Optics Communications 372 (2016) 185–195

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Simultaneous interferometric in-focus and out-of-focus imaging of ice crystals

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A R T I C L E I N F O

Article history:
Received 1 February 2016
Received in revised form
29 March 2016
Accepted 3 April 2016

Keywords:
Interferometric out-of-focus imaging
Ice crystals
Interferometric particle imaging
Speckle

A B S T R A C T

Using a freezing column, dendrite-like ice crystals are generated and characterized simultaneously using in-focus imaging and interferometric out-of-focus imaging. This simultaneous analysis allows a validation of size measurements made from the analysis of the 2D-autocorrelation of speckle-like interferometric out-of-focus patterns of ice crystals. Measurements of the same particles by in-focus and out-of-focus techniques are in good agreement for 75% of the particles tested. Simulations of out-of-focus patterns are in very good agreement with experimental images. The analysis of the 2D-Fourier transform of the speckle-like patterns confirms that it is possible to evaluate the 2D-autocorrelation of the global shape of the particle (i.e. its 2D-projection on the plane of the CCD sensor).

1. Introduction

The characterization of aerosols, droplets, ashes or ice crystals in the atmosphere has important applications in meteorology and aircraft safety. Different optical techniques have been investigated and corresponding instruments have been realized [1–5]. They are based on light scattering properties of particles, and offer the possibility to design non-invasive systems which require little space. The nephelometer is one of the most popular [1]. Interferometric particle imaging has attracted attention because it can offer a relatively large measurement field (a tenth of cm^3), it gives accurate sizing of droplets in the range [10 μm–500 μm] and real-time global image processing can be achieved [5,6]. In this technique, measurement requires the acquisition of an out-of-focus image of the particle. The particles are illuminated by a laser sheet. The size of the particle is deduced from the interferometric out-of-focus pattern. In the case of droplets, two-wave interference fringes are observed. Their frequency is inversely proportional to the size of the droplet. The so-called ILIDS technique (Interferometric Laser Imaging for Droplet Sizing) has been successfully used for the characterization of droplets in air flows in various applications [7–12]. It has been extended to the characterization of bubbles in a fluid [13–15]. In the case of irregular rough particles, speckle-like patterns are observed [16–20]. Two-dimensional angular scattering had been proposed for the characterization of aerosols by counting density and size of “islands of intensity” in their angular patterns [21]. Ulanowski et al. investigated the bidimensional structure of interferograms scattered by ice crystals in order to obtain their sizes [22,23]. Building a classical ILIDS configuration, we could demonstrate that the size of an irregular rough particle can be deduced from the determination of the average size of the speck of light in the speckle-like pattern [16–18]. The scaling factors are deduced from the set-up parameters (wavelength, distances, objective focus length, defocus parameter…). The roughness of the particle appears to be an important parameter. Despite the possible presence of high reflection domains on ice crystals, recent comparisons of ice particle sizing using interferometric out-of-focus imaging and digital in-line holography showed that the relative difference between sizes obtained using both techniques was less than 25% for 62% of the particles tested [24]. But digital in-line holography has its own limitations. In addition, in these first experiments the views obtained from hologram reconstruction and out-of-focus imaging were different and they allowed size comparisons along only one dimension (vertical axis). And, we could only create spherical ice particles.

Let us consider morphological properties of the particles. For rough particles as sand, 2D-Fourier transform of the interferometric out-of-focus image has been shown to give the 2D-autocorrelation of the contour of the particle [25]. One can wonder

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http://dx.doi.org/10.1016/j.optcom.2016.04.004
0030-4018/

whether the roughness of ice crystals is such that a similar property can be obtained. The answer requires that we can create ice crystals, and record simultaneously the in-focus and out-of-focus images of the same view of the particle. We have thus realized a new set of coupled synchronized experiments in order to achieve this goal. Section 2 shows the set-up that has been developed to realize synchronized in-focus and interferometric out-of-focus images of ice crystals. Using the cooling chamber already described in Ref. [24,26], tap water and a plant sprayer, we show that we are no more limited to the generation of spherical ice particles but that we can now generate dendrite-like ice crystals. Analyzing the in-focus and out-of-focus images of different ice crystals, we validate in Section 3 the size measurement that can be done from the analysis of the out-of-focus patterns. Evaluating the speck of light of the patterns along both transverse axes of the images, quantitative agreement with in-focus images is obtained. The rate of errors is evaluated. These results confirm for both transverse directions of the views the previous comparisons that could have been done using digital holography and out-of-focus imaging in [24]. Section 4 shows the good concordance that is obtained between our experimental results and quantitative simulations of the experiment. Section 5 shows the comparisons between the 2D-Fourier transforms of speckle-like patterns with the 2D-autocorrelation of the shape of the in-focus images. Although results exhibit more noise than in the case of rough sand particles [25], it appears that it is possible to obtain an estimation of the 2D-autocorrelation of the particle's shape from the analysis of the speckle-pattern.

2. Experimental setup

2.1. General description

Ice crystals are generated in a cooling chamber which consists of an insulated and refrigerated cylindrical column (Fig. 1(a)) [26]. This chamber has been presented in a previous paper [24] and can reach a minimum temperature of −65 °C. Water droplets are injected at the top of the column and frozen during their free fall. An optical system which combines interferometric out-of-focus imaging and in-focus imaging ensures visualization of the particles falling inside the chamber. This system can measure both liquid water droplets and ice crystals. Both imaging lines measure the same particles from the same scattering angle. At the bottom of the column, optical windows are disposed at 90° and 180° angles. A laser sheet illuminates the falling particles and the in-focus and out-of-focus images of the particles due to light scattering processes at $\Theta = 90°$ are recorded on two CCD sensors (Fig. 1(b)). A circulation of air is imposed on the outer surface of each window to avoid condensation.

One of the cameras records the in-focus image while the other one records simultaneously the out-of-focus image of the same particles. Both cameras are synchronized and are adjusted to record an image from the same scattering angle. The in-focus image gives the image of ice particles while their out-of-focus image gives a speckle-like interferometric pattern.

Both cameras have a 2048 × 2048 pixels CCD sensors, with a pixel size of 5.5 μm. The recording is made in 16 bits, 25 FPS and is synchronized at the microsecond by an external device. The synchronization device first starts the cameras recording, orders a laser pulse and then stops the recording. A laser sheet is formed from a laser beam by a combination of cylindrical and spherical lenses and a mechanical aperture. The laser source is a frequency-doubled Nd:YAG emitting 20 mJ, 4 ns pulses at 532 nm. In the measurement volume, the thickness of the laser sheet is about 1.5 mm.

Light reflected by the beam splitter is collected by the in-focus optical system, while light transmitted is collected by the out-of-focus setup.

In-focus images are obtained by using a far field objective provided by ISCOOPTIC which has a 2.6 mm × 2.6 mm^2 field of view and 1 mm depth of field (Fig. 2). The distance between the lens and the laser sheet is 293.4 mm. The out-of-focus system consists of a Nikon objective (focal length of 200 mm) with an extension tube providing a closer focus plane for a smaller sampling volume. The aperture diameter is f/4.7. Both cameras are first adjusted to obtain an in-focus image of the same point of the laser

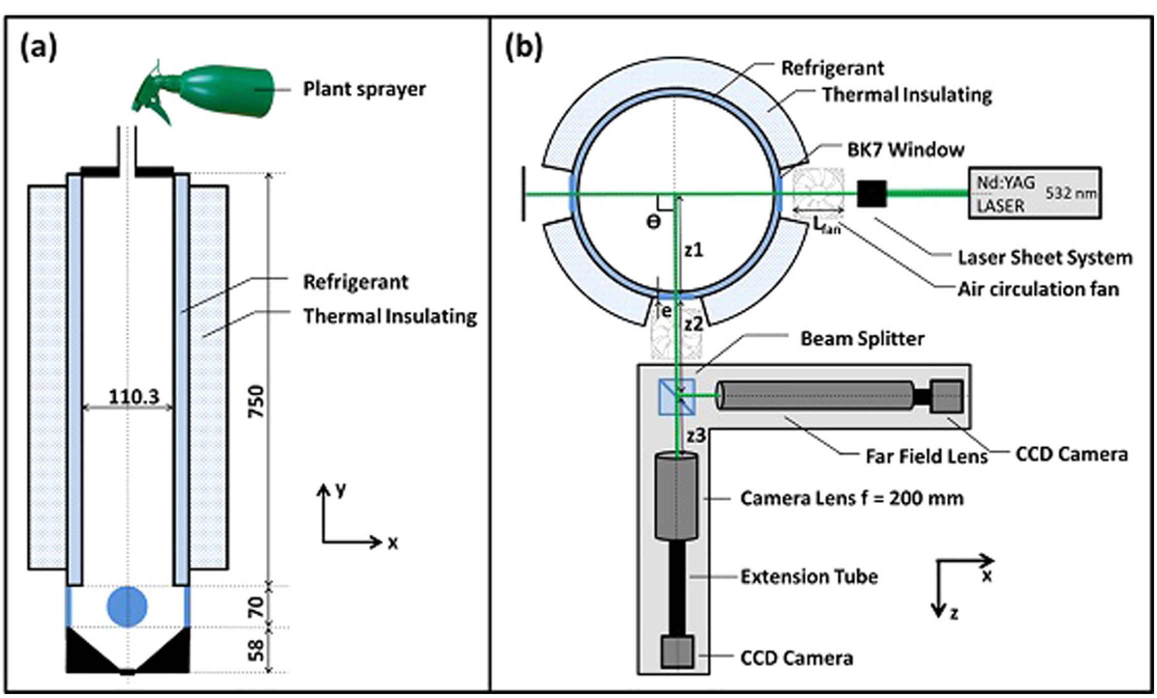

Fig. 1. (a) Side view of the freezing column (numerical values are in millimeters) and (b) top view of the experimental set-up combining in-focus and out-of-focus imaging.