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ON THE INFLUENCE OF DROPLETS NON SPHERICITY ON THEIR FIRST RAINBOW PATTERN AND OUR CAPABILITY TO CORRECTLY ESTIMATE THEIR SIZE AND TEMPERATURE

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Abstract

The influence of droplets non sphericity on their rainbow scattering diagrams is investigated with a vectorial complex ray model and experiments carried under acoustic levitation. It is shown that quasi-imperceptible change in the morphology of large droplets can significantly affect the structure of their scattering pattern and hence any estimation of their size and temperature - unless a proper particle shape and light scattering models are used.

1 Introduction

Droplets are frequently considered as spherical, although from our daily experience it is obvious that these fragile and highly deformable objects rapidly react to any perturbation. Moreover, even under stationary conditions, they can never be perfectly spherical due to asymmetric forces like gravity and fluid drag. Nonetheless, the important thing is often to know whether this deviation from an ideal model (i.e. a sphere described by a single parameter: a radius) is relevant or not in a particular situation or problem. To answer this point it is necessary to dispose of a model allowing evaluating the effect of this deviation. In the frame of the LIP conference, this model is a light scattering model. The difficulty is that the calculation of the light scattering properties of large non-spherical droplets, that are observed in nature (raindrop size: 0.5-5mm) or in industrial manufacturing processes, exceeds greatly the capabilities of actual electromagnetic codes. It is the reason why, the development of geometrical and physical optics approximation is still required, as well as validation experiments. One critical difficulty when moving to complex shaped particles lies also in the drastically increase of unknowns to deal with. In the present work, we report numerical results obtained with a geometrical optics approximation (GOA) as well as experiments carried out on ellipsoid droplets levitated and heated in an acoustic field.

2 Scattering model and experiments

The Vectorial Complex Ray Model (VCRM) [1-3] is an extended GOA allowing to predict the scattering of a plane wave or Gaussian beam by a particle having a smooth surface (analytic function). It allows accounting, with an algebraic formalism, for the direction, the amplitude, the phase, the polarisation and the local wave front curvature

of complex rays. Owing to GOA basic hypothesis, its predictions are only asymptotically valid for scatterers with a large size parameters (e.g. $x \gg 20-100$) and far from scattering angle zones where wave phenomena are dominant (e.g., forward and backward regions, vicinity of caustics,...)[4]. VCRM numerical implementation is actually limited to ellipsoids (semi-axis: a , b & c) observed in one plan of symmetry (in this plane the ellipsoid can be tiled by γ) so that the code is said to be 2D+. It allows predicting the coarse as well as the fine structure of the scattering diagrams, whatever is the aspect ratio of the droplet, in contrary to Moebius or ray tracing models [5].

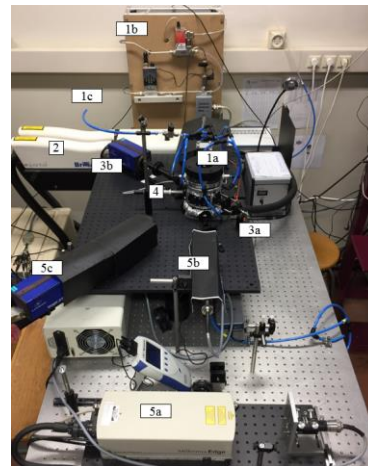


Figure 1 Experimental setup: (1) thermal and fluid loop (not all visible), evaporation chamber with the acoustic levitator; (2) PIV system for gas dynamic characterization; (3) shadowgraph illumination and imaging optics; (4) hygrometer; (5) rainbow diffractometer emission and collection components.

Experiments were carried on water droplets levitated in an acoustic trap embedded in an evaporation chamber, see Fig. 1. This setup allows regulating the temperature and humidity (H) of the gas (air plus water vapor) surrounding the droplet. By changing the pressure sound level in the acoustic trap it is easy to adjust the oblateness of the droplet which is evaporating (provided the water vapor saturation is not reached, $H < 100\%$).

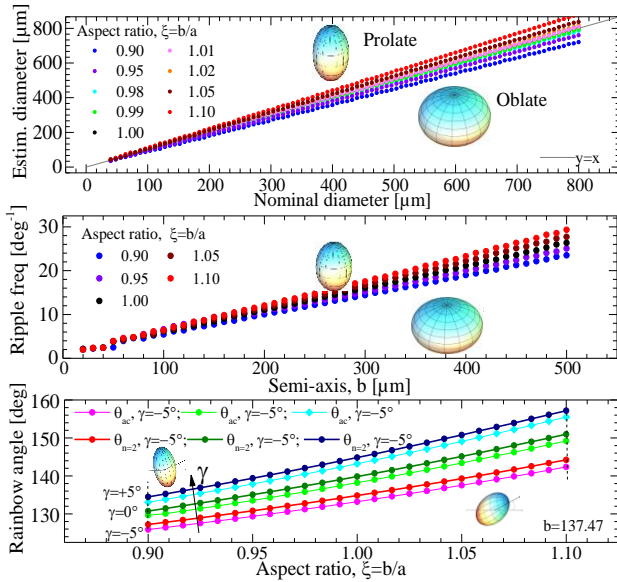


Figure 2 Direct or inverse simulations for spheroid water drops, $T = 24^\circ \text{C}$ ($m = 1.3350$). (a) Error of the diameter estimation when a spherical particle shape model and the LMT theory are used to inverse the rainbow patterns of spheroid droplets. (b) Evolution with the aspect ratio of the angular frequency of the ripple structure of the rainbow. (c) Angular shift of the geometrical rainbow angle and the first dark fringe of the rainbow with the aspect ratio and droplet tilt angle in the scattering plane of symmetry (drop of constant volume, b is fixed).

3 Exemplifying results and conclusions

We first evaluate the influence of the aspect ratio of prolate or oblate droplets on the estimation of their equivalent spherical diameter when they are assumed to be spherical, Fig. 2 (a). For that purposes, VCRM was used to generate the corresponding rainbow scattering diagrams while the inverse method [3] used the Lorenz-Mie theory (LMT, i.e. electromagnetic model for spherical particles) to retrieve the droplet properties. These results allows evaluating the importance of the deviation from the sphericity from the optical particle sizing point of view. It turns out that the deviation increases almost linearly with the aspect ratio. Fig. 2 (b) shows the evolution of the frequency of the ripple structure of the rainbow pattern. The sensitivity of this high angular frequency structure (that is not taken into account by ray models) is very clear. Fig. 2 (c) reports on the evolution of the geometrical rainbow angle (as predicted by Snell-Descartes laws, noted θ_r) with the positioning of the first minima of the rainbow (first dark fringe of the supernumerary structure, noted $\theta_{n=2}$). This comparison is performed for an oblate droplet with a variable tilt angle in the scattering plane. The change in θ_r and $\theta_{n=2}$ are considerable.

Figure 3 and Table 1 compares differences between some statistics (average and standard deviation) obtained on the parameters of a water droplet evaporating at 29°C

and for $H=60\%$. The reference value are those obtained with the shadowgraph (a & c) and thermocouples (temperature and thus, refractive index). During the course of the experiment (5'), the droplet equivalent spherical radius decreases typically from 380 to 50 micrometers. With a data acquisition rate of one image per second, these statistics are performed on about 330 little measurements (i.e. sizes).

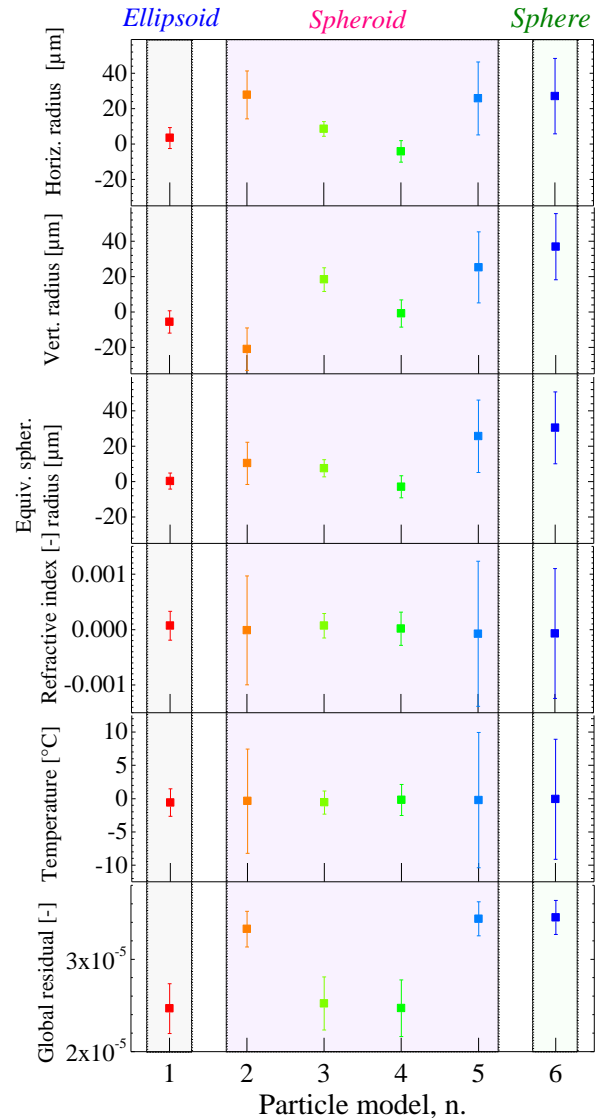


Figure 3 Differences between the average and standard deviation on the parameters retrieved, for a water droplet evaporating at 29°C and $H=60\%$, when VCRM is used to inverse the data with different particle shape model assumptions: (1) arbitrary ellipsoid, (2-5) spheroids with particular orientations, (6) sphere.

The parameters retrieved are horizontal radii (a and c), vertical radius (b), refractive index (m , that is further on converted in temperature) and the spherical equivalent radius ($R=(abc)^{1/3}$). The residual of the inverse method is also shown. The six cases tested ($n=1, 2, \dots, 6$) correspond to different hypotheses on the morphology of the droplet: (1)

arbitrary ellipsoid, (2-5) spheroids with particular orientations, (6) sphere (see Table 1 for details).

Table 1 Particle shape models employed to inverse, with VCRM, the experimental rainbow scattering diagrams obtained for a water droplet evaporating in a controlled atmosphere.

Shape model n..	Parameters : refractive index plus
1	$a \neq b \neq c$: arbitrary ellipsoid,
2	$a = c \neq b$: spheroid which symmetry axis is along gravity direction,
3	$a = b \neq c$: spheroid which symmetry axis is perpendicular to gravity direction and the optical axis,
4	$b = c \neq a$: spheroid which symmetry axis is along the optical axis,
5	$a = c \neq b$ with b/a derived from shadowgraph : spheroid which symmetry axis is along the gravity direction,
6	Sphere, $a = b = c$.

First, it is important to point out the very good agreement obtained on the mean values. The differences with the “reference” values are extremely small. For instance, for the case n. 1, the agreement found of the mean horizontal radius is better than $5\mu\text{m}$ over all the size range, while it is globally better than 1°C for the temperature. In Fig. 3, the error bars represent the standard deviation (StD) on the estimation of each parameter. This StD can be understood as the consequence of some (tiny) oscillations of the droplet and some fluctuations in the resolution of the inverse method (because of the numerical and experimental noise). The particle shape model providing the lower standard deviation is the ellipsoid (case n. 1). This is not surprising since this particle shape model allows accounting for more droplet shapes and then, in some ways, more fluctuations in its shape. This is again a clear proof of VCRM accuracy and practical interest. The worst cases correspond to the sphere model (no. 6) and the spheroid with major axis along the gravity direction when its aspect ratio is set equal to that derived from shadowgraph measurements (case n. 5). The physical meaning of these results is rather clear and consistent: the droplet is definitively not spherical and the ripple structure plays an important role in the reconstruction of the signal. More surprising, while we were expecting that after case n. 1 the best results should be obtained for case n. 2 (and the fact is that the results are good), the second best particle shape model seems to be a spheroid whose axis of symmetry is perpendicular to the gravity direction (cases n. 3 & 4). Our explanation at this moment is that the oscillations of the droplet, while extremely small, induces some change in the orientation of its axis of symmetry (that is expected to be vertical, tilt angle null). For an oblate spheroid such case n. 2, the effect of a

small tilt angle on the rainbow pattern is almost negligible because in the scattering plane the droplet cross section is circular. Conversely, the tilt angle of a prolate spheroid (cases n. 3 & 4) allows shifting efficiently the rainbow pattern as shown by our numerical study, see Fig. 2 (d). In another words, and to make the things simple, all is like it is “easier” for the inverse method to account for the droplet tilt angle oscillation with an prolate particle model than a oblate one.

4 References

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