Dynamic ILIDS measurement by means of high-speed Nd:YLF laser

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Abstract

Interferometric laser imaging for droplet sizing technique (ILIDS) is the novel Lagrangian approach for the measurement of droplet size and velocity vector to investigate the dynamic interaction between liquid and gas phases in such dispersed two phase system as spray and bubbly flows. The droplet size was obtained by the instantaneous out-of-focus image, which is captured by the high-resolution digital camera and pulsed laser. The velocity vector of individual droplet was calculated by the cross-correlational image processing procedure (PTV). The paper describes the further improvement of ILIDS technique by means of a high-speed and high-resolution camera in conjunction with the double-pulsed high-frequency Nd:YLF laser. The experiments demonstrated the several hundred microsecond size transition of the single droplet in the heated air.

Introduction

Such physical properties as droplet size and velocity vector and their spatial distribution are the significant parameters to evaluate the spray systems. Moreover the improvement of multi-dimensional and spatial-temporal spray measurement technique lead us to investigate the detailed heat and mass transport phenomena, and to construct the practical computation models for numerical simulations. Interferometric laser imaging for droplet sizing (ILIDS) technique[1] [2] was developed in order to investigate the spatial distribution of droplet size. The ILIDS technique is the method that observes the interference between reflective and refractive rays on the out-of-focus plane. The fundamental principle of the ILIDS technique was based on scattering theory, sizing method was developed by considering the optical pass difference of the scattered lights from a droplet. Although the difficulty in discriminating the overlapped parallel fringes in the captured image was overcome by optical squeezing technique[3]-[7], temporal resolution was still low due to the limitation of the imaging facility. In the last decade, the drastic development of optical sensor matrix such as CCD or CMOS camera enables the dynamic measurement of flow field whose sampling frequency is beyond several kHz with instantaneous exposure of each pixel[8]. Another contribution is the light source, Nd:YLF laser could emit the TEM_{00} coherent light with high repetition frequency. Although the previous high-power laser system, which was used for the sheet illumination such as high-speed PIV or PTV, the beam quality and energy stability were insufficient for the interferometric measurement, especially for the double-cavity oscillators. In the present study, the single-cavity double-pulsed laser system was employed in conjunction with the synchronized high-speed camera, and performed the Lagrangian investigation of the evaporating liquid droplet in heated air jet.

Sizing accuracy of ILIDS

One of the significant advantages of the ILIDS technique is that the diameters of particles are obtained not by the intensity information but by the spatial frequency of fringe. Consequently the well-established spectral analysis method such as burst signal processing for laser Doppler velocimetry could be applied to the size determination. For the investigation of spray systems, the temporal size transition is one of the significant quantities to evaluate the heat and mass transfer between liquid and gas phases.

In the image analysis of ILIDS technique, the discrete power spectrum provides a broad distribution and presents difficulties in the determination of the fine peak frequency of fringe, especially at the midpoint between the channels of fundamental frequency. Since the measured droplet size is assumed to be linearly proportional to the fringe frequency, the accuracy of frequency determination is directly connected to the sizing accuracy. Therefore the fitting method for peak determination with subpixel accuracy in the frequency domain is quite important for the accurate tracking of droplet size change and for the evaluation of the mass transfer rate. The interpolation technique enables to improve the resolution of finding the peak frequency of interferometric signals and to enhance the resolution of the measured diameter. The amount of the adjustment is simply calculated by using the Gaussian

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function fitting, which considers the peak power and neighboring power in the discrete spectrum. Denoting by k, the integer index of the peak frequency in the power spectrum, the modified frequency is described as follows.

In the simplified case, the parabolic function fitting could be applied;

$$a = \frac{1}{2}\left(\frac{P_{k-1} - P_{k+1}}{P_{k-1} - 2P_k + P_{k+1}}\right) \tag{1}$$

Gaussian function interpolation is another fitting method;

$$a = \frac{1}{2}\left(\frac{\ln P_{k-1} - \ln P_{k+1}}{\ln P_{k-1} - 2\ln P_k + \ln P_{k+1}}\right) \tag{2}$$

By using the equation (1) or (2) in conjunction with the following refinement of integer frequency, f_k, the fine peak frequency could be estimated.

$$f = f_k + a \tag{3}$$

The conventional Gaussian fitting method by equation (2) and (3) remarkably reduces the bias error of the calculated frequency to less than 1% for the fundamental frequency. Moreover, the polynomial adjustment by the following equation (4) reduces the residual bias, the resultant error for absolute diameter could be reduced to less than 0.02% [9].

$$f = f_k + 0.9169a + 0.3326a^3 \tag{4}$$

The fitting methods enable to discriminate the size change between successive images, whose time interval is less than a millisecond, and to enhance the pairing of droplet image in different image frame.

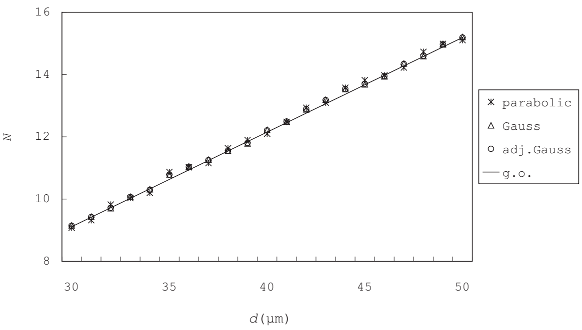

Figure 1. Relation between droplet diameter and fringe number and the dependency on the spectral fitting methods.

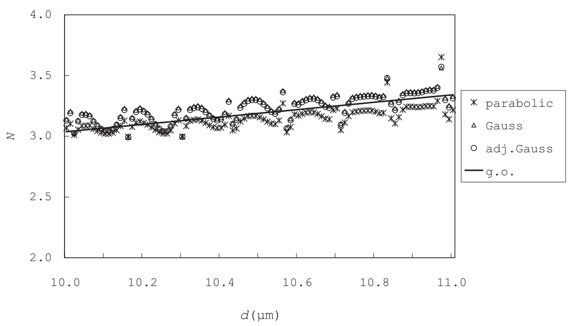

Figure 2. Detailed sizing relation in sub-micrometer range.

Figure 1 is the comparison of the fitting functions. Each plot is calculated by the power spectrum analysis of the angular intensity distribution by Mie solution. Diameter range is from 30 μm to 50 μm, refractive index is 1.36 due to our experimental configuration. The number of DFT points was 1024, angular resolution of Mie computation is 0.01 degree, collection and scattering angle are 10.24 degree and 65 degree respectively. The solid line in the figure is the conversion relation by the sizing equation derived from geometric optical (g.o.) approximation[3]. By the numerical comparison of the fitting functions, the adjusted Gaussian fitting method gives the best approximation of the droplet size. Figure 2 depicts the detailed $d - N$ relation between 10 to 11 μm of droplet diameter. The analysis shows that the conversion relation was modulated periodically by using any fitting methodology. The amount of sizing error between g.o. approximation and exact Mie solution is 1.8% in rms, becomes 10% in worst case.

In our previous works, refractive index is assumed to be constant under isothermal flow field[6], or could be ignored even in the vicinity of the heated surface[10]. Figure 3 depicts the fringe count modulation in terms of the

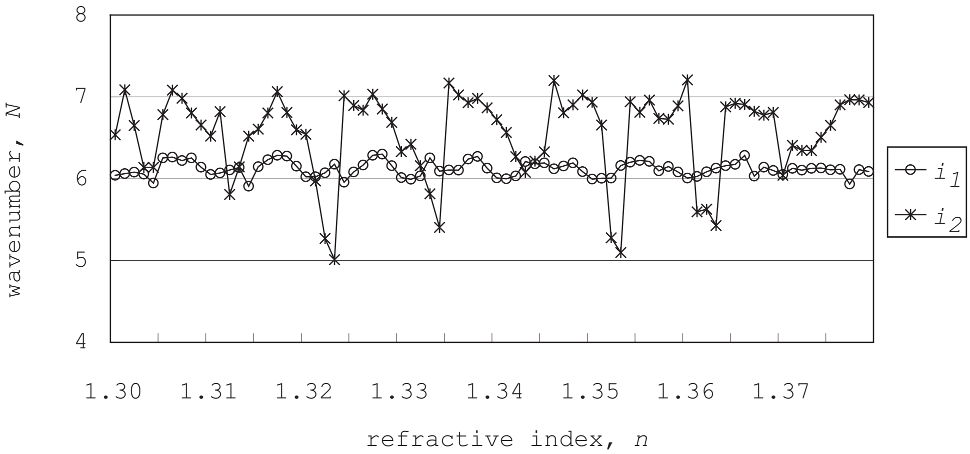

Figure 3. Fringe count dependency on the refractive index. Diameter and wavelength are 20 μm and 527 nm, α is equal to 10.24 deg.

refractive index of droplet computed by Mie theory and Fourier analysis. Size of sphere is 20μm, collection angle is set to 10.24 degree, angular resolution of calculation is 0.01 degree. The wavenumber is also obtained by the discrete Fourier transform of scattered intensity with the adjusted Gaussian fitting interpolation. Both polarized light, i_1 and i_2 were compared. The comparison shows that the perpendicularly polarized light, i_1, gives much better uniformity over the wide-range refractive index variation, the rms of conversion coefficient is 2.5 % for i_1, 10 % for i_2 observation. However, the magnitude of refractive index modulation due to the temperature variance is not significant, i.e., the actual range of refractive index change of liquid droplet in flow field under atmospheric pressure is less than 0.2 %, therefore the resultant variation of the conversion constant is quite small. For example, the difference of sizing coefficient of water droplet between 0 °C and 100 °C is only 0.02 %, that of ethanol droplet is 0.1 %.

Experiment and result

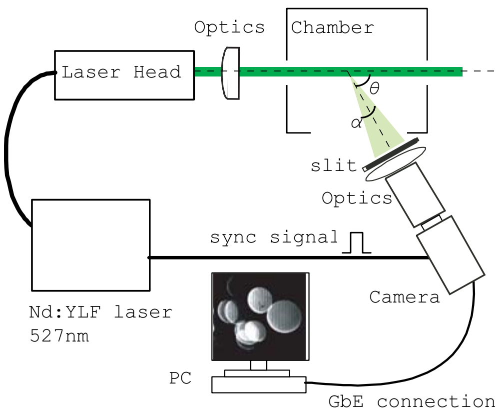

Figure 4. Experimental rig.

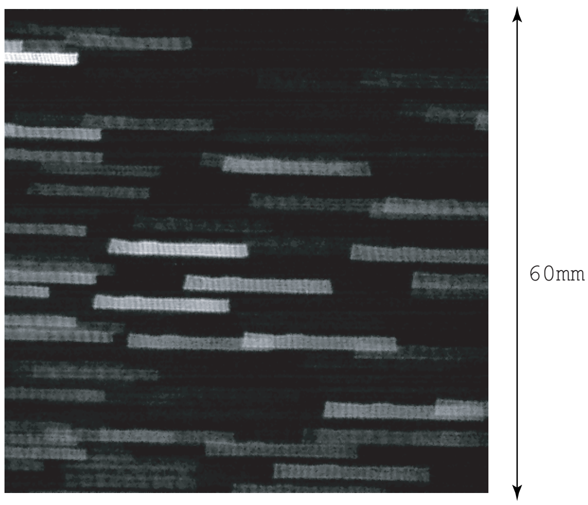

Figure 5. Example of the captured image. Pixel number and actual size are 512 × 512 and 60 mm × 60 mm.

Figure 4 depicts the simplified experimental setup. The system consisted of DM10-527 (Photonics Industries International Inc.) double-pulsed Nd:YLF laser with light sheet optics and a camera with an anamorphic focusing optics and a rectangular aperture. $\lambda/4$ and $\lambda/2$ plates were used to control the polarization of the light sheet.

The maximum output power and single pulse energy of the laser system were 14 W and 10 mJ. When the mean velocity magnitude of the fluids flow is very low, such as laminar flow, continuous-wave (CW) laser could be applied to the interferometric measurement. Wavelength of Nd:YLF laser is 527 nm that is almost the same as the frequency-doubled Nd:YAG laser. Since the sensitivity of the imaging sensor is maximum around 530 nm of wavelength, signal to noise ratio of the captured image becomes high. The MotionXtra N4 (IDT Corp.) high-speed CMOS camera with gigabit Ethernet data transfer interface was employed for the image acquisition, which has 1016$\times$1016 pixels, 10 bit grayscale accuracy. The maximum frame rate is 3000 fps under full-resolution. In this experiments, pixel number and frame rate were set to 512$\times$512 pixels, 4000 fps. Both image acquisition system and pulsed laser system were synchronized with the low voltage TTL trigger signal. Internal memory size of the camera system was 1.3 GB, resultant duration of the overall image acquisition, which depends on the frame rate of the camera, was several hundred milliseconds approximately.

Such optical facilities of ILIDS as pulsed laser with light sheet optics, digital camera and image processing software are identical as conventional PIV technique. Although the fundamental studies of the multi-dimensional simultaneous size and velocity measurement of individual droplet in denser spray have been performed by Maeda *et al.*[3], the temporal resolution of the measurement was only 15 Hz due to the limitation of the framerate of CCD camera and repetition rate of Q-switched Nd:YAG laser as well. In contrast to the previous ILIDS works, fringe image was captured in every 0.25 ms in the following experiments. Figure 5 is an example of the captured image. Each rectangular interferogram corresponds to the individual droplet. Width and height of the interferogram was 100 pixel and 10 pixel in order to improve the accuracy of the velocity vector determination.

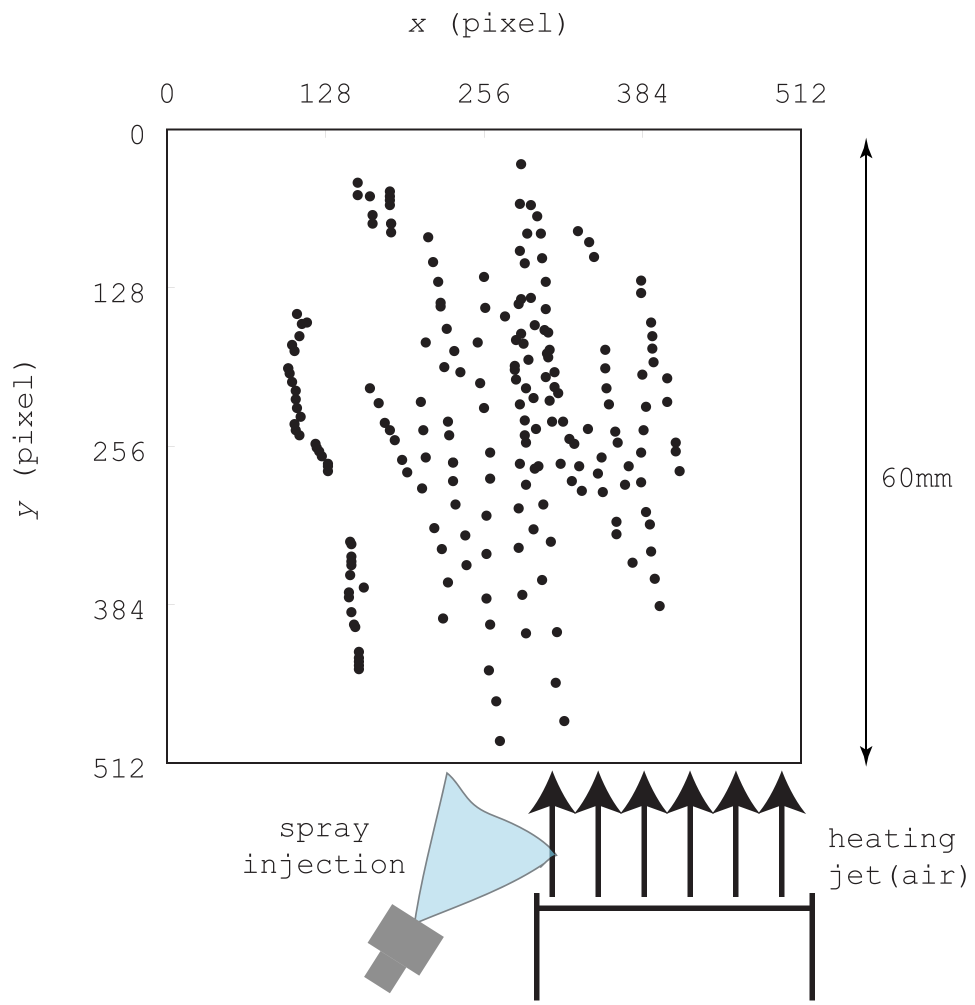

Figure 6. Digitally superimposed particle trajectory around jet boundary area within 50 ms. Pixel number and physical dimension are 512 $\times$ 512 and 60 mm$\times$60 mm.

Figure 6 shows the trajectory of droplet within 50 ms. To draw the droplet paths, 200 successive droplet locations were superimposed. The ethanol droplets were injected from the bottom of the region of interest, arithmetic mean diameter and temperature of droplet were 60 μm and 293 K. Upward heated air flow was generated by a thermal air dryer whose mean temperature and mean velocity are equal to 570 K and 20 m/s. From an instantaneous image, the droplet location and size are firstly analyzed by the spectral analysis that is followed by the cross correlation calculation for the velocity determination. Sub-pixel inter-frame displacement of the interferogram between two consecutive images was calculated by the function fitting as well. The maximum vertical displacement was 30 pixel.

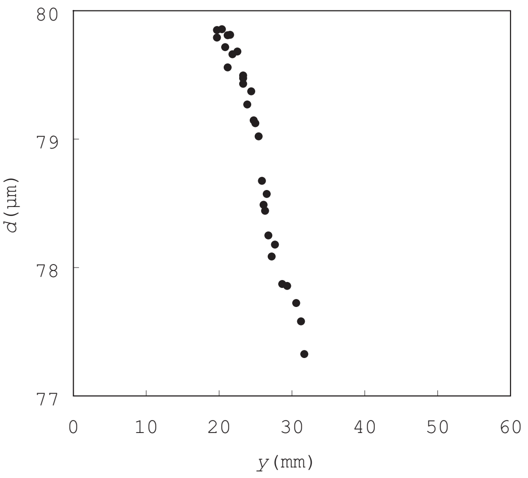

Figure 7. Droplet size decrease in terms of the vertical location in the region of interest.

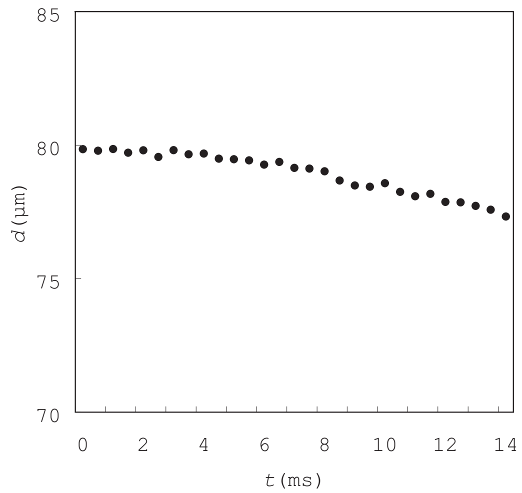

Figure 8. Temporal diameter transition of droplet in 570 K heated upward air flow.

Figure 7 and Figure 8 shows the example of the Lagrangian analysis of the single droplet, both temporal and spatial diameter transition of droplet entering the heated air were shown. Initial droplet size was 80 μm whose diameter is rapidly decreased to 77 μm within 14 ms, the mass evaporation rate of the droplet was 1.64×10^{-3}mg/s. By noting the specific heat capacity and latent heat of ethanol, total amount of heat transfer rate is 1.34 mJ/s, local heat energy flux at the droplet surface is 71×10^{-3} W/m^2. The relative velocity of the droplet, which is obtained by the displacement of the interferogram between captured images, was 8 m/s, $Rep \sim$ 10 and consequently $Nu \sim$ 5 by Ranz–Marshall equation.

Conclusion

The instantaneous size and velocity fields of evaporating ethanol droplet in a heating jet were measured consecutively at a high frame rate imaging system. A preliminary estimation of the sizing error was numerically investigated by Mie solution and function fitting technique. The accurate diameter determination by the spectral interpolation technique enables to find the corresponding particles between the image pair for the Lagrangian particle tracking. The technique was applied to the investigation of the evaporating ethanol spray with a heated jet and evaluated the heat and mass transfer rate of individual droplet.

Acknowledgment

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Nomenclature

a	amount of frequency adjustment by interpolation.
d	diameter [m].
f	angular fringe frequency [rad^{-1}]
N	fringe count, wavenumber [m^{-1}]
t	time [ms]
P	power of light intensity [W/m^2]

Subscripts

k index of power spectrum

References

[1] Hesselbacher, K.H., *et al.* “Experimental investigation of Gaussian beam effects on the accuracy of a droplet sizing method” *Appl. Opt.*, Vol. 30, pp. 4930–4935. (1991)

[2] Glover, A. R., *et al.* “Interferometric laser imaging for droplet sizing: a method for droplet-size measurement in sparse spray systems”, *Appl. Opt.*, Vol. 34 pp. 8409–84–21, (1995)

[3] Maeda, M., *et al.* “Novel Interferometric Measurement of Size and Velocity Distributions of Spherical Particles in Fluid Flows”, *Meas. Sci. Technol.*, Vol. 11, pp. L13–L18, (2000)

[4] Kawaguchi, T., *et al.* “Size measurements of droplets and bubbles by advanced interferometric laser imaging technique”, *Meas. Sci. Technol*, Vol. 13, pp. 308–316, (2002)

[5] Kobayashi, T., *et al.* “Measurement of spray flow by an improved interferometric laser imaging droplet sizing (ILIDS) system”, *Laser Techniques for Fluid Mechanics. (Springer)*, pp. 209–220, (2002)

[6] Maeda, M., *et al.* “ Improvements of the interferometric technique for simultaneous measurement of droplet size and velocity vector field and its application to a transient spray”, *Exp. in Fid.*, Vol. 33, pp. 125–134, (2002)

[7] Kawaguchi,T. and Maeda, M. “Measurement technique for analysis in two-phase flows involving distributed size of droplets and bubbles using interferometric method”, *Multiphase Sci. and Technol.*, Vol. 17, pp. 57–77, (2005)

[8] Lee,S.J., *et al.* “Dynamic PIV Measurement of a Compressible Flow Issuing from an Airbag Inflator Nozzle”, *Journal of Thermal Science*, Vol.15, No.4, 377–381, (2005)

[9] Kobashi, K., *et al.* “Measurement of fuel injector spray flow of I.C. engine by FFT based phase Doppler anemometer” *Application of Laser Techniques to Fluid Mechanics. (Berlin: Springer)*, pp. 268–287, (1990)

[10] Kawaguchi, T., *et al.* “Planar Measurement of Local Characteristics of Impinging Spray on Heating Plate” *Proceedings of the 6th ASME-JSME Thermal Engineering Joint Conference*, TED–AJ03–370, (2003)