Proc. of 12th Int. Symp. on Applications of Laser Techniques
to Fluid Mechanics, Lisbon, July 12-15, (2004)

Laser Photothermal Velocimeter by Compulsorily Operating Point Locked Optical-deflection-probe

by

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ABSTRACT

This paper describes a system for measuring velocity in turbulent flow by means of laser photothermal effect. We developed the new and simple compulsorily operating point locked optical-deflection-probe for excluding influence of turbulent phase fluctuation and detecting small phase variation of the photothermal effect. The optical-deflection-probe is operated compulsorily at zero crossing point of phase gradient curve by an electric system. The deflection angle of the probe beam is scanned by the use of a scanning mirror. To increase detecting sensitivity of deflection angle, the probe beam passed through probe point was enlarged by the use of a cylindrical lens. We used probing methods for reducing the influence of the diffusion, which is inherent problems in molecular velocimetry and for increasing the spatial resolution. The probe beam is set to partially cross the pumping spot.

Using jets of a gas mixture of nitrogen and ethylene, we confirmed that this measurement system is useful to measure the flow velocity under turbulent phase fluctuation.

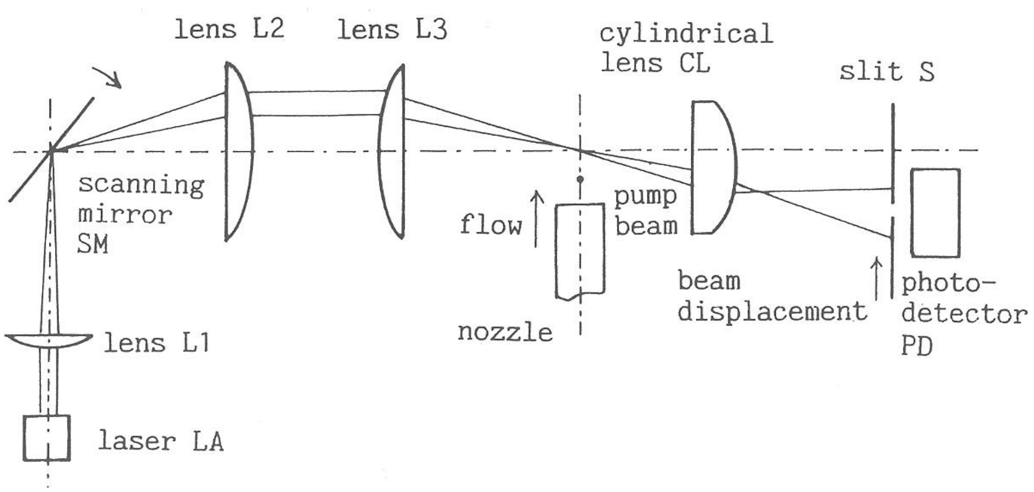


Fig. 1 Optical system for molecular photothermal-velocimeter by compulsorily operating point locked optical-deflection-probe.

1. INTRODUCTION

The laser Doppler velocimeter (LDV), which has some advantages such as non-perturbing quality, capability of remote operation and high spatial resolution, has been well developed to measure flow velocity. However, the LDV [Durst, Melling and Whitelaw (1981)] needs to seed scattering particles in flow. This is not desirable in many testing environments. For example, the seed particles do not faithfully reproduce gas flow in high speed. Especially, flow diagnostics in clean room and in vacuum chamber for semiconductor production need to keep the field clean. These reasons have provided ample motivation for investigating unseeded molecular velocimetry methods. Several molecular-based methods have been developed to alleviate the problems associated with seeding flow. In practice, many of these methods exhibits a new set of drawbacks. For example, Doppler-based methods suffer from poor dynamic range and yield large measurement error in lower velocity limits [Miles and Lempert (1990)]. Ozone tagging velocimetry using photodissociation needs to take 20 μs for induction of the ozone [DeBarver, Rivarver, Wehrmeyer, Batiwata, and Pitz (1998)]. To be freed from these problems, molecular velocimeter using photothermal effect have been investigated [Nie, Hane and Gupta(1986)] and [Nakatani and Oshio (1994)]. In the previous studies we developed the interferometers for measurement of photothermal effect to reduce the influence of turbulent phase fluctuation [Nakatani (2000)]. The probing differential point of the interferometer is separated between 0.5～1 mm. In the interferometer, the influence of the turbulent phase fluctuation is larger than one beam method of optical deflection.

This paper describes a system for detecting laser photothermal effect in turbulent flow using one beam method of optical deflection method. The new and simple compulsorily operating point locked optical-deflection-probe was developed for reducing influence of turbulent phase fluctuation and detecting small phase variation of the photo-thermal effect. The optical-deflection-probe is operated compulsorily at zero crossing point of phase gradient curve by an electric system. The deflection angle of the probe beam is scanned by the use of a scanning mirror. To increase detecting sensitivity of deflection angle, the probe beam passed through probe point was enlarged by the use of a cylindrical lens. We used the probing method for reducing the influence of the diffusion, which is inherent problems in molecular velocimetry and for increasing the spatial resolution. The probe beam is set to partially cross the pumping spot.

Using jets of a gas mixture of nitrogen and ethylene, we confirmed that this measurement system is useful to measure the flow velocity under turbulent phase fluctuation.

2. MEASUREMENT SYSTEM

The new and simple compulsorily operating point locked optical-deflection-probe was developed for reducing influence of turbulent phase fluctuation and detecting small phase variation of the photothermal effect. The optical-deflection-probe is operated compulsorily at zero crossing point of phase gradient curve by an electric system. The deflection angle of the probe beam is scanned by the use of a scanning mirror.

The experimental setup using the new compulsorily operating point locked optical-deflection-probe is shown in Fig.1. He-Ne laser of 10 mW in power is used as a light source. A laser beam LA is passed through lens L1 and is focused on a scanning mirror SM for beam scanning. The scanning beam is collimated by a lens L2 and is focused to probe point by a lens L3. By the scanning the deflection angle of the beam is varied. The beam is passed through a probe point and is enlarged by a cylindrical lens CL of 30 mm focal length for enlarging beam displacement. The beam is enlarged by 6 times that of the original beam. The enlarged beam is detected through a slit S of 100 μm in width by a photodetector PD (phtotomultiplier). When the laser power is large and the detector has narrow dynamic range, this enlargement is effective to increase the detection sensitivity of the beam deflection. This system satisfies this condition. In other system that dose not satisfy the condition, the enlargement is not effective as shown by Putman A. J., Grooth, B. G., Hulst N. F. and Greve, J. (1992).

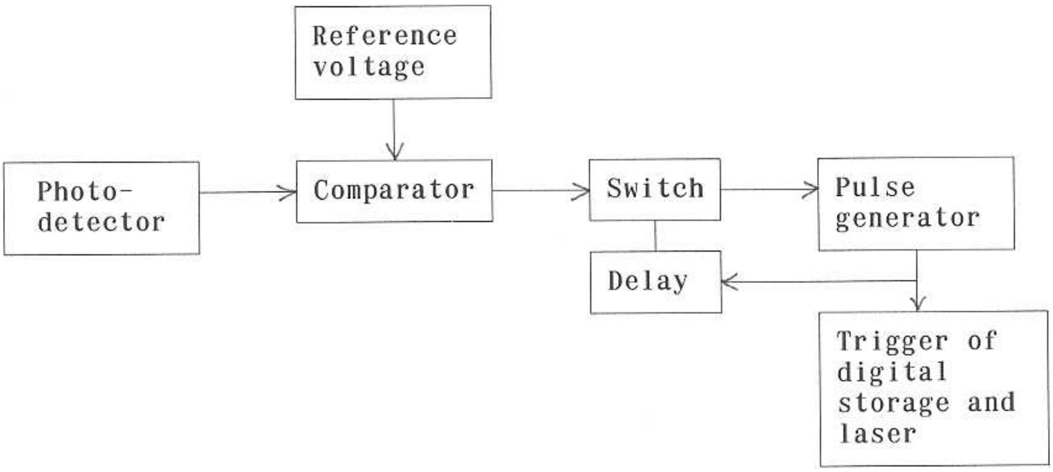


Fig.2 Block diagram of an electric system for compulsorily operating the optical-deflection-probe at zero-crossing-point of phase gradient curve.

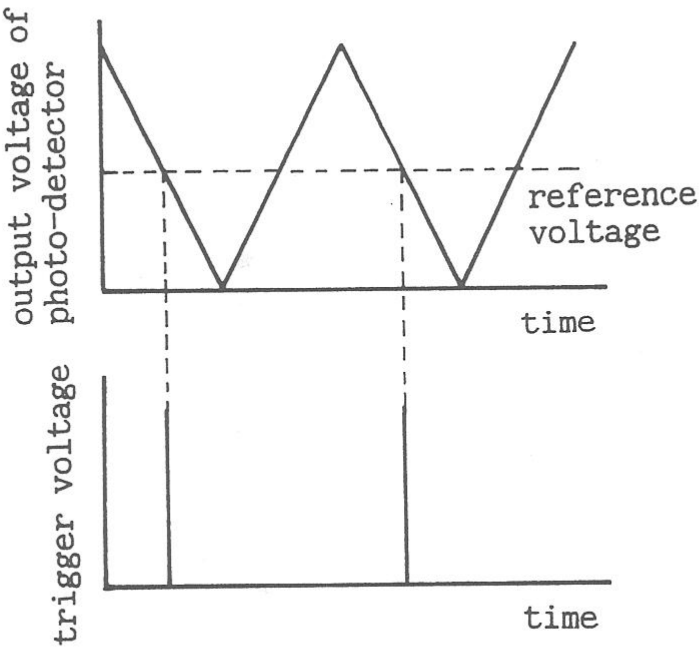


Fig. 3 Triggering data storage in the electric system.

The electric triggering system is constructed for compulsorily operating the system at zero-crossing point of deflection curve. The trigger pulse is used for triggering a pumping pulse laser and the data storage. The output of the photodetector is put into an electric triggering system and the data storage. The trigger pulse is used for triggering a pumping pulse laser and the data storage. The block diagram of the electric triggering system is shown in Fig. 2 and the relation between photodetector output and triggering pulse in Fig. 3. In the first step by a knob the switch is turned on and a comparator signal can be transmitted to a pulse generator. The output voltage V_P of the photodetector is compared with the reference voltage V_R set the voltage at the zero cross point of deflection intensity curve. When V_P crosses either over V_R or under, a pulse signal of the comparator is put out. The signal is passed through the switch and to a pulse generator. After putting out the pulse signal, the switch is turned off. By the pulse a pulse generators generates a pulse for triggering a digital storage and a pumping laser as shown in Fig. 3. In the second step the pulse from the pulse generator passes through a delay and put into the switch. The delay time is 1.5 s. By the pulse the switch is turned on and again the comparator signal can be transmitted to a pulse generator.

A TEA CO_2 pulse laser of 200 mJ in power and 50 ns in the pulse half width at half maximum is used as a pumping beam to produce photothermal puff. The beams energy is decreased to 0.5 mJ with Si plates for non-perturbing flow. The pulse laser beams are focused in the flow with a ZnSe lens of 50 mm in focal distance. The full width of the focused beam at half maximum is 0.05 mm.

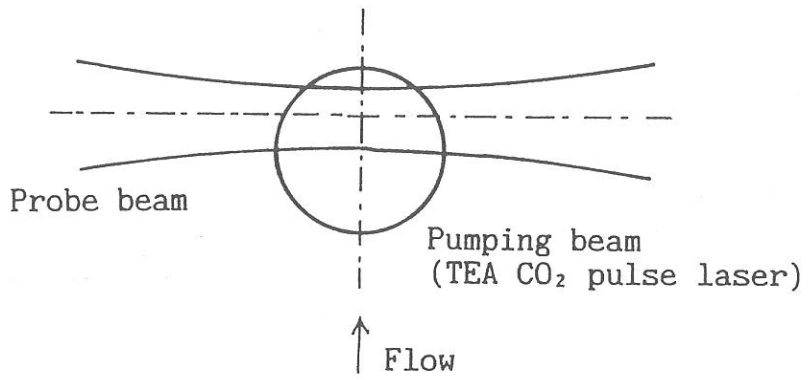


Fig. 4 Geometrical relation between a focused pump beam and a probe beam in partial crossed probing.

We used the probing method for reducing the influence of the diffusion, which is inherent problem in molecular velocimetry and for increasing the spatial resolution. The probe beam is set to partially cross the pumping spot (Fig. 4). When the puff of phase variation caused by photothermal effect passes through the probe point, the output signal of the photomultiplier is varied. The signal in the beam deflection method are compared with that in the conventional interferometer (Fig. 5). The time-of-flight method is used to measure velocity of photothermal puff for flow velocity measurement. The time interval between irradiation of pumping laser (t_0) and zero crossing (t_1) of deflection curve is used.

The influence of phase variation in one beam method of beam deflection method is smaller than that of two beam method of a differential interferometer in previous study [Nakatani (2002)]. However, the fluctuation of the phase gradient in turbulent flow causes

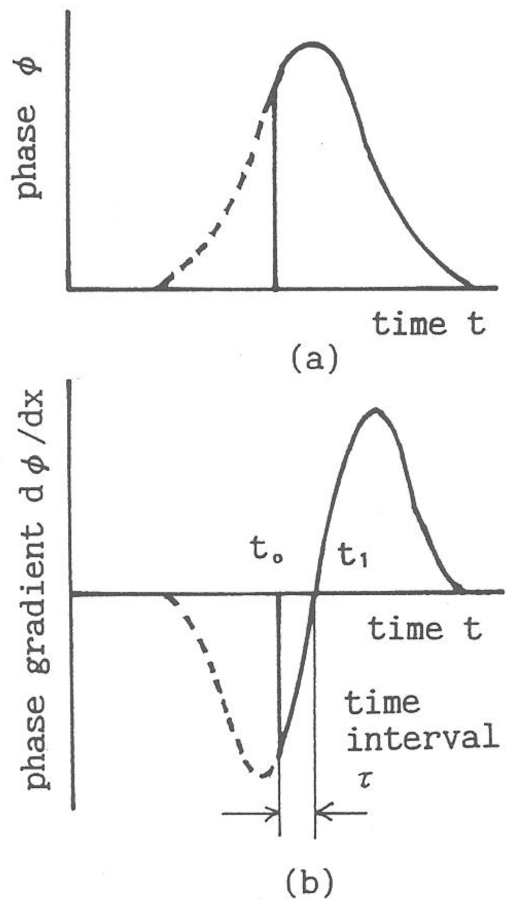


Fig. 5 Output of a photodetector. (a) Phase measurement. with interferometry. (b) Phase gradient measurement with beam deflection method.

the fluctuation of detected deflection signal. We measured the fluctuation of photodetector output and the power spectrum densities for comparing the time scale of the fluctuation with time scales of measurement signals in next section.

3. MEASUREMENT OF FLOW VELOCITY

Using a turbulent jet of a 9:1 in volume mixture of nitrogen and ethylene, we confirmed that this measurement system is useful to measure flow velocity. The optical system and the electric system respectively shown in Figs.1 and 2 was used in this experiment. A nozzle of 4.8 mm in diameter was used. Reynolds number was 3600. The pump beam was focused on the jet centerline 15 mm downstream from the exit of the nozzle. The central point of the probe beam was arranged 71 μm downstream from the central point of the focused pump beam. The phase variation arises from large scale air entrainment by the jet and turbulent mixing. A typical oscilloscope trace of the fluctuation of phase gradient put out from the photomultiplier was measured as shown in Fig. 6. The power spectrum densities of the outputs are shown in Fig. 7. Fig. 8 shows a typical oscilloscope traces of a photothermal signal in flow velocity measurement. As

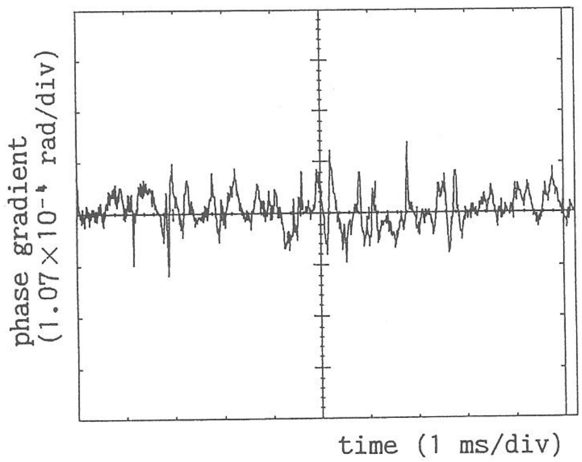


Fig. 6 Typical oscilloscope trace of fluctuation of phase gradient in turbulent flow. The Reynolds number 3600.

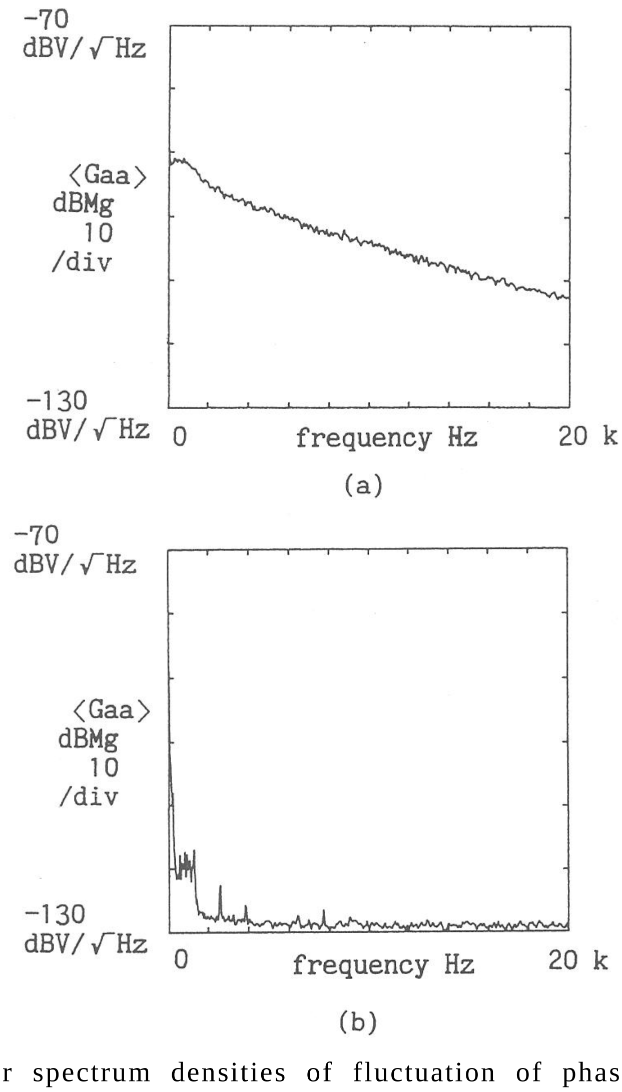
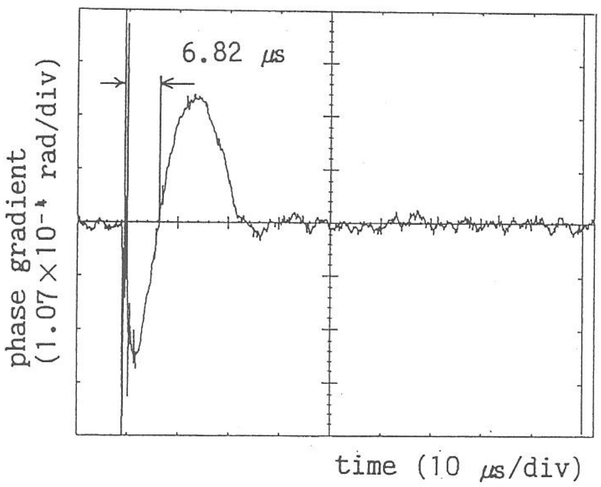
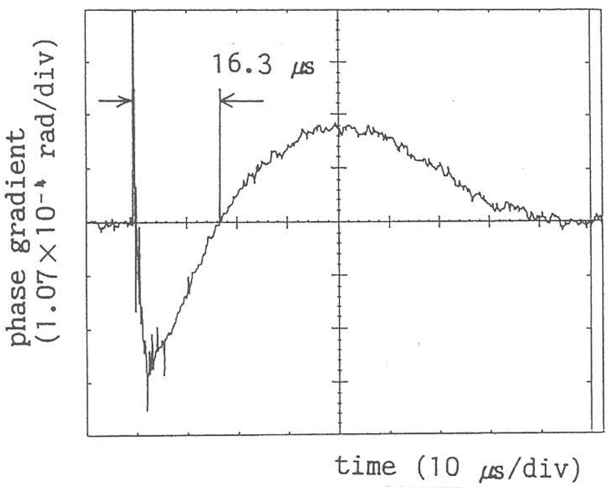


Fig. 7 Power spectrum densities of fluctuation of phase gradient. (a) In turbulent state. 0 dBV = 2.14×10^{-2} rad. (b) Laminar state.



(a)



(b)

Fig.8 Typical oscilloscope trace of photothermal signal for measurement of velocity. (a) In turbulent state. Reynolds number is 3600. (b) In laminar state.

the time scale of the measurement is about 50 μs, there is the small fluctuation of the phase gradient as shown at about 20 kHz in Fig. 7 (a). As the fluctuation is small, the measurement of the time interval is not almost influenced with the phase fluctuation as shown in the trace of Fig. 8 (a). The time intervals between pumping pulse and the zero crossing point of the signal are 6.82μs in turbulent state (a) and 16.3 μs in laminar state (b). From the time intervals and the distance between the central points of pumping beam and probe beam 71 μm, the flow velocities 10.4 m/s and 4.35 m/s are calculated. These experimental results show that the system is useful to measure the velocity in turbulent state.

ACKNOWLEDGMENT

The present research was performed under the supervision of President Shinjou Okuda of Ashiya Univesity.

REFERENCES

DeBarver, P. A., Ribarov, L. A., Wehrmeyer, J. A., Batliwala, F. and Pitz, R. W., (1998), Quantitative Unseeded Molecular Velocimetry Imaging, Proc. of the 9th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics, Institute Superior Tecnico, pp.34-1-1 - 32-1-6.

Durst, F., Melling, A. and Whitelaw, J. H, (1981), Principles and Practice of Laser Doppler Anemometry, Academic Press.

Miles, R. and Lempert, W., (1990), Two Dimensional Measurement of Density, Velocity and Temperature in Turbulent High Speed Air Flows by UV Rayleigh Scattering, Appl. Phys. vol. B51, pp.1 - 7.

Nakatani, N., Oshio, T., (1994), Measurements of Gas Flow Velocity and Temperature Using Laser Photothermal Effect with the Differential Interferometer, Proc. of the 7th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics, Institute Superior Tecnico, pp.32-5-1 - 32-5-8.

Nakatani, N., (2000), Measurements of the Velocity and Temperature in a Turbulent Flow by the Laser Photothermal Effect with the New Compulsorily Phase Locked Interferometer, Rev. of Sci. Instrum, Vol. 71, No. 5, pp.1971 -1974.

Nakatani, N., (2000), Laser Photothermal Velocimeter with the Differential Interferometer Using Orthogonally Polarized Light Source of Modulated LD, Proc. of the 10th Int. Symp. on Applications of Laser Techniques to Fluid Mechanics, Institute Superior Tecnico, pp.15-3-1 - 15-3-9.

Nakatani, N., (2002), Molecular Photothermal-Velocimeter of High Spatial Resolution by Partially Crossed Probing, Proc. of Int. Symp. on Applications of Laser Techniques to Fluid Mechanics, Institute Superior Tecnico, pp.30-1-1 - 30-1-9.

Nie, Y. X., Hane, K. and Gupta, R., (1986), Measurements of Very Low Gas Flow Velocities by Photothermal Deflection Spectroscopy, Appl. Opt. vol. 25, pp.3247 - 3252.

Putman, C. A. J., Grooth, B. G., Hulst, N. F. and Greve, J., (1992), A Detailed Analysis of the Optical Beam Deflection Technique for Use in Atomic Force Microscopy, J. Appl. Phys. 72, 1, pp.6 - 12.