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 CMOS camera in conjunction with the double-pulsed high-frequency Nd:YLF laser. The experiments demonstrated the millisecond 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 of their spots on the out-of-focus plane. The fundamental principle of the ILIDS technique was based on Mie scattering theory and was developed by considering the interference of the scattered light from a single particle. Although the difficulty in discriminating the overlapped parallel fringes in the captured image was overcome by optical squeezing technique[3]-[7], temporal resolution was 15Hz at the most due to the limitation of the imaging facility. In the last decade, the drastic development of optical sensor matrix such as CCD or CMOS enables the dynamic measurement of flow field whose sampling frequency is beyond several kHz with megapixel simultaneous exposure. Another point is that the light source is available with TEM_{00} operation with high coherency and 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 CMOS camera, and performed the Lagrangian investigation of the evaporating water droplet in heated air.

Experiment and result

Figure 1 depicts the simplified experimental setup that consists of DM10-527(Photonics Industries International Inc.) double-pulsed YLF laser with light sheet optics and a CMOS camera. The maximum output power and single pulse energy of were 14 W and 10 mJ respectively. Wavelength was 527 nm, which is almost the same as the frequency-doubled Nd:YAG laser used in the previous study[3]. The MotionXtra N3(IDT Corp.) CMOS camera with gigabit ethernet connection was used for the successive image acquisition, which has 1280×1024 pixels, 10bit grayscale accuracy, 1000 fps under full-resolution. Both image acquisition system and pulsed laser system were synchronized with 1kHz trigger signal. Internal memory size of the camera system was 1.25 GB, resultant duration of the image acquisition was less than 1 sec approximately under 1000 fps. Since the size and velocity measurement system of ILIDS, which was almost identical as PIV or PTV technique, was well-established[3], the study concentrated the analysis of sizing accuracy. The advantage of the ILIDS is that the diameters of particles are obtained by Fourier analysis of the spatial fringe frequency. Many kinds of signal processing method are available to determine such frequency information as provided by laser Doppler velocimetry. The discrete power spectrum provides a broad distribution and presents difficulties in real peak frequency determination, especially at the midpoint between the channels of fundamental frequency. Since the measured droplet size is linearly proportional to

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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. The interpolation technique enables us to improve the resolution of finding the peak frequency of interferometric signals and to enhance the resolution of the measured diameter simultaneously. The amount of the adjustment is simply estimated by using the Gaussian function fitting using the neighboring power of spectrums. Denoting by k, the integer index of the peak frequency in the power spectrum, the modified frequency, f, is described as follows.

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

$$f = f_k + a \qquad (1)$$

$$f = f_k + 0.9169a + 0.3326a^3 \qquad (2)$$

The conventional fitting by equation (1) remarkably reduces the bias error of the calculated frequency to less than 1% for the fundamental frequency. Moreover, the polynomial adjustment by equation (2) reduces the residual bias error, the resultant error for absolute diameter can be reduced to less than 0.02% [8]. The aforementioned method enabled to discriminate the size change between captured images, whose time interval is 1 ms or below, and to enhance the sizing resolution of droplet, and to improve the accuracy of the mass transfer estimation. Figure 2 shows an example of the measured diameter transition of droplet entering the heated air whose temperature was 500 K. Initial droplet size was 30 $\mu\mathrm{m}$ whose diameter is decreased to 24 $\mu\mathrm{m}$ within 10 ms. The relative velocity of the droplet, which is obtained by the displacement of the interferogram between captured images, was 10 m/s, $Rep \sim 10$ and consequently $Nu \sim 5$ by Ranz–Marshall equation. The experimental result demonstrated that the developed system will contribute to the multi-dimensional investigation of the spray systems.

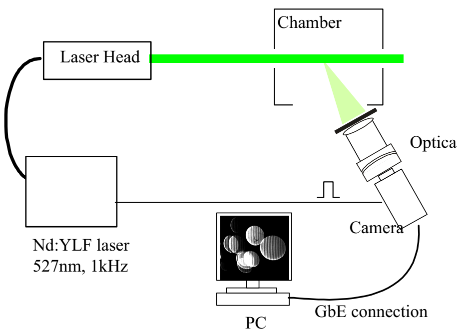

Figure 1. Laser head and laser sheet optics.

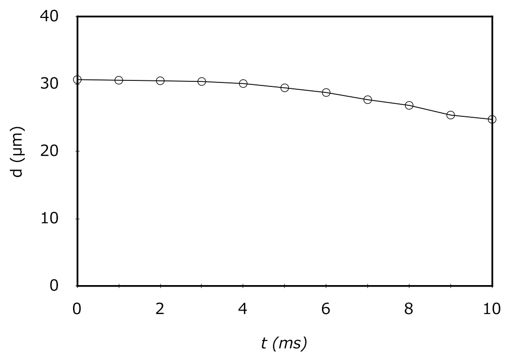

Figure 2. Diameter transition of droplet in 500 K heated air.

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