時空間コヒーレント制御光学システムによるサブミクロン粒子の画像解析*

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Image Analysis of Submicron Particles Based on Satio-temporal Controlled Coherence of Optical System*

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To obtain clear images of sub-micron particles, a procedure for the reduction of wavelength of light and apodization of optical system is adopted to improve resolution, while the imaging resolution is increased with controlling the spatio-temporal coherence of light. The particle miniaturization and composition are advancing rapidly to realize higher particle function so as to add simple optical image and shape analysis of the sub-micron particles. The imaging of profile of submicron particles has been obtained by reducing the light and luminescence wavelength width. The experimental results show that the proposed method is effective for the image analysis of sub-micron class particles.

Key Words: Sub-micron particles, Image analysis, Optical coherence.

1. INTRODUCTION

Analysis of individual particle shapes rather than measurement of particles group is a necessity. It is possible to carry out individual image analysis of particle shapes by using a scanning electron microscope and microscopic observation method. However, it is necessary to measure an extremely large number of fields to ensure statistical reliability. One of the measuring devices that meet the aforesaid requirements is the flow-type particle image analyzer FPIA-2100. However, with the rapid advancement of particle miniaturization and composition for realizing high particle function and added value, the clear imaging of micron particles and shape analysis have become a necessity. Lately, the appearance of proximity field microscope using proximity field has changed the very concept of the conventional optical resolution. As mentioned above, it is logically possible to increase the number of measuring particles, but frequently it is not practical.

In particle measurement, it is academically desirable, on the other hand, to increase the number of particles to get highly reliable data in addition to the need of micro-shapes. In order to meet this demand, it is necessary to make the particles flow at a high speed by using an optical method and to carry out optical imaging with the controlled passage observing position. Hence, a high-image optical resolution is required to realize measurement of micron particle shapes. Compared with the scanning electron microscope, the

*原稿受付　2005年6月20日.

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optical image resolution gets deteriorated but it is possible to observe the tiny unevenness shape on the surface at the vicinity. The optical resolution [1-3] is suggested to be improved by

- Increasing the refractivity,
- Increasing the numerical aperture,
- Shorting the light source wavelength
- Apodizing lighting and imaging optical systems.

In order to reduce the light source wavelength, the Seidel aberrations of imaging optical system must be taken into consideration, while extreme reduction of wavelength is difficult because of extremely limited availability of lens applicable to the wavelength less than 200 nm. Furthermore, to measure the particles of different shapes (sizes) there is a critical domain of 365 nm (line spectral) using objective lens available in the market. In this paper, improvement of numerical aperture, a procedure for the reduction of wavelength and apodization of an optical system are adopted to improve resolution, while the imaging resolution is improved by controlling the spatio-temporal coherence of light. To get clear image of the particle profile, the scattering efficiency from particle profile is a function dependent on the coherence.

2. METHODS

The photograph and configuration of experimental system are given in **Fig. 1**. The system is

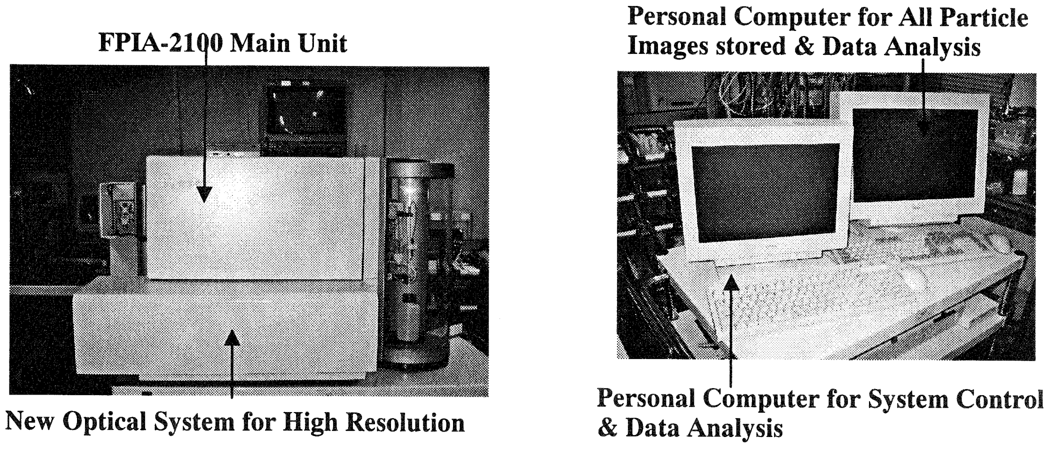


Fig. 1 Photographs of FPIA-2100.

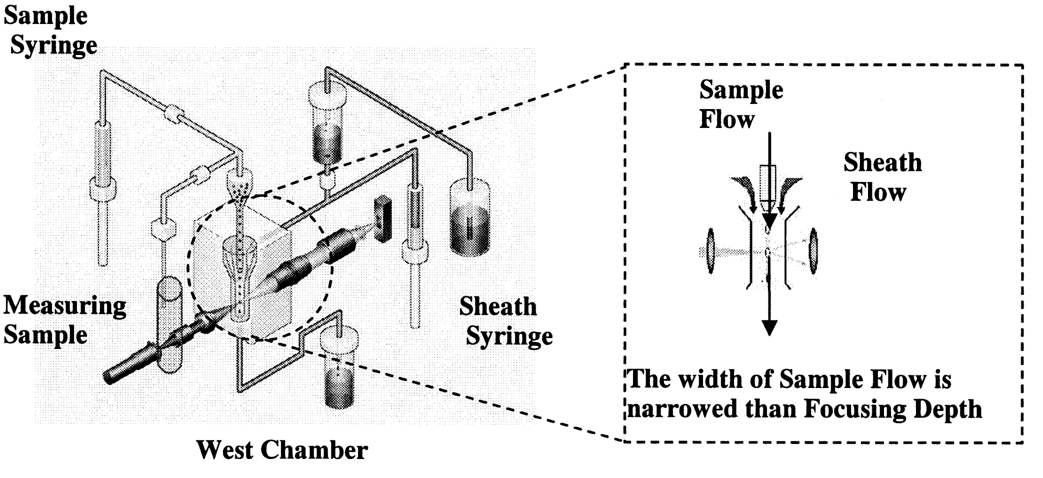


Fig. 2 The hydrodynamic system of FPIA-2100.

composed of the flat sheath flow system of the main flow-type particle image analyzer FPIA-2100 and its control system, with the set up of optical system including optical cell on the optical stool installed outside. Furthermore, an image processing system equipped with real-time, non-compressive memory of all images and particle shape analyzing function was added to the particle image analyzing capacity of the FPIA-2100 main unit. The hydro-dynamic system, image optical system and imaging light source are described below.

2.1 Hydrodynamic System

Fig. 2 shows the hydrodynamics system. The measuring sample is sucked by the syringe before being induced to the optical cell. The system features in that the sample flow (including sample particles) is enclosed by the sheath flow, and the particle passage position is subjected to hydro-dynamic and precise control (see right-bottom of **Fig. 2**). Hence, as compared with the microscopic observation method, it is possible to largely reduce the irregularity at the time of local point position adjustment. Further, there is a sheath flow hydrodynamics technology adopted in the flow-cytometer as a method for measuring a large number of particles within the focal depth in a short time. This technology is applied to Sysmex FPIA-2100 to enable stroboscopic photography using the flat sheath flow technology.

2.2 Optical Measurement System

Fig. 3 shows the lighting optical system, imaging optical system, and light source configuration. There is little difference between the basic configuration and the microscope configuration. The light source is pulse laser light source with cont-rolled coherence or the canon flash lamp + narrow permeable band. High-efficiency orbicular light optical lighting system (radiation numerical aperture: 0.90–0.4) is also used as the light source. The micron particle is lighted by the partial coherent pulse beam generated from the light source. The particle is further imaged by a 1/3" CCD camera with general magnification of 100 times by using the objective lens (Nikon CFI60×100 N.A = 0.9) available in the market and XI No. 2 objective lens (imaging lens).

2.3 Optical Light Source System

An instantaneous and powerful luminescent light source is needed for imaging the fast moving micron particles. This basically refers to the need of controlling the number of time photons, which means improvement of coherence in terms of time. However, the high-coherence light source (laser beam, etc.) causes interference pattern at the time of imaging, leading to extreme deterioration of

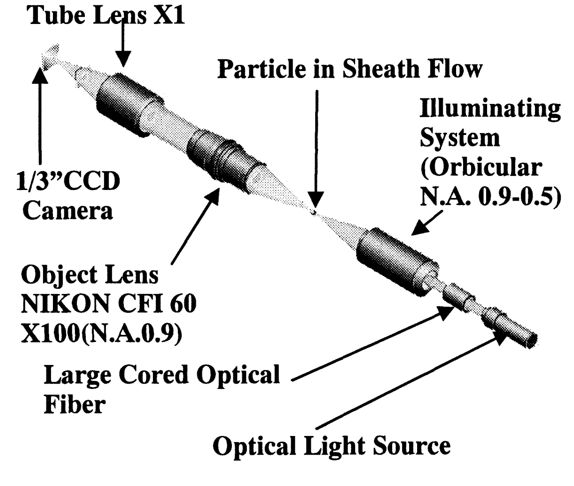


Fig. 3 Optical measurement system.

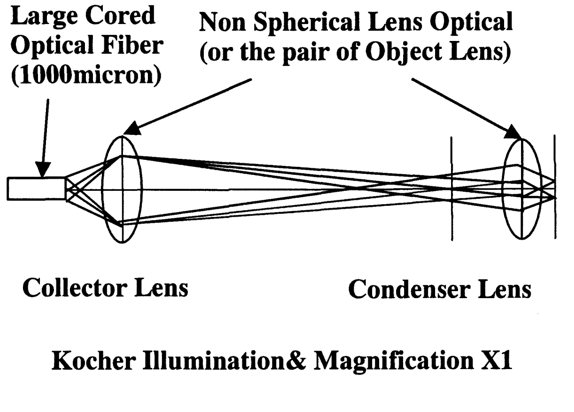


Fig. 4 Optical illuminating system.

image quality. In order to eliminate the interference pattern, the time/space coherence control using multi-mode optical fiber propagation mode diffusion and time coherence control [4] using self-phase-modulation effect of single-mode optical fiber is carried out to irradiate the micron particles. Spectra-Physics Model 7300 Series (524 nm) is used as the partial laser light source. Further, a short-pulse Canon flash lamp made by Hamamatsu Photonics + narrow-band permeable filter is used as the light source with characteristics similar to pulse laser (see **Fig. 5**).

2.4 Optical Illuminating System

Kocher illuminating method is generally used for microscope lighting. Since this system is designed for general-purpose light source, it causes problems given below when used as the micro-light source with high brightness.

- The Kocher illuminating method causes the image field luminance to get uniform, but the radiation numerical aperture distribution becomes uneven.
- Designed on the premise of uneven luminance distribution of halogen lamp, etc., the system is not designed as an optical system capable of irradiating high-brightness, micro-area light source at high efficiency.
- The adoption of diffuser for uniform brightness distribution makes the system extremely low in effective use of light source (light quantity).

To improve these shortcomings a new optical system with characteristics given below was designed and adopted (see **Fig. 4**).

- Large-aperture optical fiber and the incoming/outgoing optics
- Equivalent lighting system magnification (Kocher illumination).

With the realization of aforesaid characteristics, the lighting luminance and lighting numeric aperture in the image field domain got uniform, enabling high-efficiency illumination. The theoretical value of the light utilization efficiency of light source when the optical fiber end used as the light source was 90% (actually measured value: 85%).

The gross shape and coherence of particles in imaging are possible if the optical propagation function of cutoff frequency zone is enhanced using orbicular light for the apodization of lighting optical system. Further, the orbicular light has the advantage of enhanced focal depth and high-zone enhancement of optical propagation frequency [5, 6]. The propagation factor at the proximity of the cutoff frequency in imaging characteristics can be enhanced by controlling lighting optical system coherence [5, 6]. **Fig. 6** shows the optical propagation factor with the value in the figure indicating light cutoff rate. The orbicular light causes deterioration of contrast due to the deterioration of propagation factor in low frequency zone. However, the shortcoming was considered

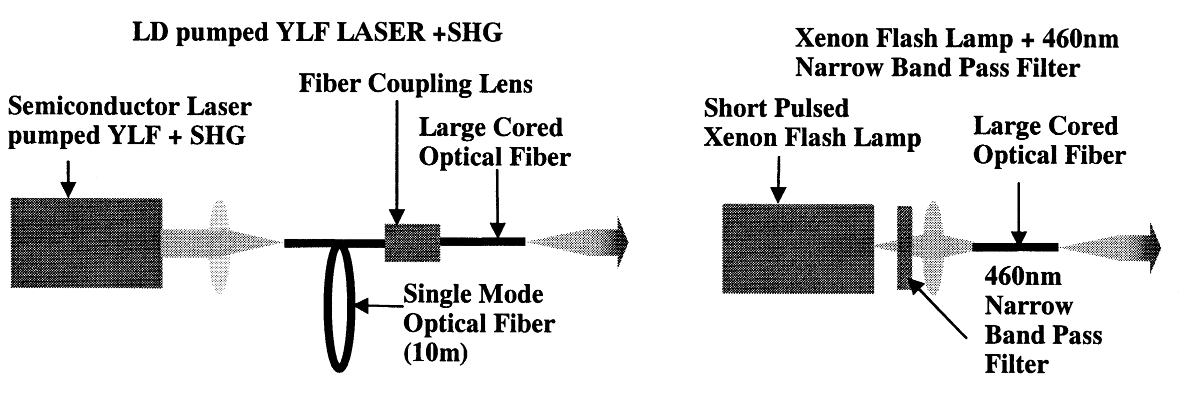


Fig. 5 Optical light source.

amendable to some extent through image measurement.

2.5 Optical Capturing System

The apdization of imaging optical system enables high resolution, but requires timely optimization depending on the micron particle shape. Hence in our research, the apodization was not adopted.

3. RESULTS AND DISCUSSION

The polystyrene particles 500nm, 300nm, and 100nm were used as samples for measurement and were measured in pure water under the state of flow. The results of imaging using pulse laser + single-mode optical fiber + large-aperture optical fiber and xenon flash lamp + 460 nm narrow-band permeable filter (FWHM 10 nm or under) as light sources are shown in **Fig. 7**.

In the case of pulse laser 100 nm-class particles have been visualized, while no particles are observed when 460nm flash lamp is used (as the light source). In the case of visible light 524nm Airy disk primary appropriate optical resolution, the visible particle size is 355nm. However, particle coherence below the optical resolution level has been visualized. The possible reason is considered to lie with the coherence of light source being higher than flash lamp light source, causing the diffracted ray at the outer periphery of the particle to concentrate in the low-order component, which leads to effective imaging of profile by the objective lens for imaging. In other words, by focusing energy to the high zone of optical propagation frequency, the required information is obtained by improving the propagation factor in the required frequency zone [6].

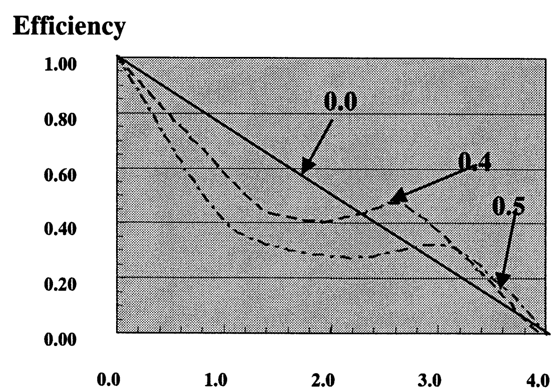


Fig. 6 Optical transfer function.

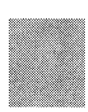
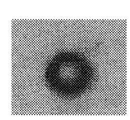
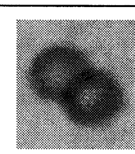
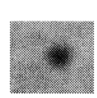
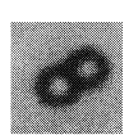
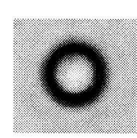
	0.1micron Particle	0.3micron Particle	0.5micron Particle
Xenon Flash Lamp (460nm)			
LD pumped YLF Laser +SHG			

Fig. 7 Particle images.

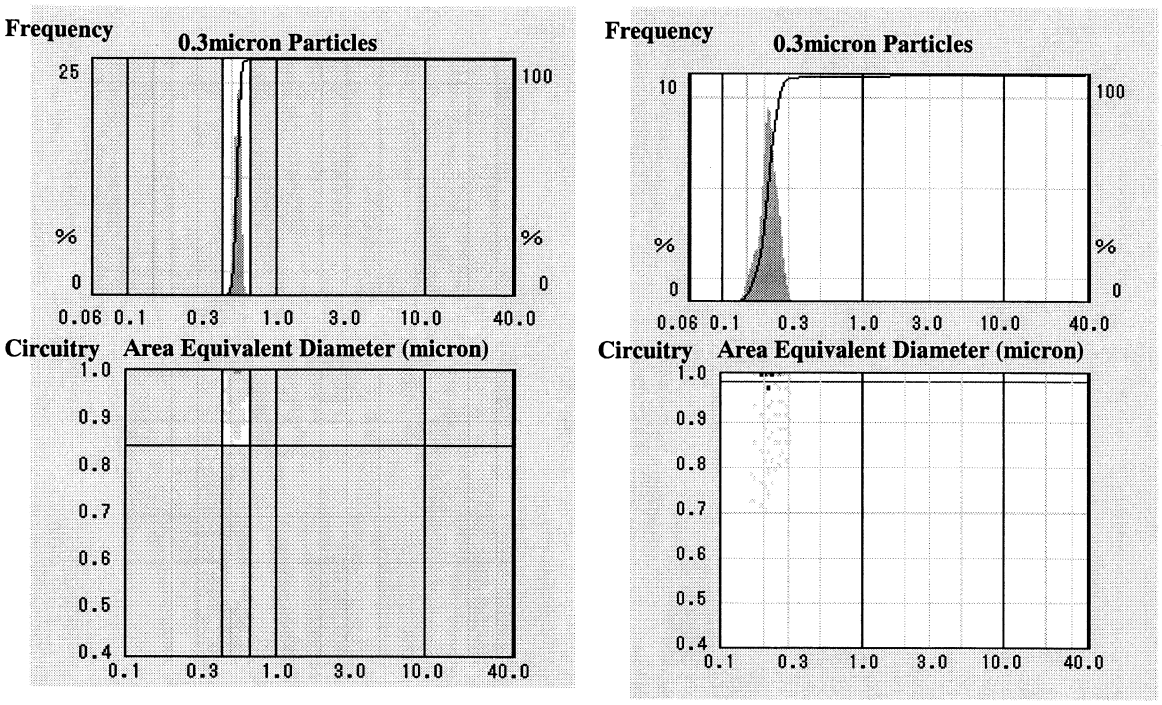


Fig. 8 Results of the image analysis for particles of 500nm and 300nm.

Fig. 8 shows results of 300 nm and 500 nm particle images analyzed by using pulse laser. The results for the particle size of 500nm (4,503 particles) image analysis are the average particle diameter of 524nm and particle diameter CV of 14.69%.

4. CONCLUSION

The analysis of individual particle shapes is necessary in particle measurements, and the number of particles for measurement must be increased to ensure statistical reliability of the parents group of particle. The particle miniaturization and composition are advancing so rapidly to realize high particle function and added value that simple optical image and shape analysis of sub-micron particles is an imminent need. In this study, the imaging of profile of submicron particles has been obtained by reducing the light and luminescence wavelength width. The experimental results show that the proposed method with the spatio-temporal coherent of light is effective in the image analysis of sub-micron class particles.

ACKNOWLEDGEMENTS

This study was supported by the Academic Frontier Research Project on "Next Generation Zero-emission of Energy Conversion System" of the Ministry of Education, Culture, Sports, Science and Technology, Japan, 2003-2007, and in part by the Research Project of Super-SINET with G-bit Network System of the National Institute of Information, 2003-2008, and the Human Security Project of Doshisha University, 2003-2007.

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