Journal of Quantitative Spectroscopy & Radiative Transfer 178 (2016) 108–116

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Size determination of mixed liquid and frozen water droplets using interferometric out-of-focus imaging

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ARTICLE INFO

Article history:
Received 17 July 2015
Received in revised form
15 September 2015
Accepted 15 September 2015
Available online 26 September 2015

Keywords:
Interferometric particle imaging
Digital holography
Ice particles
Droplets

ABSTRACT

We record simultaneously interferometric out-of-focus images and digital in-line holograms of liquid and frozen water droplets. We show that the analysis of speckle-like out-of-focus images allows a quantitative estimation of the size of the particles which is corroborated by numerical reconstruction of holograms recorded simultaneously. Interferometric out-of-focus imaging could be extended to the characterization of ice in clouds in the atmosphere.

1. Introduction

The characterization of droplets and ice crystals in the atmosphere is particularly important. In situ characterization with airborne instruments is indeed one of the key issues in cloud microphysics. The detection and the characterization of ice crystals is further essential in order to ensure the safety of aircrafts in flight. The polar nephelometer, based on the angular scattering properties of ice crystals has been tested in airplanes and is currently used in laboratory settings [1]. An optical technique as interferometric out-of-focus imaging [2–7] attracts much attention since it can measure the size of droplets with the well-developed real-time image processing algorithms [8]. This technique is based on the scattering properties of droplets. Measurements are done in an out-of-focus image plane of the droplets under study. The technique has important applications in flow visualization [9–13]. It further attracts much attention for the development of algorithms that can improve the accuracy [14].

Based on this, an Airborne Laser Interferometric Droplet Sizer has been realized recently [15]. It would be particularly interesting to extend such a device to the characterization of ice particles. The adaptation of this method to the analysis of irregular particles is however not straightforward. Recently, we have demonstrated that the size of rough particles, such as NaCl salt crystals or sand particles, can be determined from the size of the speck of light in the speckle-like out-of-focus image of the irregular object [16,17]. We expect that similar conclusions can be achieved in the case of irregular ice particles. However, it is necessary to develop characterization experiments involving real ice, combined with a second well-calibrated technique in order to validate quantitatively the measurements made. This is what will be shown in this paper: we have first built a cold chamber. Liquid droplets fall within the chamber and freeze. We then record simultaneously the interferometric out-of-focus image and the digital in-line hologram of the frozen droplet. We show that the method proposed to evaluate the size of irregular rough objects by analyzing their speckle-like out-of-focus image can be adapted to frozen droplets, and that the size obtained from

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http://dx.doi.org/10.1016/j.jqsrt.2015.09.009
0022-4073/

the size of the speck of light is quantitatively corroborated by the reconstructed frozen droplet image from the hologram recorded simultaneously. The paper is organized as follows: Section 2 is devoted to the presentation of the experimental setup. Section 3 shows the theoretical backgrounds on laser interferometric particle imaging, and Section 4 shows the experimental results. In particular, the estimation of the sizes of liquid and frozen water droplets obtained by interferometric out-of-focus imaging is corroborated by digital in-line holography (DIH) experiments. An evaluation of the measurement error completes the paper.

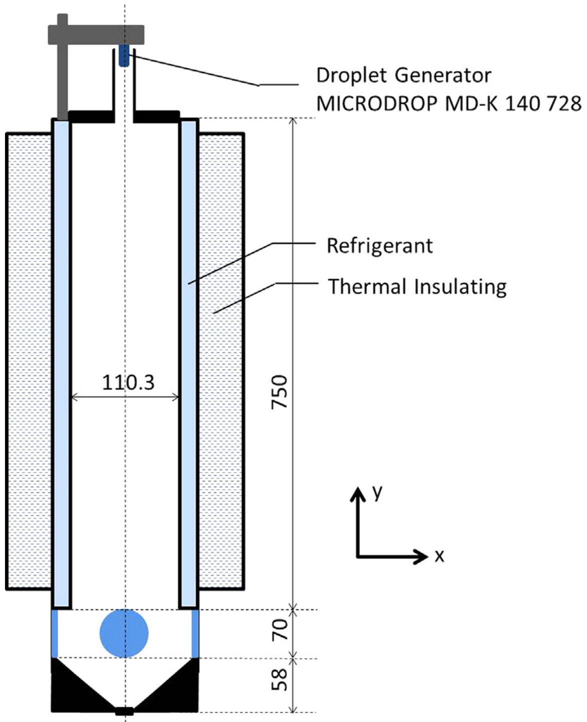

Fig. 1. Side view of the freezing column (numerical values are in millimeters).

2. Experimental setup

The cold chamber that has been realized is depicted in Figs. 1 and 2. It is based on the previous chamber developed by Barkey and coworkers [18]. It consists of an insulated and refrigerated cylindrical column, which is 750 mm tall, and 110 mm large in diameter. 7 thermocouples are placed along the height of the column to monitor the inner temperature. Water droplets from a MD-K 140 728 Microdrop generator (approximately 100 μm diameter) fall from the top of the cylindrical cavity and are cooled at the desired temperature. A test chamber with the same diameter is positioned at the bottom of the column. It has three BK7 windows, allowing optical measurement of light scattering by liquid and frozen droplets.

Let us first detail the interferometric out-of-focus imaging setup: 4 ns, 532 nm pulses issued from a frequency-doubled Nd:YAG laser are sent into the cold chamber. The beam is previously collimated in order to obtain a quasi-plane wave illumination inside the column: the wavefront is quasi-plane (divergence lower than 1°) but the intensity profile has a transverse Gaussian distribution (beam diameter of 1.2 cm at $1/e^2$). The field scattered by the inside-particles is observed around the scattering angle $\theta = 90°$. It is imaged through the window with a lens. The distance between the particles and the window is z_1. The thickness of the window is e. The distance from the window to the aperture (plotted on the inset of Fig. 2) is z_2. The diameter of the aperture is only

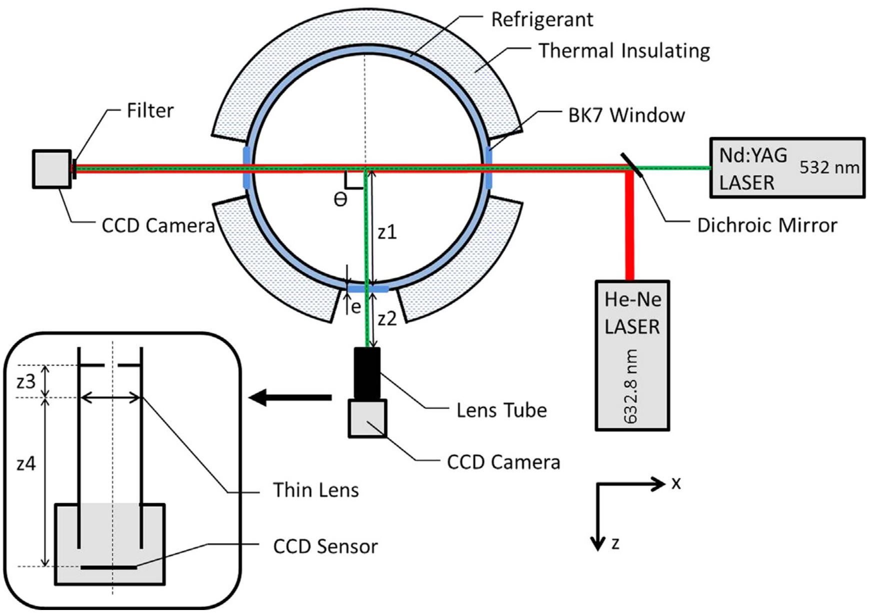

Fig. 2. Top view of the experimental setup combining interferometric out-of-focus imaging and digital in-line holography.