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Flowing thermal lens micro-flow velocimeter

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Abstract

A novel micro-flow velocimeter, the flowing thermal lens micro-flow velocimeter (FTL-MFV) is developed in which a photothermally generated local refractive index change (a thermal lens) is utilized as a micro-tracer of flow. Flow velocity is measured from the time required for the thermal lens to travel between two points. Generation and detection of thermal lenses are carried out optically without contacting the flow. By choosing the wavelength of the excitation beam pulse so that it coincides with the absorption band of the solvent used, thermal lenses can be generated without adding anything to the liquid. Synchronous detection using a lock-in amplifier makes detection of thermal lens with a very small temperature rise possible. Thus, with the FTL-MFV, non-contact in situ measurement of flow can be carried out with only slight disturbance to the microfluid. In order to make the sensor small, optical fibers and SELFOC™ microlenses are used in focusing the excitation and probe beams. A dynamic range of 25–300 μL/min is realized in measurement of flow rates in a microchannel.

Keywords: Flow velocimeter; IR absorption of water; Microlens; Noninvasive sensing; Optical fibe; Thermal lens effect

1. Introduction

Miniaturized analysis systems have been actively investigated in the past decade from viewpoints of reduced amounts of sample and generated waste, simplified operation, shortened analysis time, etc., and microchemistry has become an important branch of analytical chemistry [1,2].

In microanalysis systems, microchannels or microwells fabricated in microchemical chips are used as reaction vessels, in place of conventional apparatuses such as beakers, flasks or test tubes. As targets to be measured are so small, highly sensitive detection methods for measuring concentrations of chemical species or physical parameters, such as temperature, pressure and flow rate, become key technologies for realization of such microchemical systems. In addition, detectors for these systems must be small to ensure the whole system remains small.

Laser-induced fluorescence (LIF) which has extremely high sensitivity is one of the most widely used detection methods in microchemical analysis for determination of concentrations [3]. However, the LIF method is applicable only to fluorescent analytes.

Our research group has developed thermal lens microscopy (TLM), a sort of photothermal spectroscopy done under an objective lens of a microscope, as a highly sensitive detection method with wider applicability than LIF [4,5]. Excitation and probe beams for TLM are coaxially aligned and introduced to the objective lens. Absorption of the excitation beam produces a temperature gradient around the focus of the beam. Since the refractive index is dependent on temperature, the temperature gradient acts as a lens. The degree of the lens effect, which is proportional to the concentration of chemical species absorbing the excitation beam, is measured as a change in locus of

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the probe beam. The photothermal effect is based on photo absorption and subsequent heat release, and thus it can be applied to almost all target compounds by simply selecting a suitable excitation beam wavelength [4,6]. The photothermal signal from a very limited volume (typically a few tens of cubic micrometers) can be obtained with TLM measurements, and its sensitivity is high (typically two to three orders higher than that of conventional absorption spectrometers). Gradient index (GRIN) microlenses and fiber optics are very effective in development of small sensors suitable for microchemical systems. Recently we have succeeded in miniaturization of a TLM detector by using optical fibers and a specially designed SELFOC^{TM} microlens, a sort of GRIN lens [4,5]. Small TLM detectors using microlenses and optical fibers are suitable for microchemical chips, and integration of various assay systems onto small glass chips became possible by using TLM [7].

Photothermal spectroscopy can be used not only in determination of an analyte concentration, but also in determination of physical properties such as flow velocity [6]. Weimer and Dovichi [8,9] observed flow rate dependence of photothermal signal shapes in a crossed beam configuration and proposed that it could be used in monitoring flow velocity. Sontag and Tam [10] produced a thermal lens by a pulsed excitation beam and detected it downstream with another beam. The thermal lens acted as a tracer of flow and flow velocity could be obtained from the thermal lens deflection signal. Gupta's group thoroughly investigated photothermal spectroscopy in flowing media and obtained valuable information on this subject both theoretically and experimentally [11–14]. Bornhop and co-workers have developed a backscattering interferometer for determining refractive index change in a capillary tube or in a microchemical chip [15,16] and used the interferometer for measurement of flow velocity inside a microchannel [17]. Advantages of such flow velocity measurement methods using photothermal effects are their sensitivity and noninvasive nature, both of which are critically important in measuring microfluids. Whereas there are many flow-measurement methods on a normal scale [18], most of them are hard to implement in microchannels.

Most conventional large sensors are unsuitable for measurement of microfluids because of inadequate sensitivity or because they disturb the microfluids. The working principle of vortex flow meters does not hold in microchannels with small dimensions. Pitot tubes may also not function well in measuring flow inside microchannels. Fabricating some other mechanical structures for monitoring flow rates in a microchannel might be possible, but they may significantly disturb the micro-flow and the measurement points are limited to where these probes have been fabricated. In addition, those devices are in direct contact with the microfluids, and their chemical inertness has to be considered. Finally, any installed micro-devices have to be discarded with the microchemical chip.

Because the pressure drop is relatively large with a small hydraulic diameter, differential pressure flow velocimeters can be fabricated without making an obstruction like an orifice in a microchannel. Thus, various differential pressure micro-flow velocimeters have been designed using micro-pressure sensors [19]. However, pressure sensors also have to be in contact with the fluids, and disturbance to the flow, limited detection points and chemical resistance of the sensors are still serious problems for this type of flow velocimeters.

Some micro-thermal flow velocimeters, which are comprised of heater elements and temperature sensors attached to microchannels and which detect changes in temperature distribution caused by flow, have had some success in measurement of microfluids without causing a large disturbance [19]. However, the problem of limited detection points still remains for this type of sensor. Usually thermal flow velocimeters measure flow rate inside capillary tubes connected to a microchemical chip, and direct measurement of flow rates at arbitrary points of a microchannel is not possible with them. Since micro-flow velocimeters are commonly used to check for possible clogging somewhere in a microchannel network and for leakage at connections between the microchemical chip and tubes, a flow velocimeter with an ability to monitor at an arbitrary point in the microchannel network is much more preferable.

There are other types of micro-flow measurement methods like micro-particle imaging velocimetry and laser Doppler velocimetry in which some tracers are dispersed in the fluid and flow rates are obtained from their motion [19,20]. These optical measurement methods can be applied to the microchemical chip made from a transparent material such as glass and the detection point is not limited to a certain fixed point. A problem, though, is that tracer particles must be introduced into the solution for the flow measurement and they can be a disturbance to chemical reactions in the microchannel.

Flow velocity measurement methods using photothermal effects are free from the above-mentioned problems, and sensitive and noninvasive measurements of microfluids at arbitrary points become possible with them. However, all the reported flow velocimeters using photothermal effects required relatively long optical path lengths (typically several tens of centimeters or a few meters) and are large compared to the size of the microchemical chips.

In this work we applied our thermal lens microscopy technologies to realize a small and noninvasive micro-flow velocimeter which we have named the "flowing thermal lens micro-flow velocimeter (FTL-MFV)". Flow rate in a microchannel is a crucially important parameter for fluid control in microchemical systems, and development of a novel flow sensor that can measure microfluids without disturbing the flow is desired. Our FTL-MFV is a non-contact optical sensor that can be applied to an arbitrary point in the microfluid. It does not require tracer addition to the fluid and it can measure flow rate without significant disturbance to the microfluid. Therefore the FTL-MFV offers a possible solution for the disturbance problem.

2. Principle

The principle of the FTL-MFV is as follows.

An excitation laser beam pulse is focused on a liquid flow inside a microchannel, and a thermal lens is formed. The thermal lens moves downstream and reaches a detection point, where