3D measurement of burning coal particle field with digital holography

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Abstract

The 3D measurement of the burning coal particles in the flame is challenging and interesting. Digital holographic particle tracking velocimetry (DHPTV) is applied to perform 3D measurement of a laboratory-scale pulverized coal flame. Pulsed laser beam illumination is used to record the coal particle hologram with clear fringes in the presence of high refractive index gradient and strong turbulence. Over 30000 coal particles have been reconstructed and detected. Result shows that the particle size, 3D positions, particle number density distribution, and even 3D velocity can be determined simultaneously. DHPTV presents great potential in the 3D measurement of burning particles.

Introduction

Pulverized coal combustion is the most widely technology used for coal fired power plant. Clean coal utilization requires a deeper understanding of the burning coal particle field. Previous intensive experiments has been conducted on pulverized coal particle combustion via various advanced measurement techniques, such as PIV, LDV, PLIF and LII, but the 3D measurement of burning coal particle is few.

Holography is a real 3D imaging technique, and capable of extracting the 3D information of the interrogated particles by two steps: firstly recording and then reconstruction of particle holograms[1]. The application of holography for burning droplets[2], coal particle[3] and even metal particles[4] with film hologram can date back to 1970s. Nowadays, digital holography with digital recording by CCD/CMOS has also developed to be a prevalent and powerful tools for the 3D measurement of particle field[5], and has been employed for the diagnostics of burning pulverized coal flame[6] and combusting aluminum drops[7].

In this work, we applied digital holography to measure burning coal particles, aiming to yield the size distribution, 3D position and even the 3D velocity of the particle field.

Methodology

Fig. 1 shows the experimental setup of pulverized coal flame measurement with a digital holographic particle tracking velocimetry (DHPTV).

A digital holographic particle tracking velocimetry (DHPTV) was established based on Gabor inline configuration, and the sketch and picture of the experimental setup of digital inline holography for coal particle flame diagnostics is shown in Fig. 1a and 1b respectively. A double-pulsed laser beam produced by a Nd:YAG laser (532 nm, New Wave Research, Inc., Solo 120XT), was attenuated by an attenuator, and then passed through a spatial filter and was expanded to a collimated laser beam with a diameter of about 5 cm. The duration of each pulse is 5 ns, which is short enough to freeze the moving coal particle. The expanded laser beam illuminated the coal particle in the pulverized coal flame and propagated to the CCD. The interference patterns of the objective beam diffracted by coal particles and the undisturbed reference beam were recorded by a frame-transfer CCD (Lavision ImagePro), with a resolution of 1352×1248 and the pixel size of 7.4 µm. The CCD was placed about 185 mm away from the center of the burner. The laser pulse and the CCD were synchronized by the computer. The DHPTV system was operated at double exposures/double frames mode to record a pair of holograms. A band pass filter of 532 nm was placed before the CCD to isolate the radiation of the pulverized coal flame.

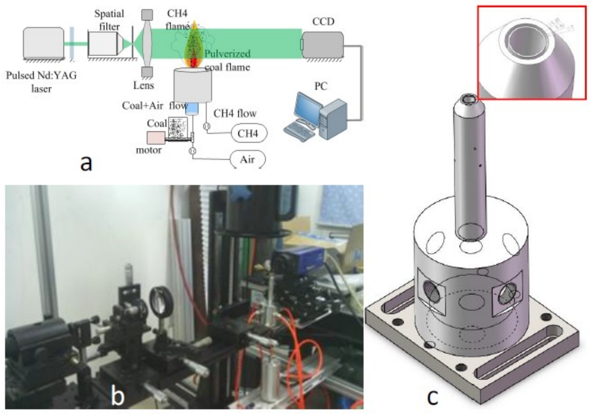

Fig. 1. Experimetal setup for pulverized coal flame measurement with digital holography. (a-b. sketch and picture of pulverized coal flame measurement with digital holography, c. laboratory-scale pulverized coal burner.)

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A laboratory-scale pulverized coal burner was used to produce a pulverized coal flame. The burner consists of two coaxial tubes. The inner diameter of the outer tube is 7 mm, and the inner tube has an inner diameter of 5.5 mm and thickness of 0.25 mm. Methane was supplied to the annular slit burner, which is between the inner and outer tubes with a width of 0.5 mm. The pilot methane flame was stabilized outside of the inner tubes, to ignite the coal particles. Pulverized coal particles were supplied by a screw feeder. The mass flow rate of the pulverized coal particle was controlled by regulating the rotation speed of the step motor, which drives the feeding screw. Then the coal particles were entrained into pipe and conveyed to the inner tube by an air flow with a flow rate of 7.5 L/min. The coal particle/air jet flow injected into the center of the pilot methane flame, and eventually was heated up to ignite and burn.

The China Pingdingshan bituminous coal was used in this study. The properties of the coal, proximate analysis, ultimate analysis and heating value, are listed in Table 1. The tested coal was grinded and sieved to a size fraction from 10 μm to 150 μm, which was similar to the actual pulverized coal used in thermal power plants, with an average diameter of 60 μm.

Table 1. Properties of coal

	Qb,ad (J/g)		Qb,ad (cal/g)		
	25483		6094		
proximate	Mt%	Mad%	Aad%	Vad%	FCad%
analysis		3.56	18.47	30.41	47.56
ultimate	Cad%	Had%	Nad%	St,ad%	Oad%
analysis	63.52	4.27	1.1	1.33	7.75

Hologram Processing

The pulverized coal particle holograms were processed to retrieve the particle size and shape, 3D position and velocity according to the algorithms in our previous work [8, 9]. The processing procedures of particle hologram mainly go as follows:

(1). **Denoise**: A series of background holograms are averaged to produce a stable background holograms. The noise can be reduced via subtracting the background hologram to enhance the intensity contrast between the particle fringes and the background.

(2). **Reconstruction**: The 3D optical particle field can be reconstructed from the recorded hologram with the wavelet reconstruction method by a convolution of the hologram and a wavelet[10]:

$$I_{image}(x,y;z) = 1 - I_{holo}(x,y) \otimes \psi_z(x,y) \qquad (1)$$

where

$$\psi_z(x,y) = \frac{\pi}{\lambda z}\left[\sin\left(\frac{\pi(x^2+y^2)}{\lambda z}\right) - M_\psi\right]\exp\left(-\frac{\pi(x^2+y^2)}{\lambda z \sigma^2}\right)$$

is the wavelet reconstruction function, and $M_\psi = \sigma^2/(1+\sigma^4)$ is used to ensure a zero mean value of $\psi_z(x,y)$. The reconstructed particle approaches the in-focus plane when the reconstruction distance equals to the recording distance.

(3). **Geometry**: Then the geometry properties of the coal particles including particle shape, size and 3D positions, are measured from each hologram. The reconstructed image slices are fused into an extended focus image (EFI) with a wavelet image fusion algorithm[8], in which all the particle are focalized. The particles were detected by applying a local adaptive threshold value to the extended focus image to segment them from the background. The region of each particle in the binary image is labeled. Then the intensity weighted centroids of the labeled particles can be computed as the transversal positions. For each detected particle, a series of local ROI (region-of-interested) images centered at the centroid of the particle along the depth direction were selected to evaluate the particle focus plane. The focus plane of the particle is determined by a criterion of Tenengrad variance, which is the local variance of the gradient magnitude of the ROI image:

$$FM = \sum_m^M \sum_n^N [Sobel(I(m,n)) - \overline{Sobel(I(m,n))}]^2 \qquad (2)$$

where the Sobel operation is used to calculate the horizontal and vertical gradient magnitude of the gray image. The in-focus image is achieved at the depth position where the focus metric curve approaches its global maximum peak. The coal particle size and shape are obtained from its in-focus image.

(4). **Motion**: The detected particles in a hologram pair is paired using a hybrid PIV/PTV method. A velocity field between the two EFIs is compute using PIV, and the velocity field helps to pairing the particle using the matching probability method[11]. The transverse velocity can be obtained from the transverse displacement of the paired particle. The depth displacement of the paired particle between the two holograms is determined by the spatial shift of the focus metric curves using cross correlation[9].

(5). **Post processing**: Post processing is performed to remove the spurious particle and vectors. The shape and peak value of the focus metric curve are analyzed to detect and remove the spurious particles, and a comparison of the particle morphology and velocity is used to detect the pairing and velocity.

Results and Discussions

Fig. 2 shows the images of the pulverized coal flame. Fig. 2a and 2b are the direct color photographs of the coal flame by Nikon D700, with the relatively long (1/200s) and short (1/4000s) exposure time respectively. The stable flame length over 10 cm. Coal particles begin to ignite about 10 mm above the burner. Comparing the flame width at different heights, the visible flame plume firstly expanded rapidly at the ignition position due to the heat release from coal particle combustion, then up to maximum and kept stable, and decreased at the downward due to the heat loss of the jet entrainment effect. The trajectory of the burning coal particle looks as streaks due to the particle motion during the exposure. The pilot flame and unburning coal particle could not be recorded in the image under short time exposure, since its visible light emission is much lower than that of the burning char and hot soot. Micro photography was employed to record the combusting behavior of the individual coal particle in the particle cloud. Fig. 2c shows the transient image of the burning coal particles with a short exposure of 1 μs, and the coal particles move less than a pixel, which is so small that can be negligible. Bright spots with irregular shape were observed, representing the combustion of the char. The volatile flame and its products such as hot soot were also observed, as evidenced by the weakly luminous brushes associated with the bright chars. The average emission intensity of the reacting char is much stronger than that of the volatile flame. Fig. 2d shows the occasional cracking of the burning coal particle during combustion, with the exposure time of 100 μs to capture the trajectories of fragments before and after cracking. The intersection of the brushes denotes at the exact moment when the burning coal particle cracks, and the brushes below and above the bright intersection represent the luminous fragments before and after cracking respectively. There is a significant change in the directions of fragment motions after cracking.

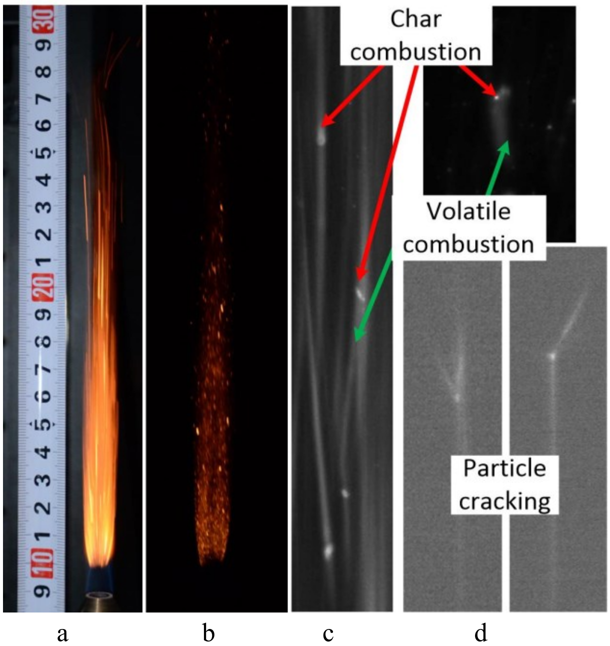

Fig. 2 images of the pulverized coal flame. (a. long exposure, b. short exposure, c. transient image, d. cracking of burning coal particle.)

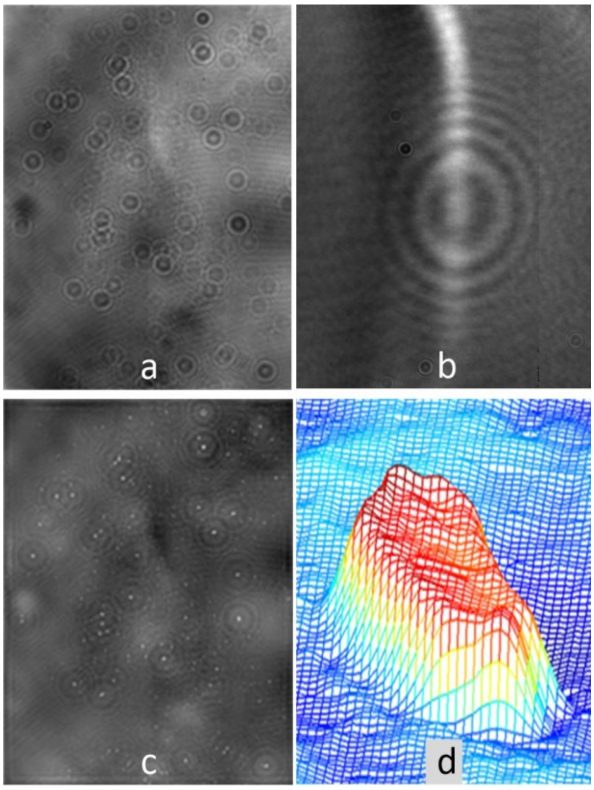

Fig. 3 typical coal particle hologram and reconstructed image. (a. coal particle hologram, b. fringe distortion at the flame front, c. reconstructed slice image. d. 3D representation of the reconstructed in-focus coal particle image.)

Fig. 3 shows typical pulverized coal flame holograms and their corresponding reconstructed images. Due to the temperature, concentration and density variations induced by the thermal turbulence, the local refractive index varied temporally and spatially, leading to the dynamically moving background. Besides, the hologram was superimposed with noises, such as the interference fringes of the dust clued on the lens. Even in the hostile environment, the interference patterns of the coal particles, which compose of concentric rings, can be recorded clearly with the pulsed laser beam illumination. The strong radiation from the flame front, as the bright irregular patterns shown in the holograms, gives rise to the great temperature and composition gradient at the interface between the burning flame front and the surrounding, which eventually leads to a great refractive index gradient at the flame front. The great refractive index might distort the hologram fringes of the particles near to the flame front, as evidenced in Fig. 3b. Fig. 3c shows the typical in-focus image of the reconstructed coal particle field. Clear in-focus images of coal particles can be observed in the best focus plane evaluated by Tenengrad variance, with sharp intensity gradient at the border of the coal particle. Calibrations through measuring a known metal fibers in the pulverized coal flame show that the error in the depth position usually is no more than 500 μm in the experimental scenario[12]. By segmenting the in-focus image from the background, thus the particle 3D position, equivalent size can be obtained. Besides, the reconstructed in-focus can be used to perform morphology measurement, as the 3D representation of the reconstructed in-focus coal particle shown in Fig. 3d.

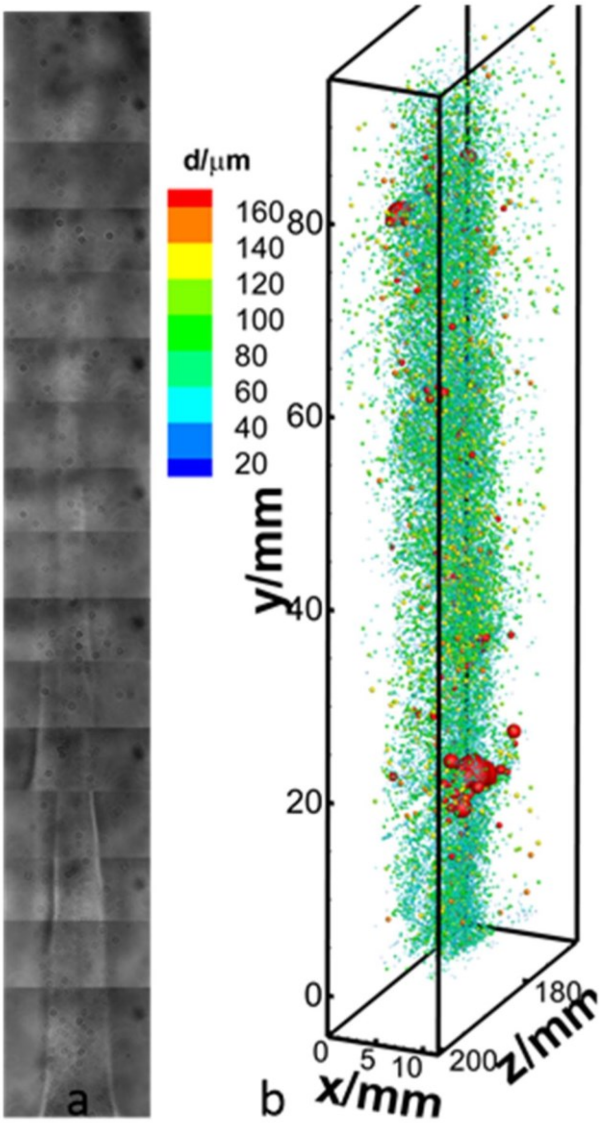

Fig. 4 panoramas of coal particle hologram and the reconstructed particles. (a. hologram, b. reconstructed particles.)

Since the field of view of digital inline holography for particle field diagnostics is limited to a small volume due to the finite size and the low spatial resolution of the CCD, the pulverized coal flame was divided into ten measurement sections. 75 holograms of each section were recorded and processed automatically to yield a large number of coal particles (up to 38,710) for statistics. The holograms at different heights were stitched to produce a panorama hologram of the pulverized coal flame, as shown in Fig. 4a. The 3D optical particle field was reconstructed, scanning from 18 mm to 22 mm in the depth direction, with a step of 50 μm between two consecutive slice images. Fig. 4b shows the 3D positions of the reconstructed and detected coal particles, with both the size and color proportional to the equivalent particle size. The coal particles locate between 175 mm and 195 mm away from the CCD, which agrees with the distance from the burner to the CCD. The particle size ranges from 20 μm to 160 μm, with the mean size of 54.8 μm.

Fig. 5 shows the particle number density of the reconstructed coal particle field. In the longitudinal section (*x*-*y* plane), the dispersed coal particles diffuse radically along the jet expansion. Almost all of the coal particles locate within the inner jet in the region near the outlet of the tube, and then spread radically along the *y* direction with a decrease of particle concentration, as shown in Fig. 5a. The coal particle density in the flame in cross section (*x*-*z* plane) is higher in the center region, and decrease with the distance away from the center, as shown in Fig. 5b. Fig. 6c shows the particle density in the *x*-*z* plane at different (*y*) heights.

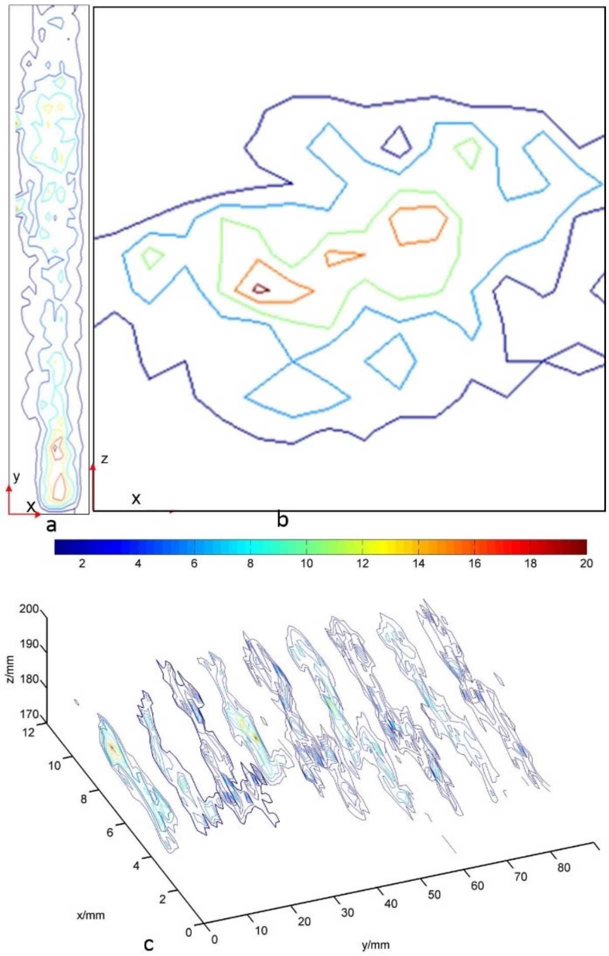

Fig. 5 coal particle number density in the flame. (a. longitudinal section, b. cross section, c. cross section at different heights.)

Hologram pairs are processed to obtain the velocity of the coal particle. Fig. 6a and 6b show a hologram pair of the coal particles. The overall intensity in the second frame is brighter than that of the first one, since the exposure time of the second frame recorded by the frame transfer CCD is much longer than the first one. Fig. 6c shows the overlapped velocity field of 400 holograms in the region above the burner 0-22 mm. Over 1800 vectors has been obtained. In the region of $0<y<10$ mm before the ignition of coal particle, the coal particles travel upward along the jet, the radial velocity in the x-z plane very small and the longitudinal velocity in the y direction dominates. The radial velocity increases dramatically at the $y = 10$ mm where the coal particles ignite and begin to burn. The mean velocity of the coal particle is 6.7 m/s, with the range from 2 m/s to 20 m/s.

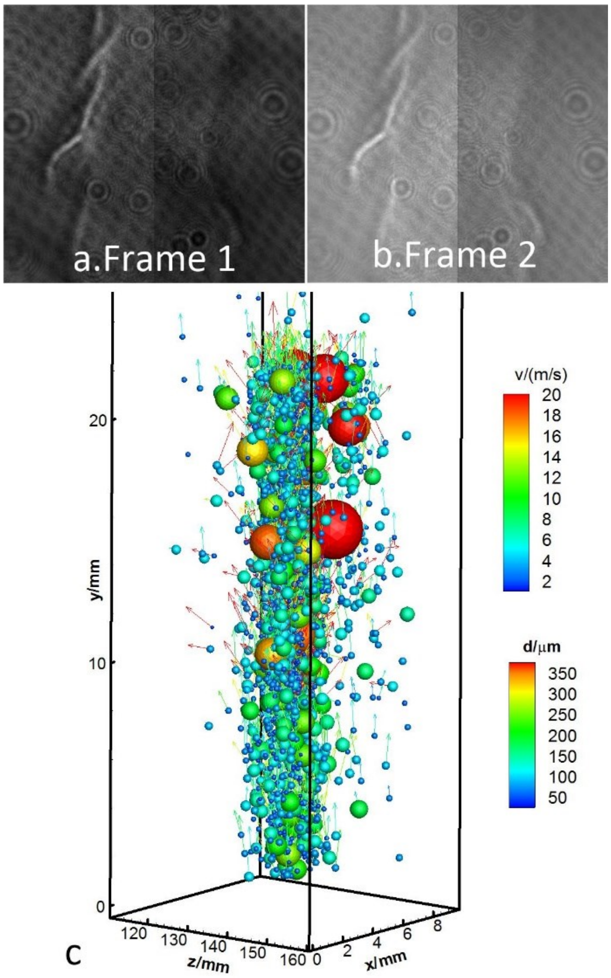

Fig. 6 velocity field of the coal particles. (a-b. a typical hologram pair, c. velocity field near the burner.)

Conclusions

Digital holographic particle tracking velocimetry has been applied to measure the laboratory-scale pulverized coal flame. Typical phenomena such as volatile combustion, char burning and cracking of burning coal particle have been observed in the transient images of pulverized coal flame. Even in the hostile environment characterized with high refractive index gradient and strong turbulence and flame radiation, coal particle hologram can be recorded with pulsed laser beam illumination with clear fringes. The flame front could distort the hologram fringes, but the in-focus image can be still reconstructed. Over 30000 coal particles in the region $0<y<100$ mm have been detected, and the particle size and 3D positions are determined. The mean particle size is 54.8 μm. The large number of the obtained particles permits the statistical evaluation of the particle number density in the longitudinal and radial sections, and even in the 3D volume. Hologram pairs of coal particles are processed and the 3D velocity field of the particles in the region $0<y<20$ mm are evaluated, with the mean velocity of 6.7 m/s. Expansion of the pulverized coal flame at the ignition has been observed in both 3D position and 3D velocity of the reconstructed particle field.

DHPTV has succeeded to measure the particle 3D position, shape and size, and 3D velocity simultaneously, and shows great potential in the 3D diagnostics of burning particle.

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References

[1] U. Schnars; W. P. O. Juptner, Measurement Science and Technology 13 (9) (2002) R85-R101

[2] J. Webster; R. Weight; E. Archenhold, Combustion and Flame 27 (1976) 395-397

[3] J. D. Trolinger; M. P. Heap, Applied Optics 18 (11) (1979) 1757-1762

[4] M. J. Adams; T. Owens, in: DTIC Document: 1979.

[5] J. Katz; J. Sheng, Annual Review of Fluid Mechanics 42 (2010) 531-555 10.1146/annnrev-fluid-121108-145508.

[6] Y. Wu; X. Wu; B. Zhou; J. Yang; L. Chen; Y. Peng; K. Qiu; K. Cen, in: *Digital Holography and 3D Imaging (DH)*, OSA: 21-25 April 2013 at The Fairmont Orchid, Kohala Coast, Hawaii, USA, 2013.

[7] D. R. Guildenbecher; M. A. Cooper; W. Gill; H. L. Stauffacher; M. S. Oliver; T. W. Grasser, Optics Letters 39 (17) (2014) 5126-5129 10.1364/OL.39.005126.

[8] W. Yingchun; W. Xuecheng; Y. Jing; W. Zhihua; G. Xiang; Z. Binwu; C. Linghong; Q. Kunzan; G.

Gréhan; C. Kefa, Applied Optics 53 (4) (2014) 556-564 10.1364/AO.53.000556.
[9] Y. Wu; X. Wu; L. Yao; Z. Wang; L. Chen; G. Grehan; K. Cen, Optics Communications (2014) (Under revision)
[10] M. Malek; S. Coetmellec; D. Allano; D. Lebrun, Optics Communications 223 (4-6) (2003) 263-271 doi:10.1016/S0030-4018(03)01693-6.
[11] S. Baek; S. Lee, Experiments in Fluids 22 (1) (1996) 23-32
[12] Y. Wu. Digital particle holography for 3D measurement and its application. Zhejiang University, Hangzhou, 2014.