Multi-view interferometric out-of-focus imaging of ice particles

Mohamed Talbi, Gérard Gréhan, Marc Brunel

12th International Conference on
Laser-Light and Interactions with Particles
March 5th-9th, 2018, College Station, Texas, USA

MULTI-VIEW INTERFEROMETRIC OUT-OF-FOCUS IMAGING OF ICE PARTICLES

Mohamed TALBI [1,*] and Gérard GRÉHAN [1], Marc BRUNEL[1,*]

[1] UMR CNRS 6614 CORIA, Avenue de l'université, BP 12, 76801 Saint Etienne du Rouvray, France

**Corresponding authors: talbim@coria.fr and marc.brunel@coria.fr*

Abstract

Multi-view interferometric out-of-focus imaging of ice particles is realized. The acquisition of two images enables a better ice water content estimation. The overlapping defocused images of two nearby particles are analyzed. If one particle is much smaller than the other one, the pattern constitutes an off-axis hologram whose analysis gives the exact size and shape of the biggest particle.

1 Introduction

Interferometric out-of-focus imaging enables the characterization of spherical droplets or bubbles in a flow with applications in sprays, combustion, meteorology, fluid mechanics [1-8]. The technique can be extended to the characterization of irregular rough particles. Interferometric out-of-focus images of such particles are then speckle-like patterns. Their analysis enables the determination of quantitative information about the morphology of the particle [9-14]. Based on this property, some information concerning the 3D-shape, and orientation of the particle can be obtained using a multi-view set-up [15]. An important application is aircraft safety. Detection and size measurements of ice crystals in the atmosphere are indeed crucial. Recent works showed that the technique can be used in the case of ice particles, with a size measurement error rate for single particles reasonable Nevertheless, the analysis of overlapping images necessitates the development of specific methods for higher concentrations of particles [16-18].

There is no theoretical model that can predict rigorously the interferometric out-of-focus images of rough particles of any shape and texture. Fortunately, recent experiments have validated a simplified approach: assimilating an irregular rough particle illuminated by a laser to an ensemble of Dirac emitters located on the envelope of the particle, a scalar expression of the electric field received by the camera can be expressed. It is then shown that the 2 dimensional Fourier transform of the interferometric pattern gives the contour of the 2 dimensional autocorrelation of the initial repartition of the emitters, i.e. of the initial illuminated particle.

In this work, we report the analysis of pairs of interferometric out-of-focus images of ice particles for the estimation of ice water content in a given field of view. Ice particles are generated in a freezing column. The interferometric out-of-focus images along two perpendicular angles of view are recorded simultaneously. Particle's sizes can then be estimated. They are compared to the in-focus images that are acquired simultaneously using two other CCD sensors.

2 Experimental setup

Liquid water droplets of random size are injected at the top of the column. The temperature inside the column is around −45°C. They freeze during their free fall to generate ice particles. 4ns, 5mJ, 532nm pulses are emitted by a frequency-doubled Nd:YAG laser. They are sent onto the freezing column through a BK7 window. A set of two out-of-focus imaging lines enables interferometric imaging of irregular particles from two perpendicular angles of view. In addition, two in-focus imaging lines are mounted for both same angles of views. It is realized with two beam splitters. In-focus images are obtained by using far field objectives provided by ISCOOPTIC (fields of view 2.45mm x2.45 mm, depth of field 1mm). Out-of-focus systems consist of Nikon objectives (focus length of 200mm) with an extension tube providing out-of-focus imaging. The set of sensors are first adjusted to obtain an in-focus image of the same point of the laser sheet in the column. Then, the whole out-of-focus optical system (camera + extension tube + lens) is translated forward by Δp=15 mm (out-of-focus imaging). In summary, four CCD sensors are synchronized on the laser pulse for synchronized acquisitions. For both angles of view, the in-focus and interferometric out-of-focus images are recorded. On the top view of fig. 1, cameras 1 and 2 are on an imaging axis that makes an angle of θ=-45° on the left while cameras 3 and 4 are on an imaging axis that makes an angle of θ=45° on the right. The dimensions of the CCD sensors used for the in-focus images are 2048 x 2048 pixels (pixel size: 5.5 µm). The dimensions of the CCD sensors used for the out-of-focus images are 1920 x 1200 pixels (pixel size: 5.86 µm). As multi-views experiments will be reported, The reference frame (x,y,z) is presented on Fig. 1 for clarity. After 2D-Fourier transforms of the interferometric images, the corresponding coordinates in spectral domain will be noted (u,v,w).

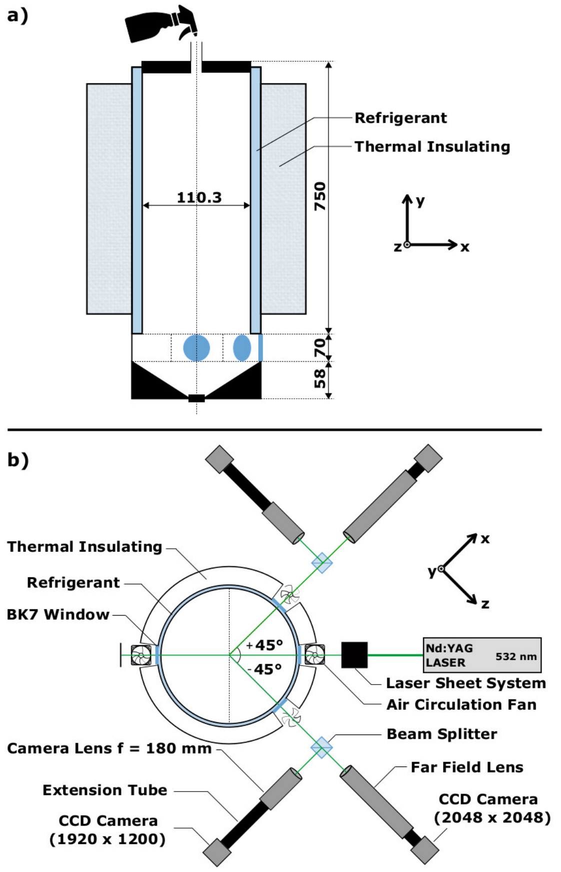

Figure 1 a) Experimental setup, side view, b) top view.

3 Results

Many cases have been recorded (single particle in the field of view, pairs of particles in the field of view whose out-of-focus images overlap). Using our multi-view set-up, it is possible to obtain a better estimation of ice water content as the estimation is based on a 3D-analysis. In our presentation, we will show a wide set of experimental interferometric images that could be recorded and analyzed. In this summary, we illustrate one of these results that is very specific and requires special analysis:

- when the out-of-focus images of two particles overlap, the initial object is a two-components objects. If separation between them is higher than their size, the 2D-autocorrelation of this 2-components object is composed of three large spots: a central one corresponding to the superposition of the 2D-autocorrelations of both particles considered separately, a spot corresponding to the cross-correlation between both particles and its symmetric spot. Finally, if one particle is much smaller than the other one, the cross-correlations reduce to the exact shape of the bigger particle, which corresponds to off-axis holography. This case is predicted theoretically, but its observation is difficult. Intensity scattered by a droplet is proportional to d^2 where d represents its diameter. If one particle is 100 times bigger than the other one, the ratio between intensities scattered by both particles should thus be around 10000. The observation of interference fringes between both signals and their analysis is then difficult. However, in the case of ice crystals, a pure reflection on a facet of a small particle can significantly reduce this ratio.

The case presented on the Fig.2 illustrates the situation where a single view would not be sufficient to know that two particles are present in the field of view. Fig. 2(a) shows the in-focus image recorded by sensor 1 while Fig. 2(b) shows the in-focus image recorded by sensor 3 simultaneously. Both figures present again a pair of ice particles. Interferometric out-of-focus images recorded simultaneously by sensors 2 and 4 are not reported. Fig. 3(a) and 3(b) show directly the 2-dimensional Fourier transforms of these patterns for both angles of view.

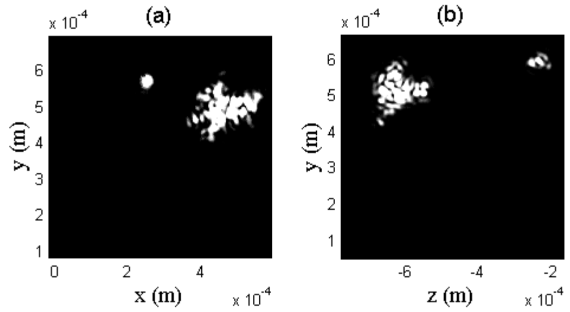

Figure 2 *In-focus images of pair of ice particles observed with sensor 1(a) and sensor 3 (b).*

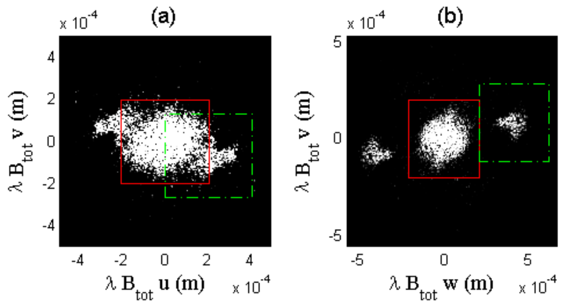

Figure 3 *2D-Fourier Transforms of the interferometric out-of-focus patterns.*

In these two last plots, the scaling factor of both horizontal and vertical axes is coefficient λB_{tot}, where λ is the laser wavelength, and B_{tot} the B-transfer matrix coefficient of the total matrix that describes propagation from the particle to the CCD sensor for the out-of-focus imaging lines. The correspondence between the spread spot in the dashed green square of Fig. 3(b) with the corresponding in-focus image of the biggest particle (Fig. 2(b)) is quantitatively very good in size and shape. Nevertheless, a similar comparison between Fig. 2(a) and 3(a) is not possible. The two particles are not sufficiently separated on this view. There is overlapping between each symmetric spot and the central spread spot of the 2D-Fourier transform of the interferometric pattern. The sole Fig. 3(a) would have been interpreted as a unique particle. This example shows the importance of a multi-view set-up to avoid an erroneous interpretation.

4 Conclusion

During the conference, a complete set of experimental results will be presented. An ensemble of conclusions will be drawn. Our results give another confirmation that the 2 dimensional Fourier transform of the interferometric defocused image of a rough particle gives the contour of its 2 dimensional in-focus shape. .

In the general case of isolated particles, a multi-view set-up enables a better ice water content estimation. In addition, as already mentioned in reference [15], a multi-view setup enables an important measurement verification: the sizes of a particle deduced from the out-of-focus images of both views must be the same along the axis that is common to both angles of view.

The interferometric out-of-focus images of two particles can overlap. When one particle is much smaller than the other one, it can be viewed as a punctual emitter that acts as a reference wave to generate the off-axis hologram of the second biggest particle. The exact size and shape of the biggest particle can then be directly obtained from the analysis of the interferometric out-of-focus image. The presence of two angles of view further enables to avoid errors in interpretation: if one view indicates that there is only one particle, the other view can show that interpretation was erroneous.

5 Acknowledgement

The authors thank the French National Agency for financial support through the CISTIC project of program Investissements d'Avenir LabEx EMC3 (ANR-10-LABX-09-01), and project ANR ASTRID NUAGE (ANR-15-ASTR-0003-01).

6 References

[1] A. R. Glover, S. M. Skippon and R. D. Boyle, "Interferometric laser imaging for droplet sizing: a method for droplet-size measurement in sparse spray systems," Appl. Opt. **34,** 8409–8421 (1995).

[2] T. Kawaguchi, Y. Akasaka and M. Maeda, "Size measurements of droplets and bubbles by advanced interferometric laser imaging technique," Meas. Sci. Technol. **13,** 308-316 (2002).

[3] N. Damaschke, H. Nobach and C. Tropea, "Optical limits of particle concentration for multi-dimensional particle sizing techniques in fluid mechanics," Exp. Fluids **32**, 143-152 (2002).

[4] S. Dehaeck and J. P. A. P. Van Beeck, "Designing a maximum precision interferometric particle imaging set-up," Exp. Fluids **42**, 767-781 (2007).

[5] Y. Hardalupas, S. Sahu, A. M. K. P. Taylor and K. Zarogoulidis, "Simultaneous planar measurement of droplet velocity and size with gas phase velocities in a spray by combined ILIDS and PIV techniques," Exp. Fluids **49**, 417-434 (2010).

[6] R. S. Volkov, G. V. Kuznetsov and P. A. Strizhak, "Influence of droplet concentration on evaporation in a high-temperature gas," Int. J. Heat Mass Transfer **96**, 20-28 (2016).

[7] M. Maeda, T. Kawaguchi, and K. Hishida, "Novel interferometric measurement of size and velocity distribution of spherical particles in fluid flow," Meas. Sci. Technol. **11**, L13–L18 (2000).

[8] H. Shen, S. Coëtmellec and M. Brunel, "Cylindrical interferometric out-of-focus imaging for the analysis of droplets in a volume," Opt. Lett. **37**, 3945-3947 (2012).

[9] M. Brunel, H. Shen, S. Coëtmellec, G. Gréhan, T. Delobel, "Determination of the size of irregular particles using interferometric out-of-focus imaging", Int. J. of Opt., Article ID 143904 (2014).

[10] M. Brunel, S. Coetmellec, G. Gréhan and H. Shen, "Interferometric out-of-focus imaging simulator for irregular rough particles," J. Europ. Opt. Soc.: Rap. Public. **9**, 14008 (2014).

[11] P. García Carrascal, S. González Ruiz and J. P. A. J. Van Beeck, "Irregular particle sizing using speckle pattern for continuous wave laser applications," Exp. Fluids **55,** 1851 (2014).

[12] M. Brunel, S. González Ruiz, J. Jacquot and J. van Beeck, "On the morphology of irregular rough particles from the analysis of speckle-like interferometric out-of-focus images," Opt. Commun. **338**, 193-198 (2015).

[13] G. E. Fernandes, Y. L. Pan, R. K. Chang, K. Aptowicz and R. G. Pinnick, "Simultaneous forward- and backward-hemisphere elastic-light-scattering patterns of respirable-size aerosols," Opt. Lett. **31**, 3034–3036 (2006).

[14] Z. Ulanowski, E. Hirst, P.H. Kaye and R.S. Greenaway, "Retrieving the size of particles with rough and complex surfaces from two-dimensional scattering patterns," J. Quant. Spectrosc. Radiat. Transfer. **113**, 2457-2464 (2012).

[15] L. Ouldarbi, M. Talbi, S. Coëtmellec, D. Lebrun, G. Gréhan, G. Perret, M. Brunel, "3D-shape recognition and size measurement of irregular rough particles using multi-views interferometric out-of-focus imaging", Appl. Opt. **55** (32), 9154-9159 (2016).

[16] J. Jacquot-Kielar, P. Lemaitre, C. Gobin, Y. Wu, E. Porcheron, S. Coëtmellec, G. Gréhan, M. Brunel "Simultaneous interferometric in-focus and out-of-focus imaging of ice crystals", Opt. Commun. 372, 185-195 (2016)

[17] M. Brunel, G. Demange, M. Fromager, M. Talbi, H. Zapolsky, R. Patte, K. Aït Ameur, J. Jacquot-Kielar, S. Coetmellec, G. Gréhan, B. Quevreux, "Instrumentation for ice crystal characterization in laboratory using interferometric out-of-focus imaging", Review of Scientific Instruments 88, 083108 (2017).

[18] M. Brunel, P. Lemaitre, E. Porcheron, S. Coëtmellec, G. Gréhan, J. Jacquot-Kielar, "Interferometric out-of-focus imaging of ice particles with overlapping images", Appl. Opt. 55 (18), 4902-4909 (2016).