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APPLICATION OF OPTICAL COHERENCE INTERFEROMETRY TO MEASURE THE SPATIAL PROFILE OF FLUID FLOW VELOCITY

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ABSTRACT

The spatial profile of fluid flow velocity in transparent glass conduits is measured using optical Doppler tomography (ODT). The flow velocity at any spatial location in the conduit is determined by measuring the Doppler shift of backscattered light from moving microspheres in the fluid. ODT is an accurate and inexpensive method for high resolution characterization of fluid flow velocity profile.

1. INTRODUCTION

Measurement of fluid flow velocity on the micro- and macroscopic levels is valuable in both science and industry. Multi-gated ultrasound imaging[1] and laser Doppler velocimetry are among the most often used techniques. Although multi-gated ultrasound imaging can be used to resolve flow velocities at different locations within conduits, the mean Doppler frequency is easily altered by many factors and difficult to interpret.[2] In laser Doppler velocimetry, use of a highly coherent light source requires a specialized geometry (e.g., two light beams) or an invasive procedure to achieve useful spatial resolution.

Optical Doppler tomography is a non-invasive technique that allows high spatial resolution (10 μm axial and 5 μm radial) determination of fluid flow velocity at discrete user-specified locations within the conduit. The method employs optical low coherence interferometry in combination with the Doppler effect.[3] In our experiments, fluid flow velocity measurements are made in both circular and square glass conduits infused with a moving suspension of polymer microspheres in doubly de-ionized water. Measured velocity profiles within conduits compare well with calculated results.

2. METHODOLOGY

Continuous near infrared light (λ_o=850 nm) emitted by a super-luminescent diode (SLD) is coupled into a fiber optic Michelson interferometer and split into two beams by a 2x2 fiber coupler (Figure 1). SLD power in the input fiber of the interferometer is set at 1 mW. Optical power in the reference arm of the interferometer is attenuated to 2 μW to reduce intensity fluctuations and thus achieve higher signal to noise ratios (SNR).[4,5] Light from a He-Ne laser

(λ_o=632.8 nm) is coupled into the interferometer using a 2x1 fiber coupler and serves as an aiming beam for the fluid probe. Optical phase of SLD light in both probe and reference arms of the interferometer is modulated (1000 Hz) by stretching the optical fiber wrapped around piezoelectric cylinders expanded by a serrodyne (i.e., ramp) wave form. Stress-birefringence is used to match the polarization of probe and reference beams and thus optimize fringe contrast.

A test suspension consisting of polymer microspheres (diameter, 2.062 ± 0.025 μm) in doubly de-ionized water ($c = 3.4 \times 10^7$ cm^{-3}) is infused through a conduit at constant velocity by a linear syringe pump. A microlens terminating the fluid probe focuses light (NA = 0.22) within the conduit to give a 5 μm diameter spot size. Light backscattered and Doppler shifted from moving microspheres in the fluid recombines with that reflected from the reference mirror in the 2x2 fiber coupler. The two beams interfere and give fringes only when their optical path length difference is less than or equal to the coherence length ($\lambda^2/\Delta\lambda \sim$ 16 μm) of SLD source light. Since the coherence envelope of SLD source light yields rapid phase decorrelation of the beams for path length differences greater than the coherence length, high spatial resolution is achieved. Backscattered and Doppler shifted light at a user-specified location can be detected by scanning either the reference mirror of the interferometer or translating the fluid probe. A photovoltaic detector (New Focus 2001) in combination with a spectrum analyzer (HP 8560E) is used to measure the power spectra of optical interference fringe intensity.

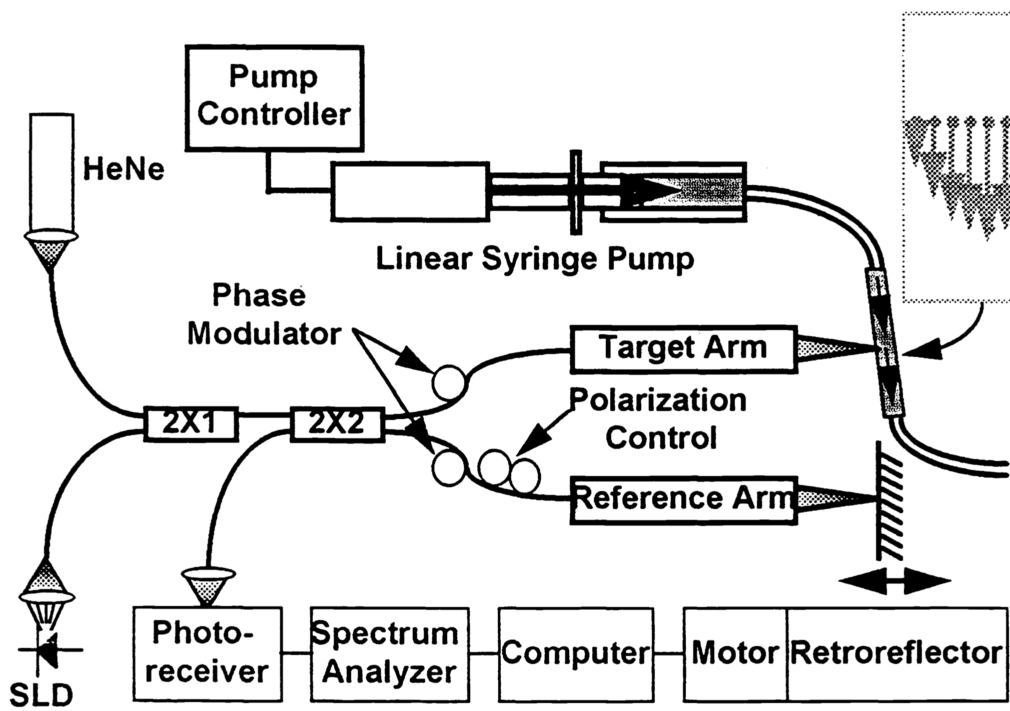

Figure 1. Schematic of ODT instrumentation.

Because flow is laminar (Reynolds number ~ 1) and one-dimensional in our experiments, a solitary fluid probe is sufficient to investigate flow velocity at user-specified locations within the conduit. To detect Doppler shifted signals, orientation of the fluid probe relative to the conduit is fixed to give a non-zero component of flow velocity parallel to the incoming light propagation vector. In this arrangement, a simple geometrical relationship exists between scanning depth (x), reference mirror position (R), and orientation of the fiber probe (φ'),

$$x = \frac{R\cos(\varphi')}{n} \qquad (1)$$

where φ' represents the angle between flow velocity and the optical axis of incoming light inside the conduit, n is the solvent (i.e., H_2O) refractive index. We assume $R=0$ corresponds to a zero path length difference when the beam waist in the fluid probe is positioned at the inner wall of the conduit. Determination of fluid flow velocity profile, $V(x)$, is derived from local measurement of the Doppler shift [$\Delta f(x)$] over a linear grid perpendicular to the flow,

$$V(x) = \frac{\Delta f(x)\lambda_0}{2\cos(\varphi)} \qquad (2)$$

where φ is the angle between flow velocity and the optical axis of incoming light outside the conduit.

3. RESULTS AND ANALYSIS

Optical low coherence interferometry is often used to study static structures, such as biological tissues.[6-8] By scanning the reference or probe arm across an empty glass conduit with square cross section, optical reflections from each surface in the conduit are detected (Figure 2). Since the coherent detection volume is small (5x5x10 μm^3), high spatial resolution is achieved. Four major peaks correspond to reflections from glass-air interfaces of the conduit. If the conduit contains flowing fluid consisting of polymer microspheres, velocity of the microspheres can be obtained by measuring Doppler power spectra.

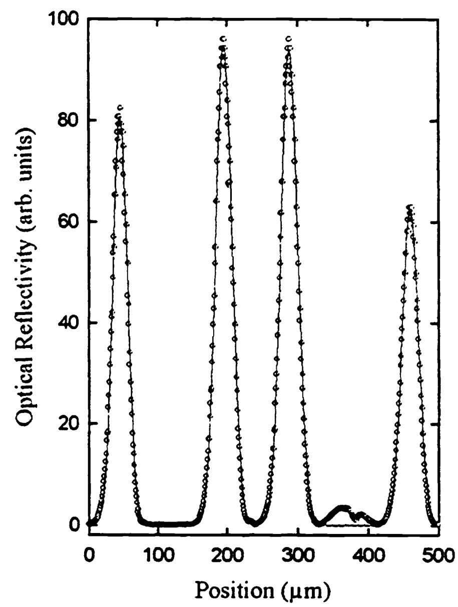

Figure 2. Reflections from the interfaces of the glass conduit with square cross section (from left to right, air-glass, glass-air, air-glass, glass-air).

Figure 3 shows recorded interference fringe intensity as a single microsphere moves through the coherent detection volume. Microsphere concentration is very dilute (average spacing is ~ 30 μm)

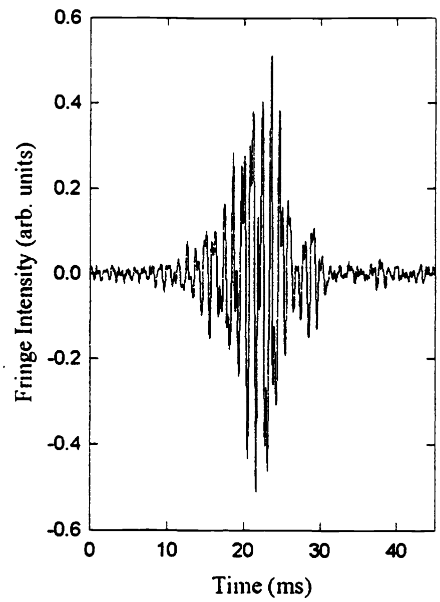

Figure 3. Optical interference fringe intensity from a moving microsphere.

so that single scattering events are detected. Suspensions with low microsphere concentrations allow the light beam to penetrate deep within the conduit without multiple scattering. Figure 4 gives Doppler power spectra (circles) at different positions along a diameter (inner diameter, $d = 400$ µm) of a circular conduit. The solid lines represent best fit to a Lorentzian function; vertical lines show the reference phase modulation frequency (1000 Hz). Maximum velocity is found on the central axis of the conduit. The velocity decreases at positions near the wall.

To deduce fluid flow velocity profile, Doppler shift (Δf) was measured over a linear grid of points lying along a diameter of the circular conduit (Figure 5). The solid line represents a least squares fit based on solving the Navier-Stokes equation for laminar fluid flow.[9] Fluid flow velocity uncertainty ($\Delta V/V \approx 7\%$) was primarily due to measurement error in Doppler shift (Δf) and incident angle (φ) and was consistent with that computed from the mean variance between measured and fitted velocities.

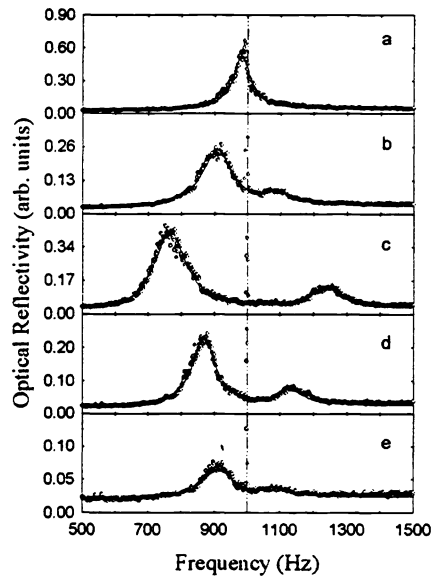

Figure 4. Power spectra at five sequential positions along a linear grid coincident with a diameter in circular conduit (a: 6 µm, 17 Hz; b: 37 µm, 92 Hz; c: 183 µm, 222 Hz; d: 330 µm, 131 Hz; e: 367 µm, 87 Hz). Band resolution of spectrum analyzer is 3 Hz.

Figure 6 shows the flow velocity profile (circles) measured across a central axis perpendicular to the walls of a glass conduit with square cross section. The probed position in the conduit is computed from Eq. 1. Theoretical fit to the collected data is computed based on a Fourier series solution of the Navier-Stokes equation (solid line).[10] Average flow velocity over the central axis calculated from our experiments is

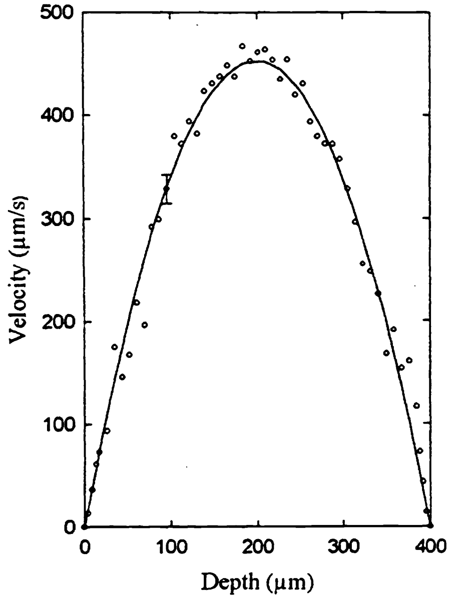

Figure 5. Experimental (circles) and theoretical (solid line) fluid flow velocity profiles in a circular glass conduit. Band resolution of spectrum analyzer is 10 Hz.

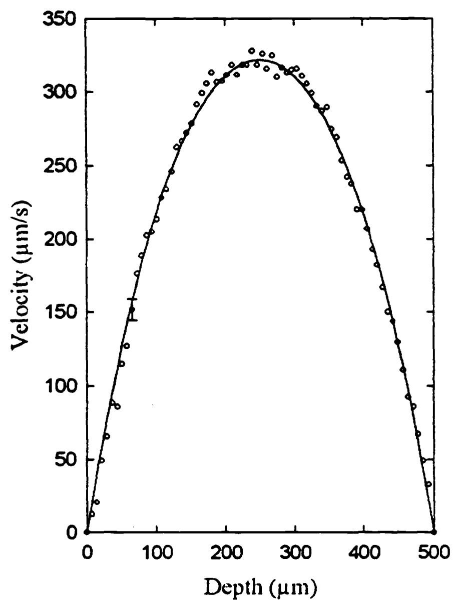

Figure 6. Experimental (circles) and theoretical (solid line) fluid flow velocity profiles in a square conduit. Band resolution of spectrum analyzer is 10 Hz.

217 μm/s and in good agreement with that computed (212 μm/s) from the pump flow rate (3.7×10^{-2} cm^3/s).

4. CONCLUSIONS

We have found that ODT is a simple and useful technique for high resolution measurement of fluid flow velocity profiles within conduits. Although flow is laminar in our experiments, when the direction is unknown (i.e., turbulence) and fluid velocity may be two- or three-dimensional, multiple probes may be used. Specifically, such a provision for three (two) probes allows measurement of three (two) dimensional velocity flows. If the optical axes of the probes are independent, flows of arbitrary direction can be characterized.

The broad Doppler peaks (Figure 4) at lower frequencies (greater intensity) are consistent with the flow direction. However, symmetrical peaks with respect to reference frequency (1000 Hz) at higher frequencies are simultaneously detected. Experiments are underway to clarify this effect. The frequency line shape is also under investigation

When the optical properties of the test suspension and/or conduit can be controlled, a relationship may exist between the size and refractive index of the microspheres and their concentration for optimum SNR. When the size of the microsphere is small, in comparison to the optical wavelength, backscattered light intensity generally increases. Thus, in some applications, reducing the size of the microspheres may improve SNR. The refractive indices of the solvent (n) and spheres (n') also affect data readings. When n'/n is near unity, signal is reduced.

When the ratio is high, however, backscattered light intensity significantly increases. The microsphere concentration can also be varied. A low concentration reduces backscattered light; a high concentration may cause multiple scatter and complicate signal analysis.

ODT has many potential scientific (e.g., medical) and industrial (e.g., mass transfer) applications, and provides a simple, effective and easily adapted technique for assessment of fluid or dry particle flow velocity within conduits. The technique is noncontact and noninvasive, so that flow can be characterized without disturbing the stream.

5. ACKNOWLEDGMENTS

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