temperatures. The pattern is formed by constructive interference of light scattered by the spherical droplets of different sizes. As in the case of natural rainbow, the non-sphericity effect is eliminated by destructive interference yielding to an uniform background.

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Several studies were developed using the Airy theory estimating the scattered light intensity as a function of the droplet diameter and temperature. With an inversion method, the droplets refractive index was determined. Van Beek and all [3] proposed inversion algorithms of the global rainbow optical signal based on the Airy theory and on the assumption that the size distribution is a log-normal function. Different data inversion algorithms are proposed but the most interesting results are obtained from the one based on the inflexion point around the main rainbow maximum. This technique was further used in different configurations investigation [4,5] proving its large applicability. Later, S. Saengkaew and all [6], using empirical correction coefficients, found that Complex Angular Momentum Theory (CAM) developed by Nussenzveig can be applied within an angular range, wider than in the Airy theory. It was demonstrated that the modified Nussenzveig theory furnishes predictions of rainbow refractive intensities close to Lorentz –Mie theory but it requires very reduced computation times, similar to those in Airy approach.

The GRT technique proved also its capacity in radial gradient temperature investigation [5,6]. The strong internal temperature gradients encountered in big droplets limit GRT applicability to domains where a uncertainty of few degrees is acceptable.

In the case of confined flows, the optical signal quality is dependent on the impact of the droplets on the viewing windows which equip the channel. Moreover, the viewing windows absorb the scattered intensity and therefore contribute to the reduction of the signal-to-noise ratio [4], but this does not disturb the angular repartition of the scattered light.

This paper is organized as follows. In the next section the experimental setup and the methodology are detailed. Then, the measured temperature, size and velocity distributions are presented and discussed.

Materials and Methods

Experimental Setup

The experimental setup consists in a vertical square cross-section channel with optical access (Figure 1). The design and characterization were presented in a previous work [7]. Preheated air (410K) is injected in a tank and passes through a turbulence generator before entering the channel. The generator has been adapted from a previous setup of Videto and Santavicca [8] and it is made of a circular plate perforated by 45 holes of 3mm diameter and a convergent. The 45 jets impinging the convergent generate a turbulence level much higher than classical grid turbulence: up to 30% for a bulk velocity of 1m/s.

The droplet injector is placed in the centre of the perforated plate and the tip of the nozzle is located at the entrance of the channel. The atomization is performed with an ultrasonic device providing a wide range of droplet diameters leading to a variety of droplet behaviours from tracers to highly inertial droplets. The bicomponent droplets are composed of octane (85%) and 3-pentanone (15%).

Measurement techniques

The positioning of the GRT and PDA equipments with respect to the channel flow is described in Fig. 2 and 3.

To measure the diameter, axial and radial velocity of each droplet, a commercial Argon PDA is used. The operating principles are largely described in the literature and will not make objective of the present study.

The temperature is deduced with the GRT technique. In the Figure 3 all the elements of this equipment are represented. The light source used is a HeNe continue laser delivering a power of 30mW. The cloud of droplets is submitted to this laser beam. Further, the light scattered by the droplets is captured in an angular range characteristic to the rainbow phenomenon. The first lens of the receiving optical system realizes an optical Fourrier transformation of the scattered light. This way, in the focal plane of the first lens, the light intensity is expressed only as a function of the scattering angle and is independent of the droplet position in the probe volume. The image of the optical Fourrier transformation is reproduced by the second lens on the CCD linear sensor. A diaphragm disposed in the image plane of the first lens lets the possibility to control the dimension of the probe volume. In this configuration the scattered light is collected in an angular window of about 19^o for 2048 pixels of the CCD sensor. Additionally, the receiving optics can be rotated in order to permit the measurement of a large range of angles.

Before starting measurements a relation had to be found between the scattering angle and the corresponding pixel on the CCD sensor. This task was achieved by the use of a mirror disposed in the probe volume. A part of the channel flow needed to be removed to allow the introduction of the mirror disposed on a micrometric rotating plate. For different angular positions, the incident laser beam is reflected by the mirror to the CCD sensor through the receiving optics. The number of the illuminated pixels is recorded and a 3^{rd} order polynomial correlation is obtained. The error of this calibration technique is less than ±0.001º.

The optical access into the channel is provided through windows of optical glass. As these surfaces represent source of numerous parasite reflections, a system of traps, based on magnets, was put in place.

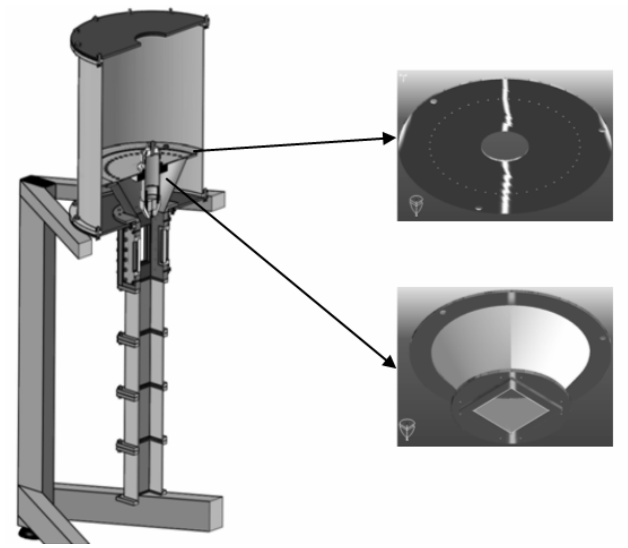

Figure 1. Experimental setup

The time of the acquisition is determined by the exposure time of the CCD camera. This is controlled such that a great number of droplets crosses the sample volume. In regions with a reduced density of droplets the exposure time had to be increased accordingly. The signal was transferred to a computer via an acquisition board.

Once the optical signal is recorded, a software application, developed at the CORIA laboratories, is used to estimate the mean refractive index of all the droplets which cross the sample volume. This code is based on an inversion algorithm that uses the Complex Angular Momentum Theory (CAMT) of Nussenzveig to estimate the scattered light intensity as a function of the droplet diameter and the refractive index. The minimization of the differences between the recorded and computed signal is done by the nonnegative least square (NNLS) method. The temperature is then obtained by means of a refractive index-temperature correlation previously found experimentally with a refractometer.

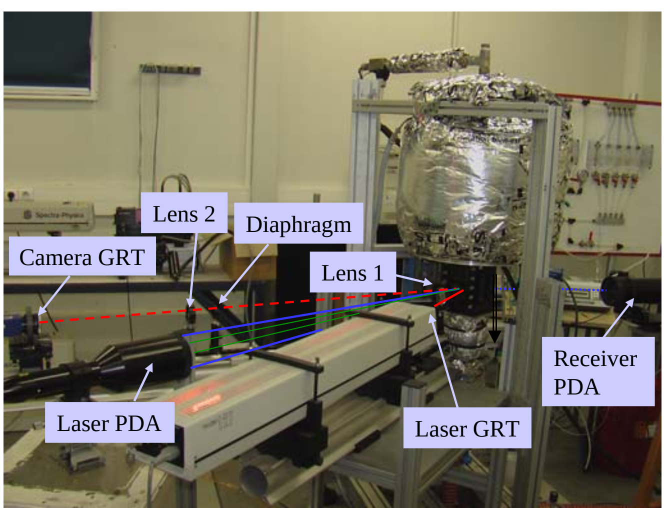

Figure 2 . Photograph of the setup

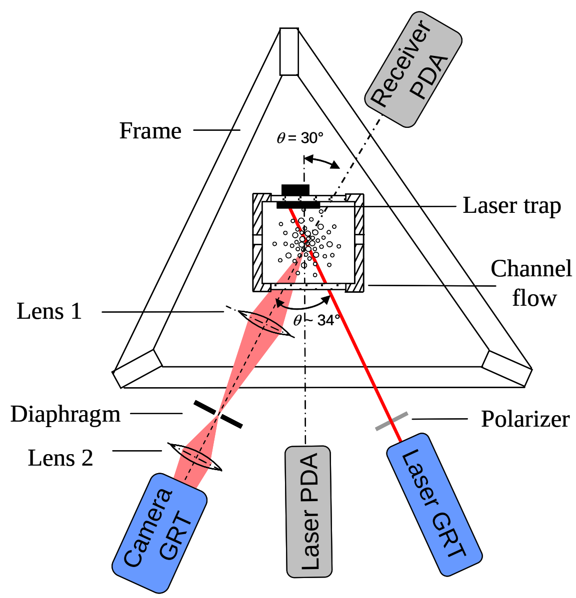

Figure 3. Schematic top view.

Operating conditions.

The temperature measurements are performed in the XZ plane at different location in the spray (Figure. 4). The origin Z = 0 corresponds both to the entrance of the channel and to the atomizer nozzle. The refined grid was chosen to build a detailed data base useful for the validation of numerical approaches. The PDA results are available only on the axis. A complete investigation is in course at IMFT laboratory.

The operating conditions are detailed in the Table 1.

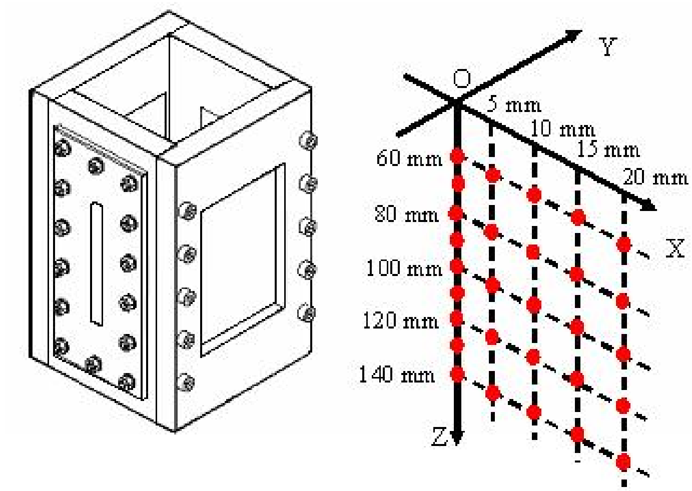

Figure 4. Measurement positions inside the channel flow.

Table 1

Temperature of the air (at the nozzle position)	137 °C
Air bulk velocity	1 m/s
Liquid mass loading	8.7 %
Liquid flow rate	0.41 g/s
Temperature of the liquid	12 °C

Results and Discussion

Air flow characterization

The air flow is characterized in terms of velocity fields using LDA with small oil droplets as tracers corresponding to a Stokes number of St < 0.001. It is shown that, after a distance of Z/H = 2.4 (where H=92 mm is the width of the channel) the radial and longitudinal velocity profiles are quite flat with a variation less than 10%.

Liquid phase characterization

The number-weighted mean diameter (D_{10}) and Sauter diameter (D_{32}) increase along the longitudinal axis (Figure 5). This result is illustrated by the evolution of the diameter probability functions for three axial points showing a reduction of small droplets amount due to the evaporation (Figure 6). This evolution is the same all along the radial profile.

The mean and fluctuating velocities of the droplets are shown in Figure 7. The fluctuating velocities are found to be nearly constant, but slightly decreasing after Z/H = 0.76mm. The mean radial velocity is roughly equal to 0 m/s. It does not exceed 5% of the bulk velocity. Particular attention is paid to the longitudinal mean velocity.

The longitudinal evolution of the turbulence intensity level for the mean droplet size is in the range of 30%, value which must be compared to the air turbulence intensity level of almost 100 %.

The evolution of the ratio of the fluctuating velocities for the two phases as a function of the Stokes number is presented in the Figure 8. The Stokes number is defined as $S_t = \frac{\tau_p}{T_e}$, where τ_p is the particle relaxation time and T_e the integral time scale of the fluid. The diameter range [0-280µm] has been divided into seven classes, and the mean value corresponding to each class is plotted. This curve shows that most of the droplets are highly inertial and only few small droplets follow the gaseous phase.

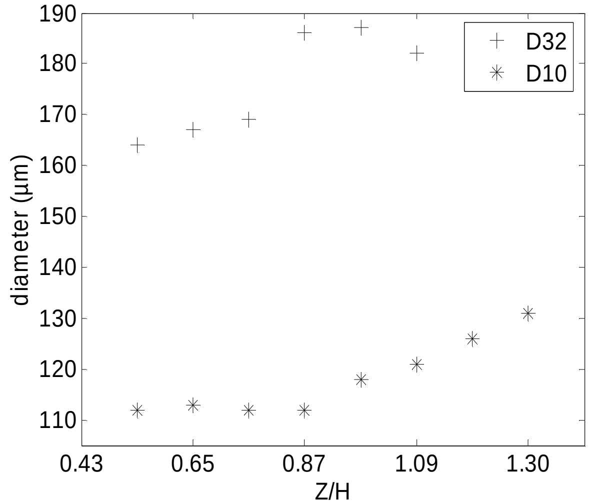

Figure 5. Longitudinal evolution of the droplets mean diameter

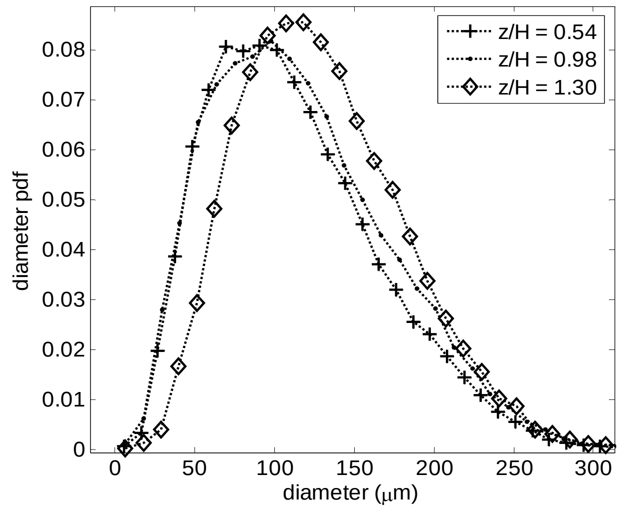

Figure 6. Longitudinal evolution of the droplets size distributions

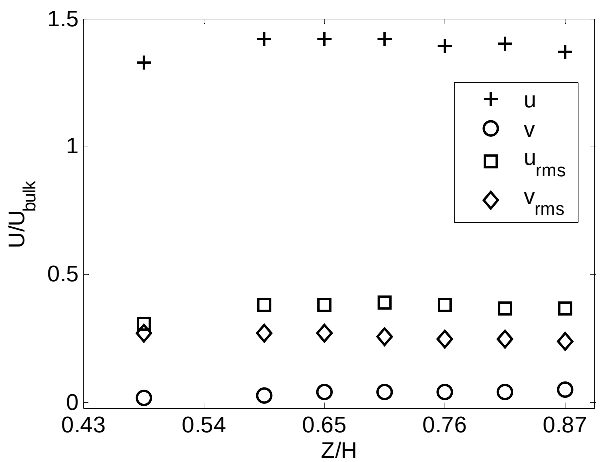

Figure 7. Radial and longitudinal evolutions of the mean and fluctuating velocities of droplets

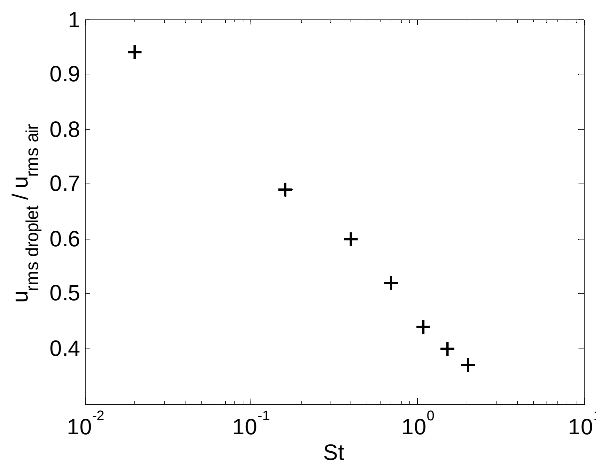

Figure 8. Evolution of the ratio between the fluctuating velocities for the two phases with the Stokes number Z/H = 1.09

Concerning the temperature results, a first measurement was done in the absence of the airflow in order to test the GRT technique feasibility. A previous validation study was realised for a non-confined spray [9] and the results were satisfactory. In the present work the liquid was injected at the ambient conditions and the droplet's temperature was measured by GRT at 60 mm from the nozzle. The difference between the injected liquid and the droplets is inferior to 1 °C.

Measurements have been next proceeded for a heated airflow. Figure 9 presents the longitudinal evolution of the droplets temperature for different radial positions. The increasing evolution of this parameter proves that the dispersed phase is in the heating phase along this distance range. Due to their big size the droplets have not yet reached the equilibrium temperature. The explorations have to be extended downstream to get an overall behaviour.

The radial temperature evolutions, for different distances from the atomizer nozzle, are plotted in Figure 10. The temperature increases close to the channel borders. Two different mechanisms could explain this behaviour. Firstly, the nature of the flow inside the square cross-section duct must be considered. The results presented in [10] for a DNS simulation of the turbulent transport of the dispersed phase show that the particles of high inertia have the tendency to accumulate in stream wise elongated structures. As for the small inertia droplets, they are homogeneous distributed in the flow. The superposition of both distributions leads to a spatially non homogeneity of the dispersed phase temperature. A more complete investigation with the PDA technique is now conducted in order to get more information about this mechanism.

Secondly, during droplets evaporation process, the gaseous phase is cooled much faster then the channel walls. As the channel walls have a temperature superior to that of the continuous phase, the droplets transported close to the channel borders have the tendency to heat more than those located in the centre of the duct.

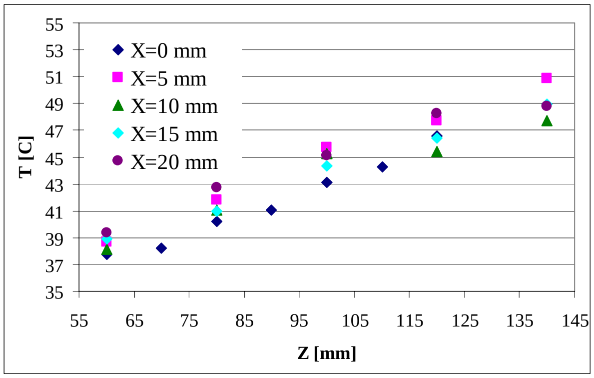

Figure 9. Longitudinal evolution of the droplets temperature

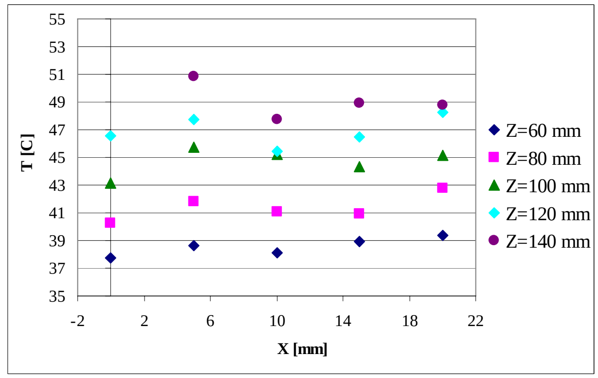

Figure 10. Radial evolution of the droplets temperature

Conclusions

The Global Rainbow Thermometry and Phase Doppler Anemometry techniques were implemented upon the IMFT facility. This experiment was put in place in order to investigate the multicomponent droplets evaporation in the presence of a highly turbulent confined flow. The measured parameters were the droplets temperature, size and velocity. A detailed database was completed and the experimental results will be compared in the near future with the numerical ones, the simulation being currently in work.

Different phenomena like the impact of droplets on the viewing windows and the multiple reflections in the channel could alter the accuracy of the measurement. Thus, an important challenge was to find the appropriate operating conditions which allow the two investigation techniques to acquire the maximum of data.

We mention that this is only a primary study, a more detailed one being at the moment developed in our laboratory.

Nomenclature

GRT Global Rainbow Thermography
PDA Phase Doppler Anemometry
St Stokes number

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