One-Dimensional Rainbow Technique to Characterize the Evaporation at Ambient Temperature and Evaporation in a Flame of Monodispersed Droplets

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Abstract

This paper represents the ability of the newly introduced One-dimensional Rainbow Technique (ORT) to characterize the evaporation of monodispersed droplet in the large range of environment temperature. At the low temperature (room temperature), the small change of drop size is measured from the phase shift of ripple structure. The size change, as small as 10 nm for 80 μm droplet, can be measured. For the evaporation under high temperature of the combustion flame, the gradient of refractive index can be realized from the transition of extracted refractive index during the time. The non-monotonic function of refractive index time variation is observed due to the change of refractive index profile inside the droplet.

Introduction

Global rainbow technique (GRT) is one attractive technique for simultaneously measuring size and temperature (or composition). Because of the simple, inexpensive setup and fully predictable configurations, it gives us the chances to develop and adapt for various applications. Classically, this technique measures size distribution and averaged refractive index of the droplets in a spray at a point, which is spatially selected by the system of lenses and pinhole [1,2]. In the system of the monodispersed droplet, the measurement of size and refractive index can be as accurate as 0.01 μm for diameter and the forth digit for refractive index by combining with the forward scattering pettern [3]. Since GRT has the point measurement probe, it does not provide the spatial evolution of droplet, i.e. the change of diameter, temperature and composition. To be able to follow those data from the moving droplets, the extension of GRT using slit apertures and laser sheet has been introduced by X.C. Wu., et. al. [4] and called as One-dimensional Rainbow Technique (ORT). The technique gives the possibility to follow the evolution (refractive index and size) of the droplet along the line.

This paper applies the recently developed technique, ORT, to characterize the evaporation of the monodispersed droplet under both cold condition and in combustion flame. The configuration of the monodispersed droplet gives a possibility to measure the change of droplet diameter (hence the evaporation rate). Since the change of droplet diameter along the line measurement probe is very small and the change of shape of the main rainbow is not sufficient for the measurement, then the phase shift of the ripple structure is observed alternatively. The refractive index is extracted without taking into account the radial gradient inside the droplet.

Experimental setup

The experimental setup is modified from the classical global rainbow technique. As illustrated in Fig 1, the continuous laser beam at 532 nm- wavelength is transformed to the laser sheet that is set to be vertical and coincident with the line of droplet. To collect the scattered light, the horizontal and vertical slits are installed in front of the first lens and at the image plane of the first lens. Accordingly, the position and dimension of the measurement volume can be specified. The distances of the first lens, the vertical slit, the second lens and the screen referred to the measurement volume are 250, 625, 710 and 1000 mm, respectively.

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Both lenses are plano-convex lenses with 150 mm – focal –length and 75 mm –diameter. The sizes of vertical and horizontal slits are 2 mm × 75 mm and 1 mm × 25 mm, respectively. The monodispersed droplets are generated by the use of the vibration of piezoceramic element breaking up the liquid jet. The studied liquid, N-heptane, is injected under ambient conditions with and without the flame. The droplet generator with 50 µm -pinhole diameter is operated at liquid flow rate 0.6 ml/min and excitation frequency 18.35 kHz. The combustion flame is produced from the propane gas. A burner head is 15 mm above the orifice. After ignition, the combustion flame is stabilized and envelopes the line of droplets.

The rainbow patterns scattered from the droplets at the different vertical position in the control volume are instantaneously recorded in one image. The relationship between the position of droplet and the position of the rainbow signal appeared on the screen is linear, while the magnification is the function of the focal length of the 1st and 2nd lenses and the distance of the 1st lens to the control volume and the 2nd lens to the screen [4]. In this experiment, the length of the control volume is 10 mm. Ten strips are selected from the image that corresponds to 10 vertical level of the droplet in the control volume with 1 mm apart, as illustrated in Fig 2. Each strip is averaged along the column. The measurement position is varied from 5 to 35 mm away from the burner head by 5 mm step. Hence, 5 mm overlap between the measurement positions is obtained. At each measurement positions, a series of images are recorded continuously at 67.6 ms of exposure time and 14.7 fps of sampling rate. The averaged images for each position are used to extract the average size and refractive index.

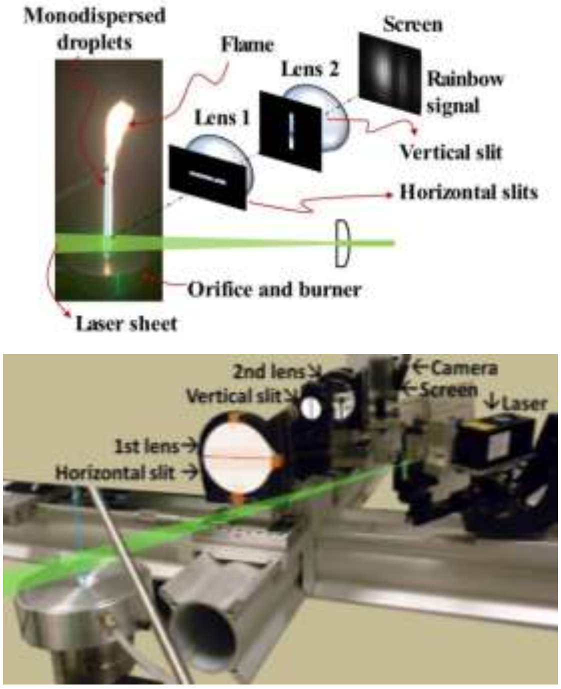

Figure 1: The schematic diagram (top) and the real setup (bottom) of ORT

From each averaged image, the phase shift of ripple of rainbow signal at each level relative to the rainbow signal at the lowest level of the image is calculated. The global rainbow inversion program based on Nussenzvieg theory is used to extract the size distribution and averaged refractive index of droplets. The measurements are carried out at two conditions, (i) evaporation in ambient conditions and (ii) evaporation in the combustion flame.

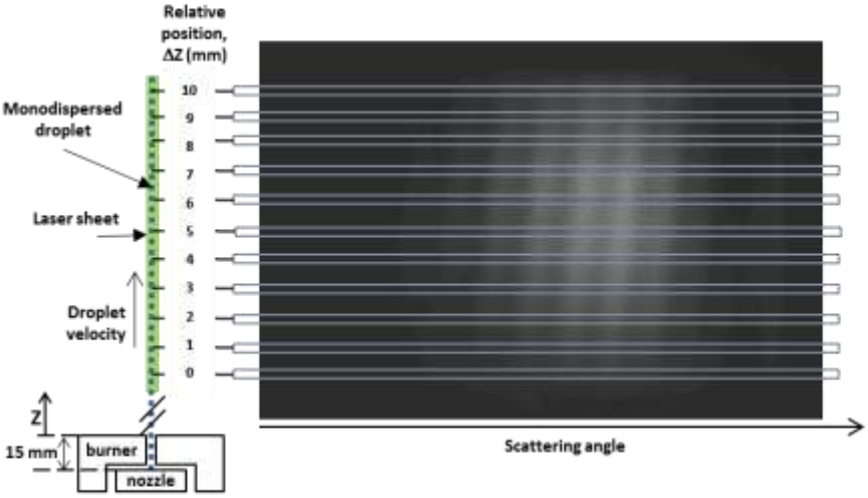

Figure 2: The selected rows and the corresponding relative position of droplets

Evaporation in atmospheric conditions

In the first case, the averaged rainbow images show clearly the ripple structure as shown in Fig 3. The plot of intensity distribution versus the calibrated scattering angle shows that the ripple structure shifts to the higher angle when the droplet moves farer from the nozzle as the diameter decreases. The phase change is almost in fully one period (2π) within measurement range of 10 mm. The intensity at each row is affected by the Gaussian distribution of the laser sheet.

Firstly, the global rainbow inversion program is used to extract size and refractive index of droplets. From this process, the size of droplet is around 75-85 µm. As shown in Fig 4, the obtained refractive index is varying between 1.390 and 1.392, which higher than its refractive index at 20°C. This means the temperature of droplet reduces to its saturation temperature corresponding to the room temperature and pressure, in this experiment is 20°C and 1atm, respectively. After that, the phase change of the ripple structure is calculated. The calculated phase shift is used to calculate the diameter change of the droplets by using the relationship provided from the rigorous simulated rainbow signal correlated to its extracted phase shift. The plots of the obtained phase shift (Δθ) and diameter change (ΔD) versus the relative position are shown in Fig 5. In order to estimate the evaporation rate, the velocity of the droplet is necessary to transform the relative position of droplet into time. In this work, droplet velocity is 5.1 m/s, which is the velocity of the liquid jet at the orifice estimated from the liquid flow rate and pinhole diameter. Then, the D^2-t curve is performed, as shown in Fig 6. The initial time (t=0) is referred to the position closest to the burner in the measurement; that is about 5 mm from the burner. The evaporation rate of droplets is estimated from the linear regression following the D^2 law equation as:

$$D^2(t) = (D_0 - \Delta D)^2 = D_0^2 - Kt \qquad (1)$$

where D_0 is the absolute diameter of droplet and K is the evaporation constant.

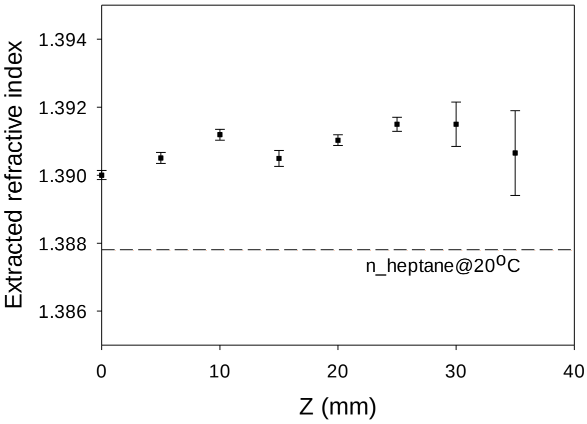

Figure 4: The extracted refractive index of droplets in the atmospheric conditions

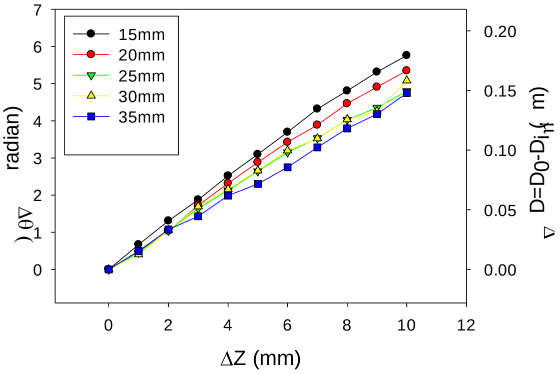

Figure 5: The ripple phase shift and corresponding relative diameter under 20°C and 1 atm

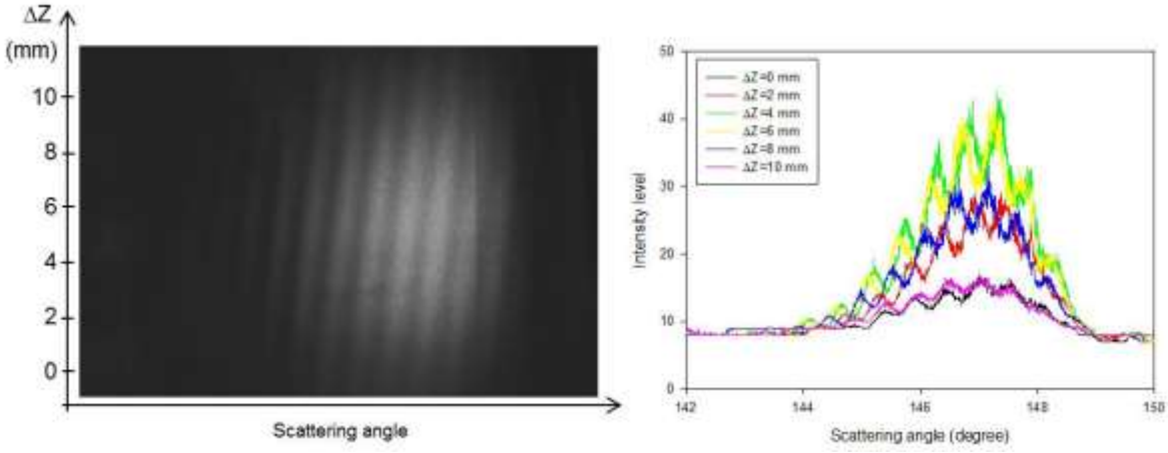

Figure 3: The recorded rainbow signal and the intensity distributions.

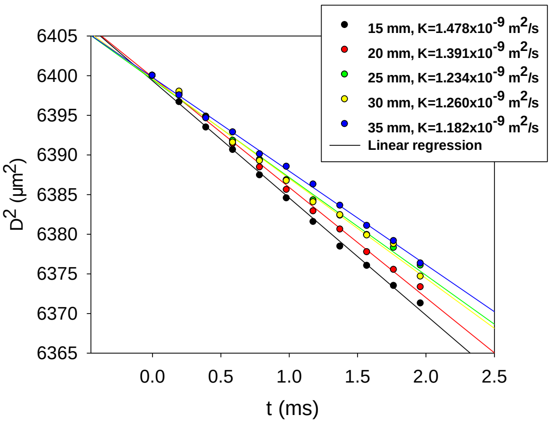

Figure 6: D^2-t curve of data from Fig 5 by assuming D_0=80 µm and v=5.1 m/s

Evaporation in combustion flame

When the combustion flame is introduced, the turbulence and high temperature of the flame enhance the evaporation rate of droplet and affect to the droplet velocity. Moreover, the temperature or refractive index inside droplet is not uniform.

The numerical study on the effect of the radial gradient of refractive index on the rainbow signal can be found in published papers [5-8]. Generally, the refractive index profile is assumed to be the exponential function as:

$$n(\tilde{r}) = n_c + (n_s - n_c)\left(\frac{e^{b\tilde{r}} - 1}{e^b - 1}\right) \qquad (2)$$

where $\tilde{r}$ is the dimensionless radial distance from droplet center, n_c and n_s are respectively the values of the refractive index at droplet center and surface. The parameter b defines the shape of the refractive index profile. In the burning or heating process, in which the heat transfers from the environment to the droplet surface, the gradient is strong at the droplet surface and, hence, the parameter b is positive.

Firstly, the rainbow signals from the droplet with the radial gradient are numerically simulated and then inversed by the inversion program to extract the rainbow refractive index, n_{rg}, which is a single value of refractive index of the non-uniform droplet. Based on the defined value n_s=1.3446 (the refractive index of n-heptane at the boiling point), the plot of rainbow refractive index versus b is shown in Fig 7. The interesting result is that the rainbow refractive index is non-monotonic function and is mostly outside the range of the values of refractive index in the droplet. This specific behavior is supposed to obtain in this experiment.

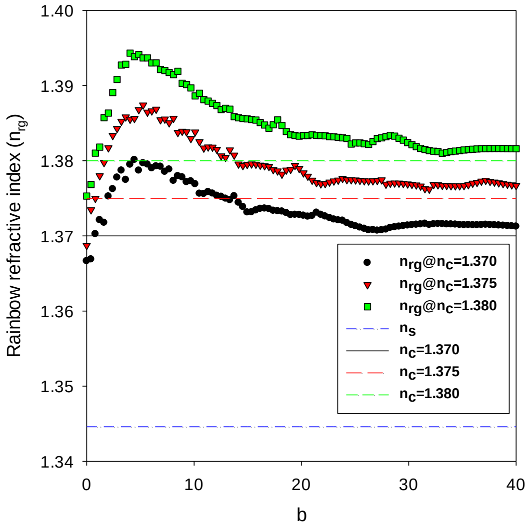

Figure 7: Rainbow refractive index extracted from the simulated rainbow signal of non-uniform refractive index droplet at n_s=1.3446 versus the varied value b corresponding to Eq (2).

Same experimental configuration is carried out but with the presence of combustion flame. During 15 minutes of the experiment, including recording, saving data and changing the measurement point, the flame is maintained. Hence, the air between the orifice and burner head is heated up by the flame. It was found that the temperature of the air increases around 10°C in a roll of the experiment. With exposure time of the camera at 67.6 ms, the rainbow pattern from a large number of droplets of different sizes and refractive indices are summed up eliminating the ripple structure. The size change of droplet is no longer measured by the approach mentioned earlier. Only the inversion program based on the Nussenvieg theory is used to process the signal. Plot of refractive index measured under combustion flame is shown in Fig 8 compared with that measured in room temperature. The results show that the droplets behavior can be traced well and continuously. Note that, the inversion process for the refractive index is based on the assumption of homogeneous refractive index inside droplet. Then, the obtained refractive index is called rainbow refractive index. At the beginning, just before the droplets reach to the flame, the refractive index of droplet in the flame is lower than that of droplet in the room condition. In the opinion of authors, this is because the air between the orifice and burner head is heated up and then the saturation temperature of droplet increases. After that, the refractive index increases up to the maximum value. As the consequence of gradient of refractive index, the time variation of rainbow refractive index is not the monotonic function. From the maximum point, the refractive index decreases continuously and tends to reach the refractive index at the boiling point. As expected, the results are similar to the rainbow refractive index of the droplet with radial gradient refractive index. It can be realized that the gradient of refractive (or temperature) inside droplet is presence especially at the first 10 mm from the burner.

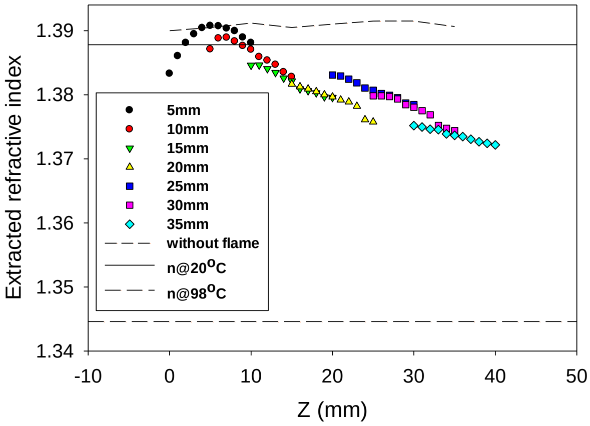

Figure 8: Measured refractive index of monodispersed n-heptane droplets with and without flame from 7 setup positions corresponding to 70 measurement points from 5 to 35 mm

Conclusions

The recent work shows the application of the One-dimensional Rainbow Technique on the characterization of evaporating monodispersed droplets under two different conditions. First, at the cold temperature where the evaporation rate is small, the recorded rainbow signal is close to that obtained from the Standard Rainbow Technique (SRT). Hence, the nanometric change of droplet size can be measured by observing the phase shift of the ripple structure. The refractive index (or temperature) of droplet is nearly constant. The accurate calibration method and measurement of droplet velocity are suggested to improve the accuracy of the evaporation rate.

Second, for the rapid heating and evaporation under the combustion flame, the characteristics are more complicate. This paper presents the possibility to measure the gradient of refractive index inside the droplet. The presence of refractive index gradient is realized from the non-monotonic function of the obtained rainbow refractive index. To approximate the refractive index profile, the numerical calculation and the boundary values (refractive index at droplet center and surface) are required.

Acknowledgements

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