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The effect of initial diameter on rainbow positions and temperature distributions of burning single-component n-Alkane droplets

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ABSTRACT

The effect of initial diameter on rainbow positions of burning single-component n-Alkane droplets has been investigated experimentally for the first time. The droplet diameters are determined with interferometric laser imaging for droplet sizing, and the temperature distributions inside burning droplets are assessed by rainbow refractometry together with a droplet combustion model developed in our previous work. Temperature gradients inside burning droplets influence rainbow positions, which first make the experimental scattering angles of the rainbow maxima increase and then decrease. The variations of initial diameter lead to variations of both experimental rainbow maxima and simulated temperature of n-Alkane burning droplets.

1. Introduction

Spray combustion has been widely used in many industrial processes, such as furnaces, boilers, gas turbines, diesel engines, liquid rocket engines [1,2], and even nanoparticle production [3,4]. During spray combustion, droplets vaporize and burn in a gas environment. The understanding and modeling of droplet vaporization and combustion are fundamental for the design of energy efficient process.

Non-intrusive laser light scattering techniques have been widely applied to determine droplet size, velocity, composition, and temperature. Interferometric laser imaging for droplet sizing (ILIDS) takes advantage of the interference pattern of light scattered in the forward direction to measure droplet size [5–10] and can reach an accuracy of 2% [6,9]. Rainbow refractometry (RRF) can provide information on refractive index, temperature and size of droplets [11–15]. Roth et al. [11] first described RRF and used the angular position of the rainbow (rainbow angle) to determine the droplet temperature. Most previous studies of RRF are focused on homogeneous droplets with constant size and constant temperature. However, droplet sizes and droplet temperatures change with time in spray combustion. Temperature variations result in refractive index gradients inside vaporizing or burning droplets, which change the rainbow scattering pattern. Therefore, temperature or refractive index gradients have to be considered in the application of RRF to vaporizing or burning droplets.

Theoretical and experimental studies of rainbow positions or RRF on droplets with temperature or refractive index gradients have been reported earlier. Kai et al. [16] used a finely stratified sphere model to calculate scattering electromagnetic fields from radially inhomogeneous spherical droplets. They found that radial gradients of the refractive index change the ray paths within large spherical droplets into curved lines, resulting in time variant rainbow angles. Anders et al. [17] investigated the effect of refractive index gradients within droplets on rainbow positions, and pointed out that refractive index gradients lead to a shift in rainbow angles compared with homogeneous droplets with constant refractive index. van Beeck et al. [18] observed the unusual temperature evolution inside a burning droplet, and attributed it to the strong temperature gradients during its transient heating phase. Massoli [14] calculated the light scattering of a radially inhomogeneous vaporizing droplet with reducing diameter and varying temperature, and indicated that the internal temperature gradients could produce intrinsic uncertainty to temperature measurement of inhomogeneous droplets. Vetrano et al. [19,20] generalized the rainbow Airy theory to a single droplet exhibiting internal refractive index gradients, and assessed refractive index gradients inside a burning n-Octane droplet with RRF. Saengkaew et al. [21] applied RRF to particles with radial refractive index gradients, and quantified the effect of radial gradients on rainbow measurements with a high accuracy. These investigations indicate

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that temperature gradients and refractive index gradients inside droplets influence rainbow positions.

For single-component droplet combustion, refractive index gradients are caused by temperature gradients inside burning droplets. Therefore, measurement of rainbow positions can be used to assess temperature distributions inside burning single-component droplets [17,19,20]. Our previous work has confirmed that varying temperature gradients inside burning micro-size n-Alkane droplets can be detected with RRF together with a droplet combustion model [22]. The burning droplets investigated in our previous work have all similar initial droplet diameters of 100 μm. Droplets with different initial diameter have different specific surface area or volume for heat absorption during combustion, which will lead to different evolutions of temperature gradients inside burning droplets and then affect the rainbow scattering pattern. In principle, a small droplet will heat up faster than a large droplet due to its large specific surface area or small volume. As a result, this kind of influence should be reflected on rainbow positions and temperature distributions inside burning droplets with different initial diameter. However, to the best of our knowledge, experimental evidences is still missing in order to clarify this effect.

The purpose of this paper is to investigate the effect of initial diameter on rainbow positions and temperature distributions of burning single-component n-Alkane droplets. We will first describe the experimental and analytical procedure, then present experimental results of droplet diameter and rainbow maxima, finally we will compare between experiment and simulation and discuss the simulated temperature distributions.

2. Experimental setup and procedure

2.1. Experimental setup and materials

A sketch of experimental setup for the detection of refractive index and diameter of single isolated droplet during combustion is shown in Fig. 1 (left). The experimental setup includes a droplet-on-demand generator (Piezodropper [23]), a green laser (Opus 3 W – 532 nm TEM_{00}), ignition electrodes, gas supply, a solvent reservoir, a mass flow controller (Bronkhorst - EL Flow) and two linear array CCD cameras (DALSA - Spyder 3). The laser beam with an initial diameter of 2 mm is expanded to a laser light sheet by lens for the purpose of covering the whole combustion process of the droplets. As shown in Fig. 1 (right), the cross section of the laser light sheet is in a shape of a vesical piscis, which is 20 mm in length and 2 mm in width. Pure n-Alkane is stored in a solvent reservoir, and fed to the droplet generator with the help of a plastic tube. The droplet generator reproducibly ejects single isolated droplets at a frequency of 4 Hz. The initial droplet velocities are in the range from 0.5 to 1 m/s. After ignition by the spark electrodes, the burning droplets move upwards through a laser light sheet. Co-flowing oxygen (purity 99.95%) is delivered to the plastic square frustum at a flow rate of 1.4 L/min. The oxygen sheath around the upward droplets provides an oxidizing atmosphere, keeping the flame spherical and concentric around the droplet. Thus, buoyancy effects on the burning droplets can be neglected in our experiments [24,25]. It is necessary to mention that rainbow refractometry is very sensitive to the shape of the droplet, and deformation of spherical droplet will cause caustics [26] and change the rainbow scattering pattern [27]. The scattering light from the droplets is recorded with two linear array CCD cameras (Spyder3 CL, S3-24-01K40-00-R) at a frequency of 67 kHz. To focus objects from infinity, one lens is fixed in the front of each CCD camera with a focal length of 6.56 ± 0.25 mm. Both CCD cameras have a center of image area of 30 mm in length, and a scattering range of 10.2° for recording the scattering light. The linear array CCD camera uses a single line of sensor pixels to build up a two dimensional out-of-focus image, which consists 1024×1024 pixels and a resolution of 96 pixels/inch. Both CCD cameras are synchronized with the droplet-on-demand generator in order to obtain time-resolved images. While the backward CCD camera captures the rainbow scattering pattern, the forward CCD camera records the interference pattern. The two CCD cameras and the burning droplet are located at the same vertical level.

N-Octane (SIGMA Aldrich, 98% assay), n-Nonane (SIGMA Aldrich, 99% assay), and n-Hexadecane (SIGMA Aldrich, 99% assay) are used as combustion liquids. The properties of n-Alkane investigated in this study are shown in Table 1 [28]. Their refractive indices in the temperature range from 20 to 90°C are measured with an Abbe refractometer (Carl Zeiss [29]) (See Fig. 2).

2.2. Calibration and diameter measurement

For the purpose of calibration, the rainbow scattering pattern (see Fig. 3(a)) and the interference pattern (see Fig. 3(b)) were

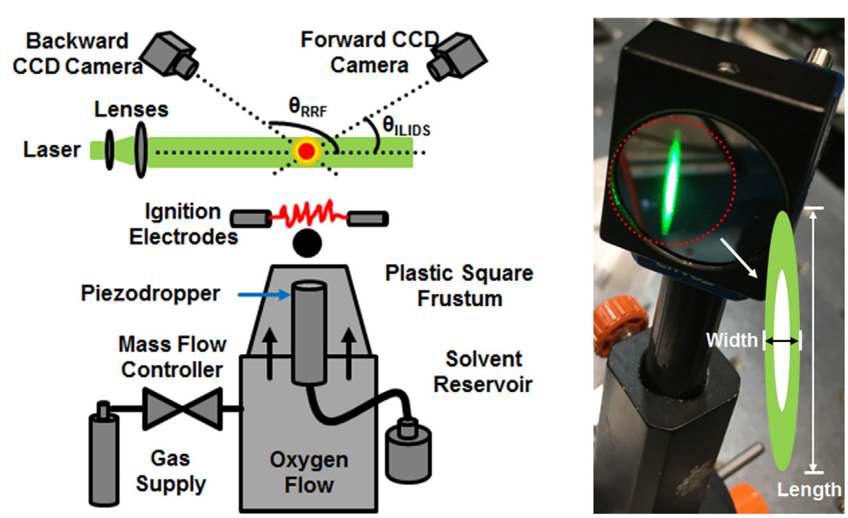

Fig. 1. Sketch of experimental setup for the detection of refractive index and diameter of single isolated droplet during combustion (left), and the laser light sheet before it is interacting with the droplets (right). θ_{ILIDS} (acute angle) is the scattering angle of the forward camera with respect to the laser sheet, and θ_{RRF} (obtuse angle) the scattering angle of the backward camera with respect to the laser sheet.