

Dual-Beam Rainbow Refractometry and Its Application to the Temperature Measurement of Liquid Drops

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ABSTRACT

Phase Doppler systems are widely used for simultaneous size and velocity measurement of individual liquid drops. These systems can now be upgraded to provide simultaneous refractive index (temperature) measurement on individual drops that are useful in studies of liquid fuel combustion. The refractive index measurement is based on detection of the rainbow pattern generated by the drop. Earlier upgrades were based on single-beam Rainbow™ refractometry that required a dedicated beam for rainbow pattern measurement. This required significant changes in the opto-mechanical hardware of the standard phase Doppler system.

Furthermore, an Argon-Ion laser, which is typically used for phase Doppler measurements, offers significant energy in only three wavelengths. These are sufficient for measurement of all three components of velocity and size in a stand-alone phase Doppler system. However, if one of the wavelengths is dedicated to Rainbow measurement, the phase Doppler is restricted to two velocity components.

Dual-beam Rainbow system offers an easier upgrade path for phase Doppler systems for simultaneous measurement of droplet velocity, size, and refractive index (temperature). It does not require a dedicated beam for refractive index measurement. Instead, it utilizes one of the monochromatic pair of beams that already exist in the phase Doppler system. Hence, the hardware modification is minimal and the capability of the phase Doppler system to measure up to three components of velocity is not compromised.

The dual-beam setup generates two rainbows from each drop that are overlapped in the symmetry plane of the two laser beams. The dual-beam Rainbow™ receiver is located in this plane. In order to obtain strong rainbows at this location, the electric vectors of polarization for the two beams are positioned within the plane of the beams. This is a non-conventional choice of polarization for the phase Doppler measurements. However, it is shown to work well at small off-axis angles, such as 30 degrees.

Experimental results based on a combined phase Doppler system (PDPA™ of Aerometrics/TSI) and Dual-Beam Rainbow™ system are presented. The temperature measurement accuracy provided by this configuration is equal to or better than that of a single-beam configuration while also providing good size and velocity measurement.

1. INTRODUCTION

Rainbow™ refractometry is a non-intrusive, laser-based technique for measurement of particle refractive index. Typically, this is done with a single projected laser beam, to generate a single rainbow scattering pattern, which is a series of bright and dark rings in the backscatter direction. Using two crossing laser beams (as is done for LDV and phase Doppler) will generate two rainbow patterns of slightly differing angles, but this allows the same beams to be used for phase Doppler measurements. A Rainbow™ Receiver in the plane of symmetry of the two beams will register rainbow signatures that are essentially identical to the signatures generated by a single-beam system.

Obtaining rainbow signals with this arrangement requires the polarization of light to be in the plane of the beams, which is not the best choice for phase Doppler measurements. It does, however, permit expanding an existing phase Doppler system to refractive index measurements with a minimum of hardware modifications. This paper shows the difference in phase Doppler performance with the new polarization, and that it is indeed possible to use the same beam pair for both diameter (phase Doppler) and Rainbow™ measurements. The dual beam arrangement was used to obtain measurements of burning and non-burning monodisperse methanol droplet streams. The results are compared to traditional single-beam Rainbow™ measurements of the same droplet streams.

2. PRINCIPLES OF RAINBOW™ REFRACTOMETER

The basic principle behind the Rainbow™ is that the angular location of the scattered rainbow pattern depends on the droplet refractive index. Knowing the temperature as a function of refractive index for a given liquid allows for the determination of drop temperature. The angular location of the main rainbow for a sub-millimeter drop is a function of both drop refractive index and drop size. Hence, an independent measurement of drop size is needed for determination of the refractive index. Although the drop size can be determined by the spacing between successive rainbow fringes, a more accurate determination of size can be made by using a phase Doppler system.

The measurement of the primary rainbow position is made by a Rainbow™ Receiver which collects light on a circular aperture and then focuses the light down to a line perpendicular to the rainbow. This light is focused onto a linear CCD array which, once calibrated, allows for the precise determination of the angle at which the primary rainbow occurs. A more complete explanation of the Rainbow™ measurement technique can be found in previous works. (Sankar, et al., 1993 and 1994)

In the past, several changes in the transmitting optics were needed in order to extend a phase Doppler system to rainbow measurements. In a standard PDPA (Phase Doppler Particle Analyzer) system, the multi-wavelength Argon Ion laser beam is delivered directly to frequency shifting / color separation optics (Fiber Drive™). The Rainbow™ extension requires a green beam pick-off prior to the Fiber Drive. Also the standard four beam transmitting probe needs to be replaced with a five beam probe, which emits the green light as a central beam that is used for rainbow measurements. This setup restricts the velocimetry capability of the system to two components as one of the three colors is used exclusively for rainbow detection.

In order to simplify the Rainbow™ extension and overcome the above limitations, a novel design is proposed, theoretically evaluated, and finally tested experimentally. In the proposed arrangement, the transmitting probe is not modified and a superposition of two rainbows is measured.

As illustrated in Fig. 1, the rainbows scattered by two beams are completely separated in the plane of the beams and fully superimposed in the plane of symmetry of the two beams. Due to this superposition, it is possible to measure the rainbow location by placing the Rainbow™ Receiver on the symmetry plane.

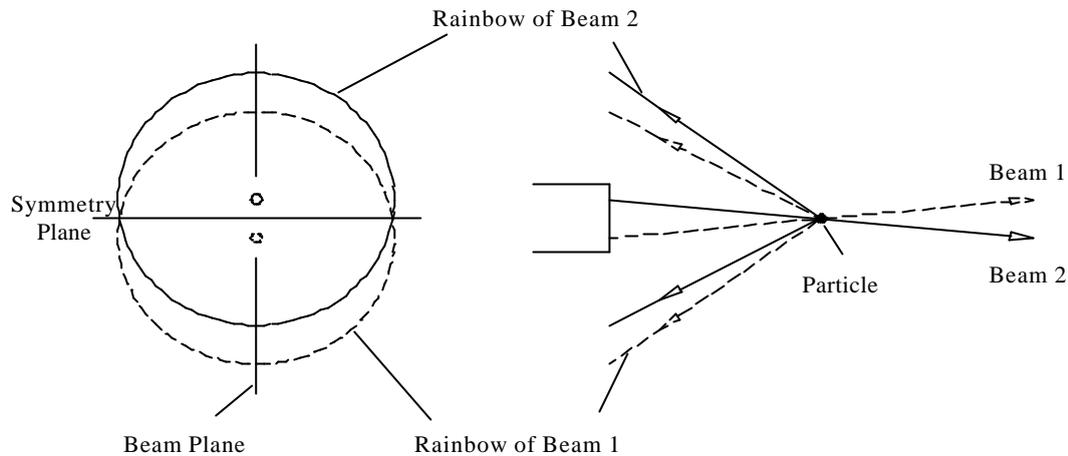


Figure 1: Interaction of Rainbows in a Dual-beam Setup

Another practical issue concerns the laser polarization. Standard PDPA uses linearly polarized light with polarization parallel to the scattering plane (or perpendicular to the plane of the laser beams). The scattered rainbow pattern resulting from this polarization would have very weak intensities along the symmetry plane. This is a result of being too close to the Brewster angle for internal reflection. To overcome this problem it is necessary to switch the polarization 90° , resulting in polarization perpendicular to the scattering plane for PDPA. Although this allows for strong rainbow signals along the symmetry plane, perpendicular polarization makes PDPA measurements more difficult. However, good phase Doppler measurements can be obtained with an appropriate optical configuration, which is evaluated theoretically as well as experimentally. The results are given in Sec. 4.

Light scattering simulations based on the Mie scattering theory show that the two rainbows are indeed overlapped in a practical system. The results presented in Figure 2 pertain to a pair of laser beams with 514.5 nm wavelength. The beam spacing is 40 mm and they are focused into a measurement volume by a 500 mm focal length lens, resulting in a 4.6° beam angle.

Computations are done for a 1000 pixel array, where each pixel covers an angle of 0.012° in the symmetry plane and 6° out of the symmetry plane. These values represent an existing rainbow receiver.

Figure 2 shows the rainbow signatures for water drops of diameters 100, 50 and 25 μm . The dual beam rainbows do not show any significant deviation from the single beam case, provided that the receiver is in the symmetry plane. The 100 μm chart also shows the low intensity of the rainbow scattering pattern if the incorrect case of parallel (standard PDPA) polarization is used.

The results shown in Fig. 2 are based on the assumption that high-frequency temporal fluctuations in the dual beam signals are filtered out as a result of integration of light at the pixels. The incoming signals have a 40 MHz shift frequency and actual signal frequency normally exceeds 20 MHz. Hence, fluctuations are averaged out if the exposure time exceeds 50 ns. Typically, rainbow signals would be integrated for a microsecond or longer; hence, high-frequency fluctuations are not a matter of concern.

Finally, the Dual Rainbow™ is likely to be more sensitive to particle sphericity and inhomogeneity than a single rainbow. We need to determine if this feature can be utilized effectively in a practical system.

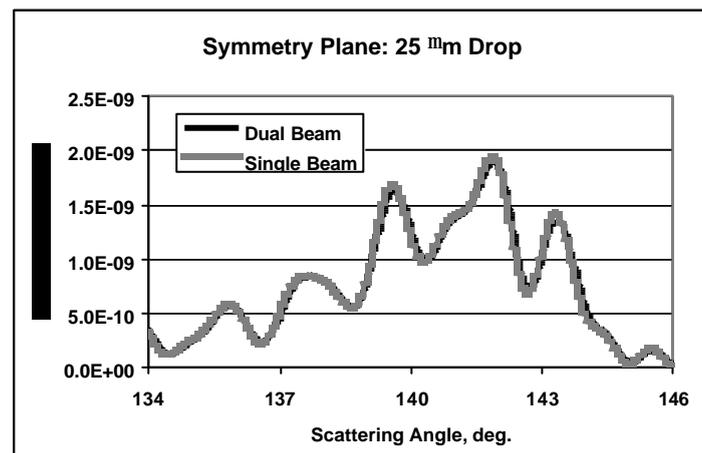
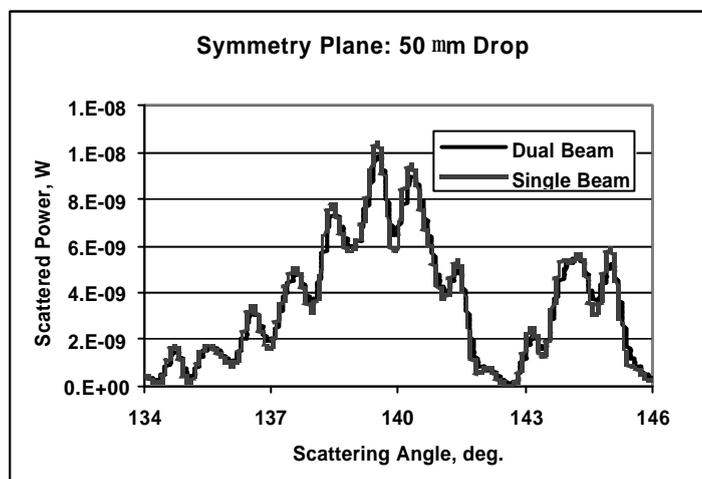
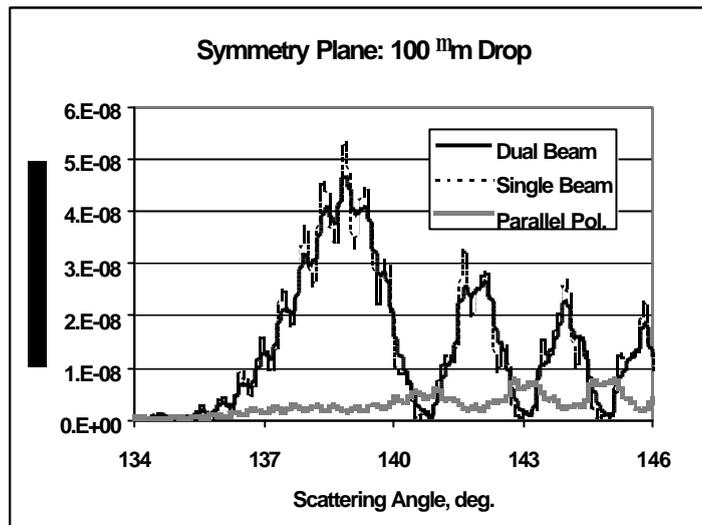


Figure 2: Simulated signals for the Rainbow™ Receiver in the symmetry plane

3. EXPERIMENTAL VERIFICATION OF DUAL RAINBOW

Experimental measurements using a monodisperse drop generator were used to test the accuracy of the Dual Rainbow™ technique. The results show that Dual Rainbow™ is capable of the same measurement accuracy as the earlier single beam rainbow. Figure 3 shows an image containing the measured rainbow signatures from 200 water droplets. In this image each row corresponds to the Rainbow scattered from one drop and captured by the line-scan camera. The most intense peak towards the left side of the image is the primary rainbow, with successive supernumerary fringes shown as you move across the image to the right. Moving across the image from left to right corresponds to a changing scattering angle and the droplet refractive index is determined by the scattering angle at which the peak of the primary rainbow occurs.

Table 1 shows a preliminary comparison of both the mean and standard deviation of the refractive index. The difference in mean refractive indices is due to a lack of calibration and slightly different Rainbow™ Receiver positions for each of the two runs. The standard deviation is significantly better for the Dual Rainbow™ method but we are not sure yet whether this is because the Dual Rainbow™ actually gives better results or if it is due to other factors.

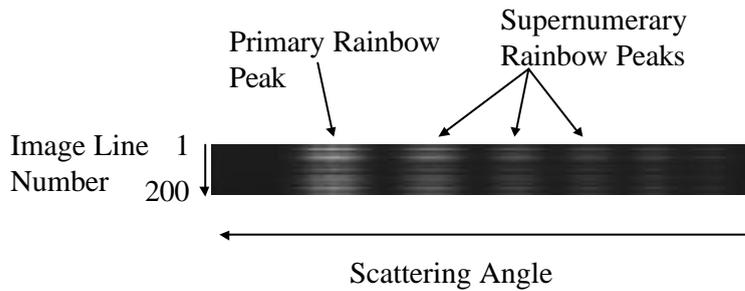


Figure 3: Portion of the Dual Rainbow TIFF Image

Table 1. Comparison of Rainbow™ Results for Monosize Water Droplets

Method	Mean Index	Std Dev in Index
Dual Rainbow™	1.3301	0.00013
Single Rainbow™	1.3386	.00049

4. EXPERIMENTAL VERIFICATION OF PDPA PERFORMANCE USING PERPENDICULAR POLARIZATION

When operating a standard phase Doppler system a user wishes to collect scattered light from one dominant mode (reflection, refraction, or internal reflection). The choice of parallel polarization allows for excellent measurements of transparent drops, utilizing refraction because the reflected light is to a large extent removed due to being near the Brewster condition. Operating with perpendicular polarization therefore causes some problems when attempting to collect purely refracted light as a substantial amount of reflected

light is mixed with the refracted light. Errors in particle sizing due to this can affect both the linearity of the phase-diameter response and also cause completely erroneous size measurements when particles near the edge of the measuring volume scatter only reflected light which is then interpreted as being refracted light.

Fortunately, these polarization problems are easily surmountable for sprays that would typically be used with Rainbow™. Scattering characteristics of spherical particles (see Naqwi & Durst, 1991) show that by operating near a scattering angle of 30 degrees the ratio of refracted to reflected light is still fairly large, even with perpendicular polarization (see figure 4). The problem with particles at the edges of the measuring volume can be eliminated quite effectively by utilizing an intensity validation scheme. By rejecting large particles (as measured by their phase) with low intensities most of the erroneous particles can be eliminated. Furthermore, comparison of two measured phase shift signals also helps eliminate inaccurate measurements. Finally, the Rainbow™ Refractometer also provides a rough measure of particle size, which can be compared to the PDPA size, allowing for an additional validation to ensure that the correct size particle has been measured.

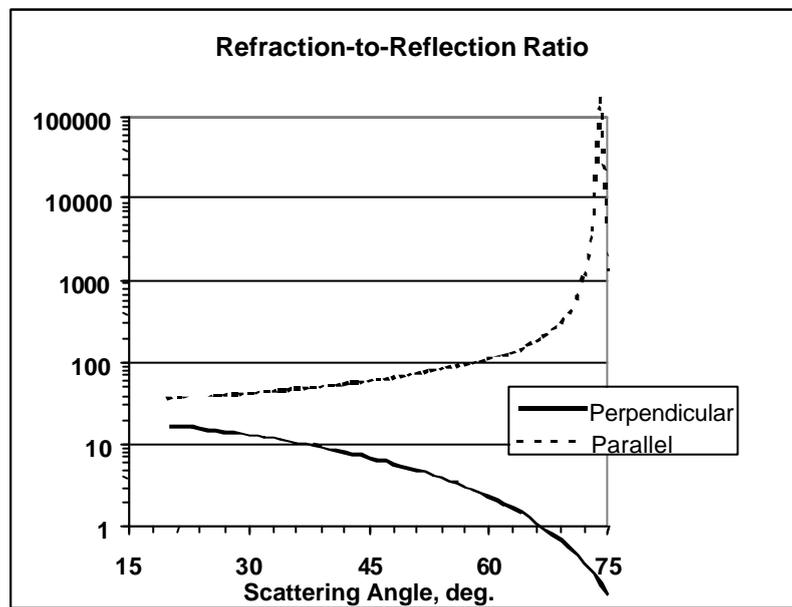


Figure 4: Refraction-to-reflection ratio for the two cases of polarization

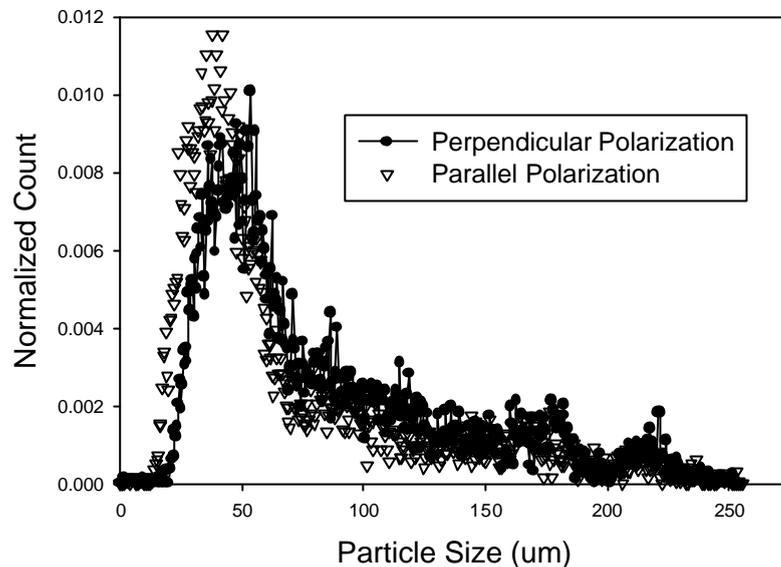


Figure 5: Spray Size Distributions with two cases of polarization

Figure 5 shows an identical spray measured with both the cases of polarization. The two distributions are very similar even without any corrections based on rainbow measurements. The main difference is that there are a few more large particles showing up with perpendicular polarization.

5. CONCLUSIONS

The above work has shown that Dual Rainbow™ is a simplified hardware system capable of simultaneous measurements of particle size, velocity, and temperature while providing the same performance as the earlier single beam systems. Furthermore, Dual Rainbow is capable of measuring all three components of velocity, as opposed to a maximum of two components measured by the earlier hardware.

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