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Influence of spatial curvature of a liquid jet on the rainbow positions: Ray tracing and experimental study

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ABSTRACT

Rainbow refractometry is largely used in optical metrology of particles thanks to its advantages of being non-intrusive, precise and fast. Many authors have contributed to its development and the application in the characterization of liquid jets/droplets. The researches reported in the literature are mainly for the spherical droplets or the liquid jets which can be considered as a cylinder of constant section. However, the section of a real liquid jet, even in the simplest configuration, varies with distance from the exit. The influence of the spatial curvature of the jets must, therefore, be taken into account. In this paper, we report experimental measurements of the shifts of the rainbow positions in the horizontal and vertical directions of a liquid jet and the theoretical investigation with the vectorial complex ray model. It is shown that the shifts of rainbow positions are very sensitive to the spatial curvature of the jets. This work is hoped to provide a new approach to characterizing the structure and the instability of liquid jets.
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1. Introduction

The study on the liquid atomization is still intensive for its wide applications in liquid-fuel combustion, drug delivery, painting, powder production, etc. The basic theory in treating this process is the well-known Rayleigh theory [1] which deals with liquid jets of low velocity and describes the jet instability in the linear scope. In the Rayleigh breakup regime, continuous flow of liquid ejected from a nozzle forms a liquid jet [2–4]. It is subjected to gravitational, inertia, viscous, and surface tension forces [5]. The surface tensions between the liquid jet and the surrounding air amplify small perturbations, and it is the amplification of perturbation that causes the jet breakup [6]. In the process of amplification, the initial (infinitesimal) disturbances grow exponentially, and the component with the largest growth rate will dominate the breakup [7].

In terms of the measurement of the jet instability (frequency and amplitude), the main method is the imaging with high-speed cameras. But, its precision is often not enough to capture the initial disturbances. The rainbow refractometry [8–10], based on the analysis of the scattering diagram around the rainbow angles, is proven to be a promising way to solve the problem. The advantages of the rainbow refractometry are attributed to the high sensitivity of the rainbow feature to the particle size and refractive index (hence the temperature).

In a previous paper [11], we demonstrated that the initial disturbances can be characterized by rainbow refractometry with high accuracy. In 2013, Song et al. [12] proposed an optimization scheme based on the Debye theory to characterize the jet parameters (size and refractive index). And in 2016, Song et al. [13] proposed an excellent method to measure the temperature gradient in a heated liquid cylinder (jet) by the rainbow refractometry assisted with infrared thermometry. Since the theories used in these papers were based on the light scattering by a sphere or an infinite circular cylinder, the results were convincing only in the region where the diameter of the jet is constant. However, the size of a real jet varies as function of the distance from the exit and cannot be considered exactly as an infinite cylinder [14]. This means that the curvature of a liquid jet surface is not constant, neither in the horizontal direction nor in the vertical direction. And these spatial curvatures affect the directions of the emergent rays and cause shifts of the rainbow positions. Thus it is necessary to take into account the spatial curvatures in the analysis and measurement of liquid jets.

In the present paper, a ray tracing method based on vectorial complex ray model (VCRM) [15] is proposed to trace the light rays scattered by a real liquid jet. The positions of the geometric rainbows of the jet are calculated numerically. Experiments are also carried out to explore the influence of the spatial curvature of the jet on the rainbow positions. The rest of the paper is organized as follows. The experimental setup and observation of the rainbow position shifts are presented in Section 2. The theoretical model to

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explore the results and the method used to extract 3D profile of the liquid jet are described in Sections 3 and 4, respectively. Then Section 5 is devoted to the investigation of the experimental and the theoretical results. The conclusions are given in the last section.

2. Experimental setup and rainbows of a liquid jet

The experiment setup and the top view schema are shown in Figs. 1 and 2, respectively. The light beam with wavelength of 532 nm emitted from a diode laser passes firstly through a polarizer (a). The divergence angle of the laser beam is very small (0.5 mrad), and the distance of the jet from the laser is about 1.2 m. Without lenses, the diameter of the laser spot at the position of the jet is 4.0 mm. The radius of the laser spot is defined as the distance between the spot center and the point where the light intensity is I_0/e^2 (I_0 is the light intensity of the spot center). Although the light spot of the laser beam is not an ideal circular spot, what we need is a beam which can be regarded as plane wave in the horizontal plane and is sufficiently thin in the vertical direction to localize the measurement position. To achieve this, the beam is then condensed in the vertical direction with two cylindrical lenses (b) and (c) of focal length equal to 100 mm and 25.4 mm, respectively, and expanded in the horizontal direction with two cylindrical lenses (d) and (e) of the same focal lengths but exchanged in the order and rotated by 90°. Thus we obtain a beam of 15.7 mm wide and 1.0 mm high. As the diameter of the jet under study ranges from 0.8 mm to 1.3 mm, much less than the width of the incident beam in the horizontal plane, so the laser beam after the four lenses satisfies our needs.

It is known that the line width of the diode laser is not as narrow as that of single-mode lasers. To be sure that the coherence length of the laser beam is long enough for the present study, we have enlarged the incident beam in the vertical direction to enable the reflected rays to encounter the high-order rays, and we observed clearly the ripple structure which results from the interference of the reflected rays with high-order rays. This proves the coherence length of our diode laser is at least at the order of the diameter of the jet. The supernumerary (Airy) bows we are concerned about are formed by the rays in the neighborhood of the rainbow angles, so the conditions are largely satisfied.

The liquid jet is generated from a circular metal tube of 9 cm length with inside and outside diameter equal to 0.95 mm and 1.32 mm, respectively. The liquid used is distilled water under a pressure from a tank of 5 liters to ensure the stability of the flow rate, value of which is controlled by the current meter. A camera A is used to capture the profile of the jet. The scattered diagrams are registered with two CCD cameras: a linear CCD camera acquires the scattering diagram around the rainbow angles in one side, and a 2D camera B takes the scattering diagram projected on a screen (f) in the other side.

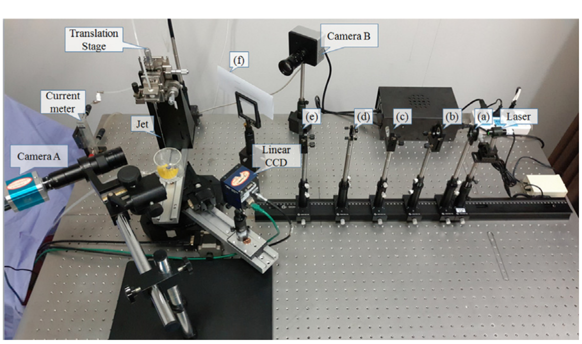

Fig. 1. Experimental setup.

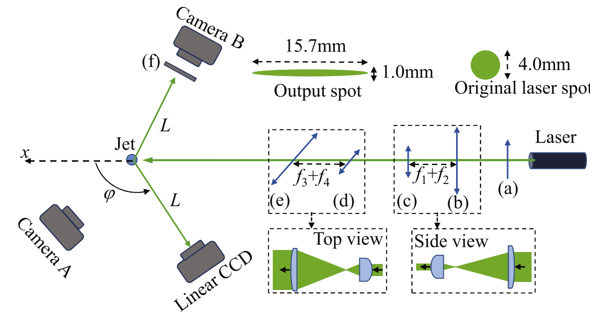

Fig. 2. Schematic plan of the experimental setup.

At first, two angles φ and ψ are defined in order to quantify the spatial positions of rainbows and the directions of light rays (shown in Fig. 3). φ is the azimuth angle measured in the horizontal plane from the incident direction of the laser beam, i.e. x axis, and ψ is the elevation angle relative to the horizontal plane.

A typical 2D scattering diagram, captured by the camera B, of water jet at 20 °C is shown in Fig. 4. We can see that the reflected light ($p=0$), the rainbows of the first ($p=2$), the second ($p=3$), the fifth ($p=6$) and the sixth ($p=7$) orders are well separated. They are distributed not only in different azimuthal positions (a well-known fact), but also in different horizontal planes. The latter phenomenon results from the fact that the normal vectors of the jet surface slant downwards, which leads to the reflected rays ($p=0$) slant downwards, while the rays of higher order ($p \geq 1$) slant upwards (see Fig. 5 which illustrates how the light rays are reflected and refracted by the jet). And the higher the order of the ray is, the larger the deviation from the horizon will be.

In Fig. 4, the angles marked in the abscissa axis are the azimuthal positions of the four rainbows and are obtained by experiment according to the maximum intensity in the first Airy bow of each order. The ordinate axis depicts the heights (vertical distances) of the rainbows relative to the reflected light. The values indicated in the ordinate axis correspond to the heights of the four rainbows relative to the reflected light when the distance of the incident light from the nozzle h equals 2.8 mm and the distance L equals 36.75 cm. The value of h is modulated by a translation stage shown in Fig. 1. Here we note D_{02} as the vertical distance of the first rainbow from the reflected light, and D_{03} the second rainbow. They will be used in the calculation of the elevation angles relative to the reflected light.

In contrast to the rainbows of a sphere or an infinite cylinder, there is no interference between different orders of rays in our study. Fig. 6 shows the scattering intensity of the primary (first) rainbow of the jet. We can see that only supernumerary bows appear in the rainbow, while the high-frequency ripples do not appear, the reason for which is the spatial separation of the ($p=2$) rays from the ($p=0$) rays. The other orders of rainbows have a similar phenomenon. Details about the supernumerary bows and high-frequency ripples can be found in Ref. [16].

It is important to point out that, compared to the rainbows of an infinite cylinder, the rainbows of a real liquid jet are shifted not only in the vertical direction but also in the horizontal plane, which means that the azimuth angle φ and the elevation angle ψ of the main peak for each order of rainbows depend on the spatial

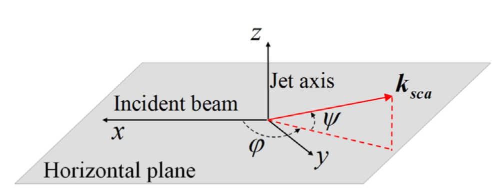

Fig. 3. Definition of the azimuth angle φ and the elevation angle ψ.

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