Simultaneous Measurement of Evaporating Droplet Diameter Using Phase Doppler Anemometry and High-speed Camera

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Abstract

In order to discuss the measurement accuracy of diameter and sphericity of droplet using dual-mode phase Doppler anemometer (Dual PDA), measurements of diameter and sphericity of evaporating ethanol droplet using Dual PDA and visualization of CCD camera with long-distance microscope simultaneously were carried out. Dual PDA can measure droplet's vertical and horizontal sphericity using the combination of standard PDA and planar PDA. Target droplet is evaporating ethanol droplet levitated in ultrasonic levitator. Three main conclusions can be drawn in this research. Dual PDA can measure the droplet diameter of evaporating droplet avoiding 2π ambiguity. Measurement error due to 2π ambiguity in Dual PDA can be understood for larger droplet over maximum measurable droplet diameter. It is possible to measure droplet sphericity using Dual PDA. However, further consideration for more oblate droplet should be needed to discuss the measurement accuracy of droplet sphericity using Dual PDA precisely.

Introduction

In the port fuel injection engine, fuel is injected into the intake port of each cylinder to take advantage of the warm valve and port surfaces for vaporization. In general performance, efficiency, noise and pollutant emissions in port fuel injection engines (PFI) are extremely dependent on injector nozzle geometry. The selection of injector nozzle geometry in PFI is one of the important steps in designing PFI engine. The atomization process can be related to the energy balance. This energy brought to the liquid under the form of pressure is divided into four parts: aerodynamic energy, the frictional losses, the non-axial energy and the turbulent energy. The energy dissipated in friction is definitely lost and also does not participate in the atomization process [1]. Once spherical drops are created, after primary atomization has been completed, secondary atomization starts and its governing mechanisms are common for any type of spray [2].

In order to understand the spray characteristics formed by PFI injector, many investigations of gasoline injection sprays using several measurement techniques like laser sheet method with high-speed camera [3-5], laser-induced (exciplex) fluorescence (LIF), laser and phase Doppler anemometor (LDV/PDA) [6], particle image velocimetry (PIV) have been carried out for better control of spray and combustion characteristics. However, one of the key processes affecting spray behavior is the primary spray break-up, because it defines the starting conditions for the spray distribution, the evaporation process, and mixture formation. Liquid fuel forms the liquid column very close to the nozzle exit, and then makes liquid ligament and droplets due to the break-up of liquid ligament. Droplets, which were formed by the break-up of liquid ligament, were non-spherical shape. Therefore detection of non-spherical droplets was needed to understand break-up of liquid ligament. Some of the authors discussed primary fuel break-up very close to nozzle exit using high-speed video camera with long-distance microscope [7-10]. Jet breakup and droplets breakup have been visualized using photographic method. Droplet stroboscope techniques, which are good for freezing the movement, have been usually used for droplet deformation process and droplet breakup. On the other hand, Dual-PDA system can measure the non-spherical droplets [11]. Dual PDA system combines two-detector standard PDA and a planer PDA [12]. In the standard PDA, the detectors are arranged at an off-axis angle perpendicular to the plane of the transmitting beams, on the other hand, in the planar PDA, the detectors are put in the same plane of transmitting beams. This combination allows us to measure the sphericity of droplets.

The purpose of this study is to investigate measurement accuracy of evaporating droplet (ethanol) diameter and sphericity measured by Dual PDA with comparing to visualization result using CCD camera with long-distance microscope. Measurement accuracy of PDA is not unclear in primary atomization region of PFI injector and non-spherical droplet. Dual PDA can measure droplet's vertical and horizontal sphericity. Simultaneous measurement of Dual PDA and visualization using CCD camera with long-distance microscope is necessary for understanding of measurement accuracy of Dual PDA. Single ethanol droplet is formed by ultrasonic levitator

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(vibrating frequency: 60 kHz) [13]. Levitated droplet is evaporated in time. Measurement accuracy of droplet diameter and sphericity of evaporating ethanol droplet using Dual PDA is discussed.

Experimental Methods

Dual PDA system

PDA system can measure the droplet diameter and velocity simultaneously. The measurement volume is defined by the interaction of two focused laser beams and the measurement can be performed on single droplets when they are passing through the measurement volume. Phase difference Φ obtained in PDA system is determined using Equ. (1).

$$\Phi = 2\pi S' \frac{m}{m-1} \frac{d}{4} \frac{2\sin\left(\frac{\theta}{2}\right)}{R\lambda} \tag{1}$$

Here, m: refractive index of droplet, λ: wavelength of laser, θ: beam crossing angle of transmitting optics, S': distance between Standard PDA and Planer PDA, R: focal length of receiving optics

Receiving optics is placed at off-axis location with a certain valid angle in Dual PDA system. Figure 1 shows the optical set-up of Dual PDA system [14]. Dual PDA system combines two-detector standard PDA and a planer PDA [12]. In the standard PDA, the detectors are arranged at an off-axis angle perpendicular to the plane of the transmitting beams, on the other hand, in the planar PDA, the detectors are put in the same plane of transmitting beams. Four receiving detectors are used in Dual PDA system. Dual PDA system has been developed to eliminate the trajectory effects or Gaussian beam effect and the slit effect [15]. Dual PDA system can measure the droplet diameter avoiding 2π ambiguity. The standard PDA results are referred to the planar PDA in order to avoid 2π ambiguity. Vertical sphericity can be measured using the standard PDA; horizontal sphericity is measured using the planar PDA. This combination can allow us to measure sphericity of droplet. Figure 2 shows the phase difference of standard PDA (C-PDA) and planar PDA (P-PDA) from non-spherical droplets. Solid line is shown as relationship of spherical droplet between standard PDA and planar PDA. Droplet 1 is almost spherical, therefore the phase difference of standard and planar PDA is plotted on the solid line as linearity. Droplet 2 is prolate droplet, in this case, the phase difference of standard PDA is larger than the phase difference of planar PDA. Droplet 3 is oblate droplet, therefore the phase difference of planar PDA is larger than the phase difference of standard PDA. Simultaneous measurement of standard PDA and planar PDA can allow us to measure the sphericity of droplets.

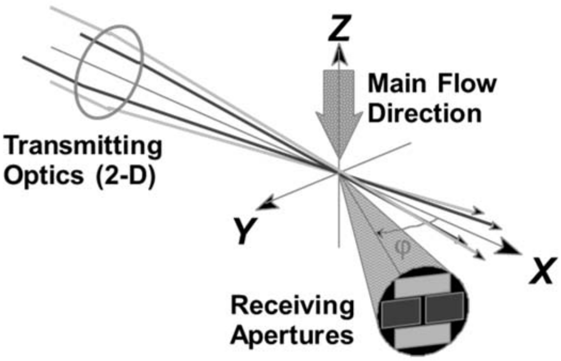

Fig.1 Optical arrangement of Dual PDA [14]

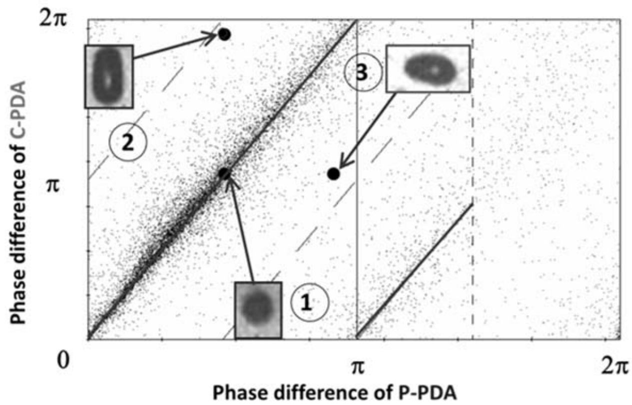

Fig.2 Scatter diagram of phase-difference

Ultrasonic levitator

The present work focuses on sphericity of single droplet, therefore the ultrasonic levitator is used. Acoustic levitation using standing waves is a useful technique for studying the visualization of single or multiple droplets, because it allows steady positioning of sample. The droplet is suspending non - intrusively in the pressure node of a standing acoustic wave. There are some clear advantages to using the ultrasonic levitator for such studies, as opposed to falling drops or drops suspended on a needle. The obvious advantage is that there is no heat loss to the needle and / or that the droplet can be steadily positioned. Figure 3 shows the levitated droplets at the pressure nodes on ultrasonic levitator. The levitator is operated at a frequency of 60 kHz, which corresponds to a nominal sound wavelength λ_0 of 6 mm at an ambient temperature of 298 K. A flat reflector is positioned 18 mm above the transducer to create 5 pressure nodes in the standing wave between the transducer and the reflector. The distance between the transducer and the reflector can be accurately adjusted by means of a micrometer screw. In this experiment, an ethanol droplet was positioned in an acoustic pressure node, and changes in shape of the droplet were measured using CCD camera with long-distance microscope.

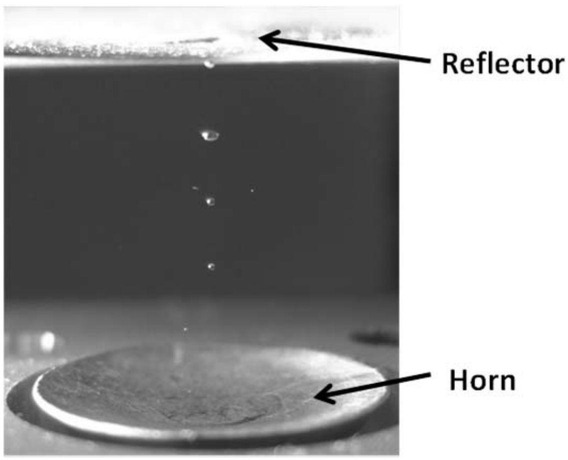

Fig.3 Levitated droplets in ultrasonic levitator

Measurement apparatus and conditions

A sketch of the experimental apparatus is shown in Fig. 4. For droplet sphericity measurements, dual-mode phase Doppler anemometer (Dantec Dynamics) was used. The receiver was positioned at a scattering angle of 22 degrees to collect the light scattered due to refraction. The scattered light is focused through a unique spatial mask and is collimated to a segmented lens. Each part of this lens guides the light in a multimode optical fiber. The evaporation behavior of the droplet was determined as a function of time using a high-speed CCD camera (nac imaging technology, inc., GX-1) with backlighting. A CCD camera was used with high resolving long-distance microscope [10]. Backlighting method was used for detection of droplet shape. Barlow lens was used for changing the spatial resolution. Simultaneous measurement of Dual PDA and visualization were carried out. PDA set-up, size of measurement volume and measurable maximum droplet diameter were shown in Table 1.

Initial droplet diameters are decided in two cases in order to discuss the measurement accuracy of droplet diameter and sphericity using Dual PDA.

Condition #1 smaller droplet diameter (130 μm) less than maximum measured droplet diameter using Dual PDA

Condition #2 larger droplets over maximum measurable droplet diameter (230 μm) using Dual PDA

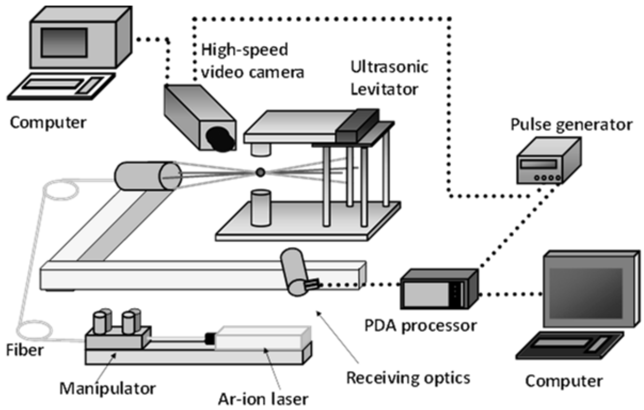

Fig.4 Experimental setup

Table 1 Optical parameters

	Focal length (Transmitter, Receiver) (400mm, 600mm)
Diameter of measurement volume, mm	0.194
Length of measurement volume, mm	4.09
Maximum measurable Diameter, μm	230

Results and Discussion

Smaller droplet diameter (130 μm) less than maximum measurable droplet diameter

Figure 5 shows the time-series of evaporating ethanol droplet obtained using CCD camera with long-distance microscope. Laser beam from transmitting optics for Dual PDA system was entered from right-hand side. Laser beam can be seen at the right-hand side of droplet. Camera speed is 100 fps, and exposure time is 2ms in order to obtain the time-evolution of evaporating droplet. Droplet diameter is decreasing due to laser power from transmitting optics, light for backlighting and acoustic force from ultrasonic levitator. Evaporating droplets shows almost spherical, as shown in Fig. 5.

Dual PDA can measure the phase difference of standard PDA (C-PDA) and planar PDA (P-PDA) with visualization using CCD camera with long-distance microscope simultaneously. Figure 6 show the scatter diagram of Dual PDA system. The phase difference can be plotted on the linearity of two receiving optics. Figure 6 shows that the measured droplets are almost spherical in agreement with Fig. 5.

Measured droplet diameter and squared droplet diameter using Dual PDA and visualization using CCD camera with long-distance microscope were plotted in Fig. 7. Black circle is measured using Dual PDA and white circle is measured by visualization using CCD camera. Droplet diameter is decreasing due to evaporation of ethanol. Squared droplet diameters are plotted rather closely to straight lines with a constant negative slope. Evaporation of ethanol droplet approximately corresponds to the so-called d^2 -law [d^2 (t) is linear]. Until 8 second form the start of measurement, droplet diameters measured using Dual PDA are almost agreed with visualization using CCD camera. However, after 8 second, measured diameters using Dual PDA show a little fluctuation. Smaller droplets less than 100 μm show oscillation vertically due to secondary flow field in ultrasonic levitator [16]. It is difficult to measure the droplet diameter of vertically oscillating droplet precisely using Dual PDA. Larger droplets can be measured using Dual PDA in agreement with visualization results. Smaller droplets less than 100 μm are affected by the secondary flow in ultrasonic levitator. Therefore it is difficult to discuss the measurement accuracy of droplet diameter and sphericity of droplets precisely in the case of the smaller droplets.

Fig.5 Time-series of levitating droplet image

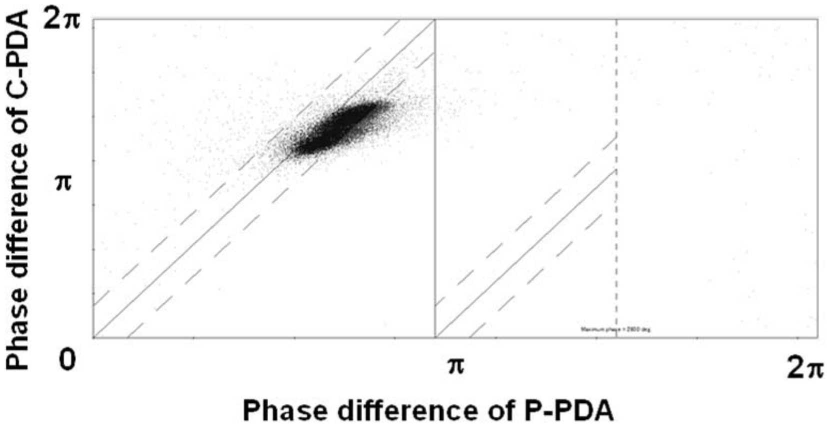

Fig.6 Scatter diagram of the condition #1

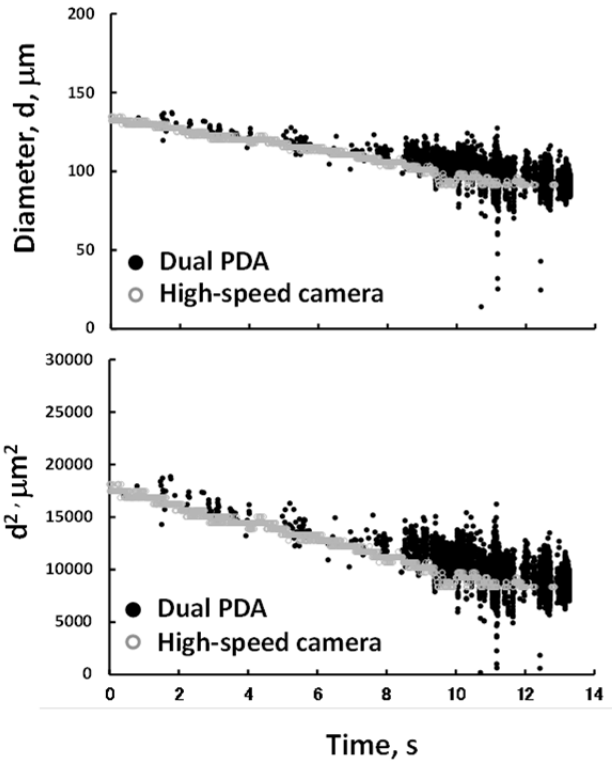

Fig.7 Time variation of droplet diameter under the condition #1

Larger droplets over maximum measurable droplet diameter (230 μm)

In order to measure the sphericity of droplets, initial droplet diameter is determined as larger droplet diameter over the maximum measurable droplet diameter (230 μm) using Dual PDA. Figure 8 shows the temporal evolution of evaporating droplet over maximum measurable droplet diameter using Dual PDA. In this case, initial droplet diameter is about 320 μm. Droplet diameter is decreasing due to evaporation of ethanol. Larger droplet shows larger mass, therefore oscillation of droplet is very small.

Figure 9 shows the measured droplet diameter and squared droplet diameter using Dual PDA and visualization using CCD camera with long-distance microscope. Black circle is measured using Dual PDA and white circle is measured by visualization using CCD camera. Using visualization of droplets, droplet diameter can be measured over 300 μm. Squared droplet diameter is plotted on straight line with a constant negative slope, which is same behaviour with smaller droplets. However, the results of Dual PDA are different trend with visualization. From the measurement start timing to 20 second, Dual PDA show the smaller droplet diameter less than 50 μm. From 20 second to 60 second, Dual PDA doesn't show any droplet diameter. From 60 second, Dual PDA can measure the droplet diameter about 230 μm. Dual PDA cannot measure the droplet diameter until 60 second, however measured droplet diameter from 60 second is good agreement with visualization using CCD camera. Until 60 second, larger droplet over maximum measurable range of Dual PDA with current optical set-up is levitated in ultrasonic levitator. Dual PDA cannot measure the larger droplet over maximum measurable range due to 2π ambiguity. In order to understand to avoid 2π ambiguity in PDA system, scatter diagram of phase difference of standard PDA (C-PDA) and planar PDA (P-PDA) is shown in Fig. 10. Here, measurement duration from the start of measurement to 20 second is determined as region①, from 20 to 60 second as region②, from 60 second as region③, is written in Fig. 9. From the start of measurement to 20 second, phase difference of planar PDA shows 2π ambiguity, therefore smaller droplet diameter was detected with misunderstanding. From 20 to 60 second, phase difference of standard PDA shows 2π ambiguity. In this optical set-up, maximum phase difference of planar PDA is 1.44π. Therefore, Dual PDA cannot measure the droplet diameter from 20 to 60 second due to larger droplet. After 60 second, scatter diagram of phase difference of both PDA is plotted on the correct region. At 60 second, measured droplet diameter is about 230 μm, which is maximum measurable droplet diameter under current optical set-up. This confirms that Dual PDA system can check the 2π ambiguity, and show the correct droplet diameter in measurable range.

After 60 second from the start of measurement, measured droplet diameter using Dual PDA system is good agreement with visualization results using camera. In order to understand the sphericity of droplets, aspect ratio was evaluated using Dual PDA results and visualization results using CCD camera with long-distance microscope in this region③. The aspect ratio of the spheroid is defined using Equ. (2), i.e., the ratio of the horizontal and vertical axes *a* and *b* of the elliptical meridional section of the droplet.

$$r = \log_2 (b/a) \tag{2}$$

The aspect ratio can define the prolate or oblate droplet, r=0 means spherical droplet, r<0; prolate droplet, r>0; oblate droplet. Figure 10 shows the measured aspect ratio using Dual PDA and visualization using CCD camera. Black circle is measured using Dual PDA and white circle is measured by visualization using CCD camera. Measured aspect ratio using both Dual PDA and visualization using CCD camera shows a little oblate droplet. Acoustic force of ultrasonic levitator affect the droplet sphericity, and shows oblate droplets. It is a good agreement with Dual PDA result and visualization using camera.

In the future, we are going to try to measure the sphericity using more oblate droplet in ultrasonic levitator. We need some improvement of stability of ultrasonic transducer. This improvement can allow us to measure the stability of levitated droplet in ultrasonic levitator, and to discuss the measurement accuracy of droplet sphericity using Dual PDA.

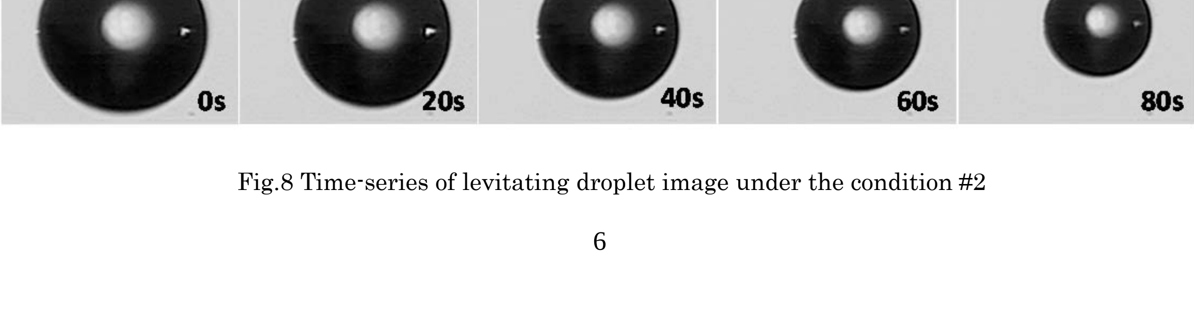

Fig.8 Time-series of levitating droplet image under the condition #2

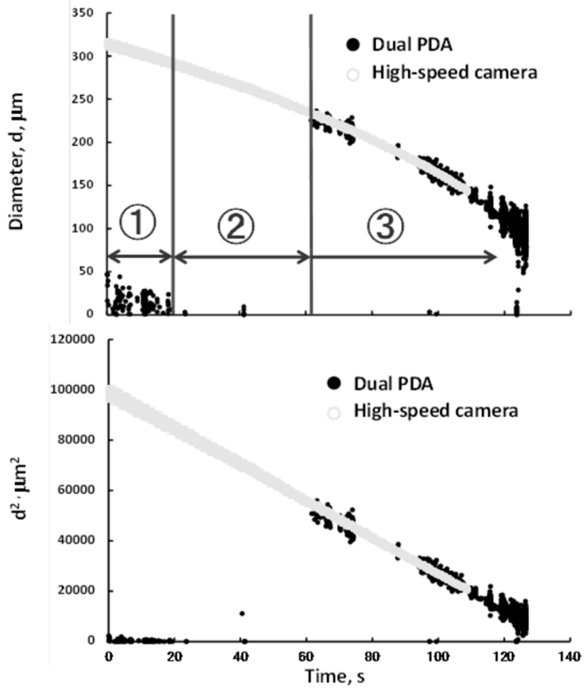

Fig.9 Time variation of droplet diameter under the condition #2

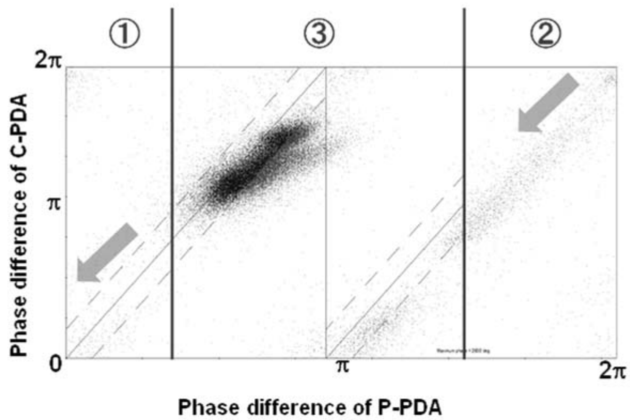

Fig.10 Scatter diagram of the condition #2

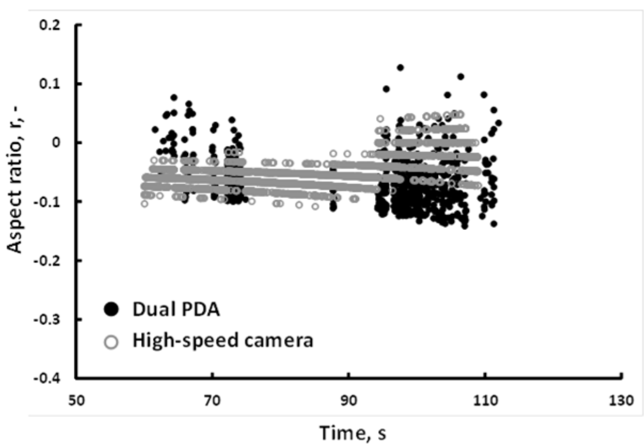

Fig.11 Time variation of droplet aspect ratio of region ③ in Fig.10

Conclusions

In order to discuss the measurement accuracy of diameter and sphericity of droplet using dual-mode phase Doppler anemometer (Dual PDA), measurements of diameter and sphericity of evaporating ethanol droplet using Dual PDA and visualization of CCD camera with long-distance microscope were carried out. The results obtained in this research are summarized as follows:

(1) Dual PDA can measure the droplet diameter of evaporating droplet avoiding 2π ambiguity.
(2) Measurement error due to 2π ambiguity in Dual PDA can be understood for larger droplet over maximum measurable droplet diameter.
(3) It is possible to measure droplet sphericity using Dual PDA. However, further consideration for more oblate droplet should be needed to discuss the measurement accuracy of droplet sphericity using Dual PDA precisely.

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