Thermophoretic Particle Separation

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Abstract

We present a study of thermophoretic particle separation on micro scale. Thermophoresis is the migration of particles or species in thermal gradients. A thermal gradient of $2 \cdot 10^4$ K/m is set up in the microchannel. Laser Induced Fluorescence is used to determine the thermal gradient, by use of temperature sensitive Rhodamine dye. Micro Particle Image Velocimetry is used to determine the position and displacement of the particles. A measurement of the temperature from the Brownian motion of the 490 nm particles has been made with an accuracy of 1 K.

In this paper we will show polystyrene particle separation in micro channels. Separation of particles can be achieved in 100 seconds with an efficiency of 83%.

1. Introduction

Integration and miniaturization are major focus points in today's research and development. In microfluidics much attention is directed to mixing, as one cannot rely on turbulence to mix at these scales. However, in a lab-on-a-chip we could use a element that increases the concentration of DNA near a sensor or in a factory-on-a-chip, we would like to separate products from waste at the end of a process. This separator has to be energy efficient and avoid large electric fields. Thermophoresis (Wiegand 2004) can be used to increase concentrations or separate particles from fluids. Thermophoresis is the phenomena of particles migrating due to a thermal gradient. It was discovered over 150 years ago by Ludwig and Soret and is understood in gases by the Chapman-Enskog theory (de Groot 1951). For liquids however there are several models being considered to predict the magnitude and even the sign of the Soret coefficient, which is the ratio of the diffusion coefficient and the thermal diffusion coefficient, and determines the magnitude of separation.

Thermophoresis has advantages when applied in a microfluidic device. Setting up a large thermal gradient on micro scale requires low power. For biological applications thermal boundary conditions can be strict, in this setup a large gradient can be made within those boundary conditions.

Thermophoresis has advantageous scaling effects; the smaller the particles and device are, the stronger the effect becomes. It can even be used to separate miscible fluids such as water-ethanol mixtures.

2. Laser Induced Fluorescence Temperature Measurement.

A micro machined micro channel has been etched in silicon, the width of the channel is 70 μm and the depth 20 μm. The side walls are sloped due to the preferred crystalline plane of the etching process. The two sides of the channel are separated by an etch from the bottom side of the wafer and one side is heated by an aluminium heater, see figure 1.
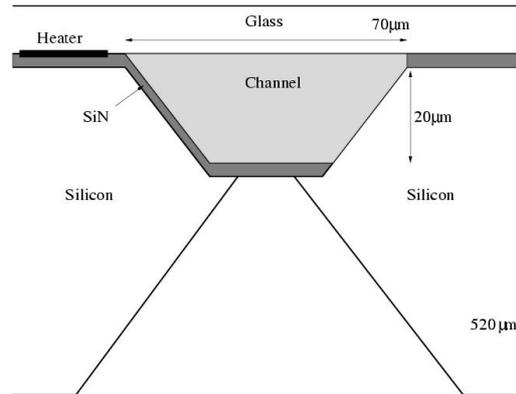
Figure 1: Schematic representation of a cross-section of the microchannel

1 Watt of electrical power is provided for the 40 mm long channel. The device is placed on a inverted epi-fluorescent microscope. It can be illuminated by a laser or a mercury lamp. The images are recorded using a CCD camera. The thermal gradient is measured using the temperature dependent fluorescence of Rhodamine (Walker 1987). The intensity of Rhodamine fluorescence decreases with 0.0187 1/K and thus if we record the intensity distribution of the fluorescent light in the channel we find a temperature difference with respect to the reference. Before switching on the heater we take a series of 10 images to establish the reference intensity distribution. The reference is required to correct for any reflections or concentration variations that exist in the channel. There are two further sources of error in this measurement technique especially for this experiment. The first is bleaching of the dye; when the illuminating intensity is too high the dye will be damaged and loose its fluorescent properties. This effect is integrated over time so continuous illumination, although favorable for its constant intensity, is not usable for temperature measurement. A pulsed laser is used to reduce the bleaching effect. The intensity decay for the lamp and the laser are plotted in figure 1. The fluorescence intensity are equal. Clearly the lamp illuminated dye looses its fluorescence much faster than the laser illuminated dye. The variations in laser intensity can be seen in the graph. Both profiles have been normalised on the intensity of the first image, this explains why the intensity of the laser illuminated dye levels off at 99%. The first pulse of the laser after switching it on is always more powerful than the following pulse. The variation in laser intensity makes it impossible to obtain a reliable estimate for the absolute temperature but since we are interested in the gradient we can correct for the variation.
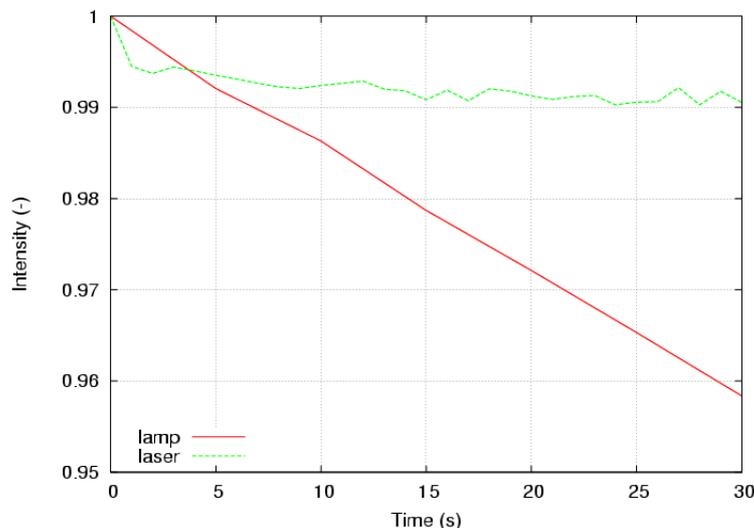

Figure 2: Fluorescent intensity decay over time for continuous lamp illumination and pulsed laser illumination.

The second source of error is the thermophoresis of the dye itself. Under the thermal gradient the dye will migrate towards the colder region. This will increase the concentration there and the fluorescent intensity will increase giving a bias towards colder temperatures. Fortunately the thermophoresis is slow compared to the temperature gradient set-up. We therefor neglect the thermophoresis of the dye although it requires further investigation. A two-dye approach was not attempted since the experimental set-up does not support two cameras or two di-chroic filters.

The temperature gradient in the channel was found to be 2.5K over 70μm, as figure 3 shows. The anomalies at the edges are attributed to the sloped sidewalls of the channel.
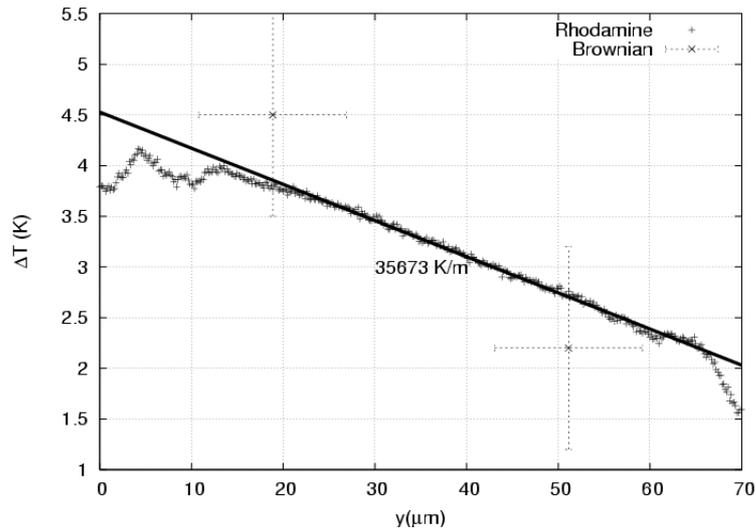

Figure 3: Temperature distribution across the channel measured with Rhodamine dye and Brownian motion

3. Brownian Motion Temperature Measurement.

Brownian motion provides us with the means to measure the temperature of the fluid (Hohreiter et al 2002). The random motion of particles caused by the collisions with water molecules was described by Einstein (Einstein 1905) and we will use this to extract the temperature from the variance of the particle position measured with micro particle tracking. To obtain a reliable estimate for the variance we need to have sufficient realisations, typically of the order of 10^4. The Einstein expression for the diffusion coefficient can be rewritten so that all the temperature dependent variables are on the left hand side, and all the measured variables on the right: the particle diameter d_p, the time delay Δt, the Bolzmann constant k_B and the measured variance σ^2.

$$\frac{T}{\eta(T)} = \frac{3\pi d_p \sigma^2}{2 k_B \Delta t}$$

It is important that we consider the viscosity η as a function of temperature T. For water it decreases with 3%/K at room temperature, therefor the left hand side of the equation increases more due to the viscosity decrease than the absolute temperature increase. With the known viscosity of water this gives us a more accurate estimate for the temperature.

As particle tracking can yield false displacements due to mismatching image pairs we do not calculate the variance directly. Since Brownian motion is Gaussian distributed we use this a priori knowledge to improve the estimate. First the particles are tracked and the displacements are converted in a histogram. A Gaussian is fitted to the histogram and the variance is determined. The histogram in figure 4 is made from 18000 particle images, particles are 490nm polystyrene and Δt=0.05s. The variance of the displacement σ^2=0.083μm^2. Taking into account the viscosity of the fluid the temperature of the liquid surrounding the particles would then be 291K. The actual measured

temperature of the fluid was 293K. This bias can be attributed to the size of the particles which is given by the manufacturer with an uncertainty of 1%. Splitting up the isothermal data set in two and performing the operation again results in 1% deviation of the measured variance which translates into 0.5K. We therefor say that we can measure thermal gradients with an accuracy of 1K. A measurement at 318K with the same particles gave a Brownian temperature of 316.5K.
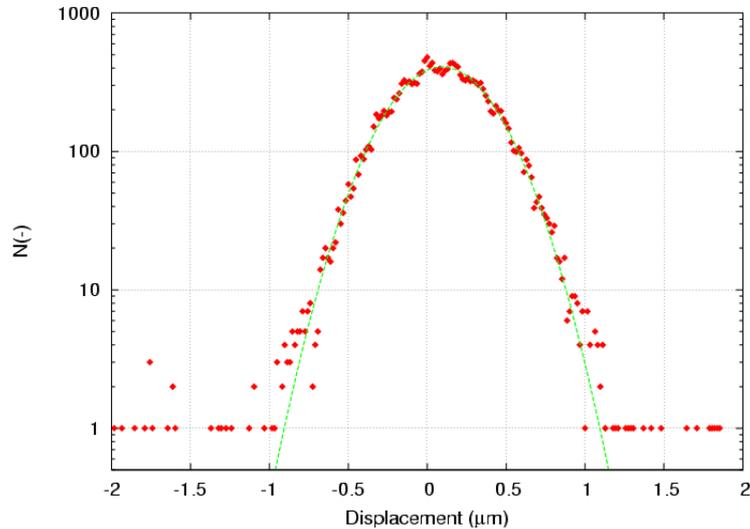

Figure 4: Displacement histogram of particles in Brownian motion

When measuring in the channel during the thermophoretic separation process the Brownian temperatures on the cold and hot sides measured 297 and 299 K. This is close to the temperatures measured by the Rhodamine dye, as shown in figure 2.
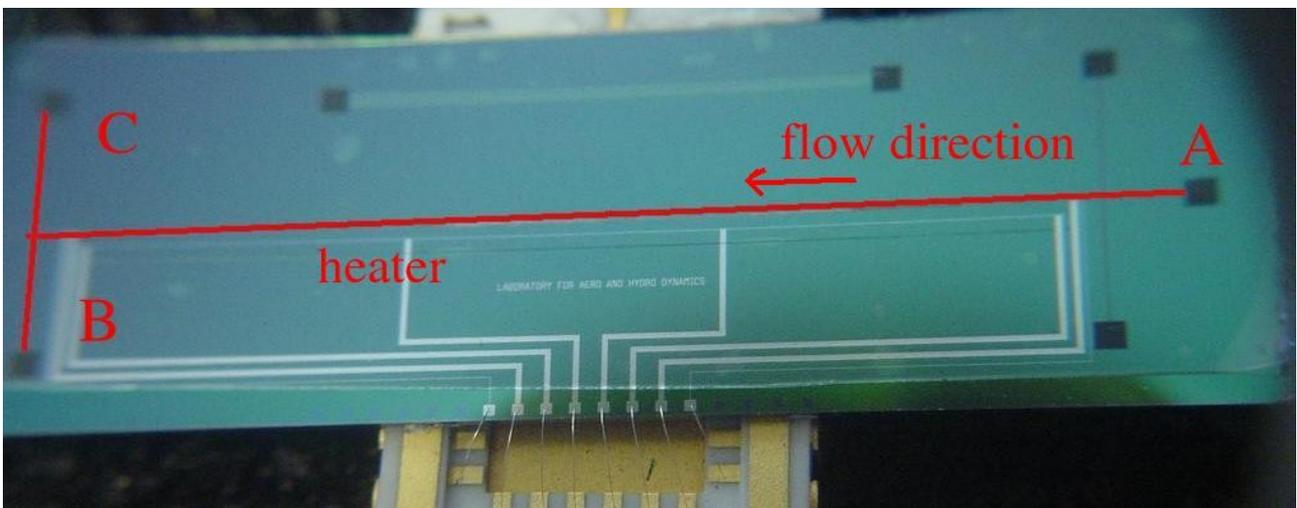

Figure 5: Photograph of the microchannel. Fluid enters at port A, flows along the separator and splits to port B and C.

4. Thermophoresis

The flow is split at the end of the separator to exits B and C, see figure 5. We use micro Particle
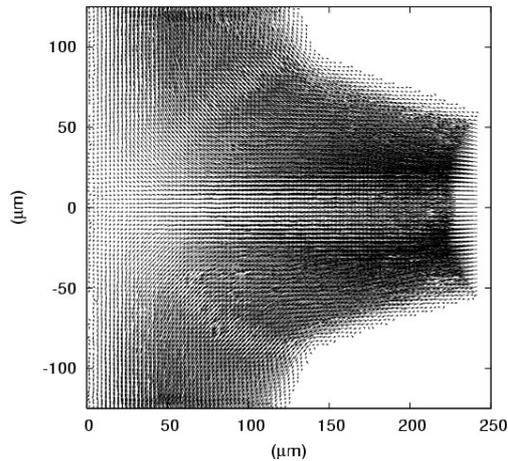

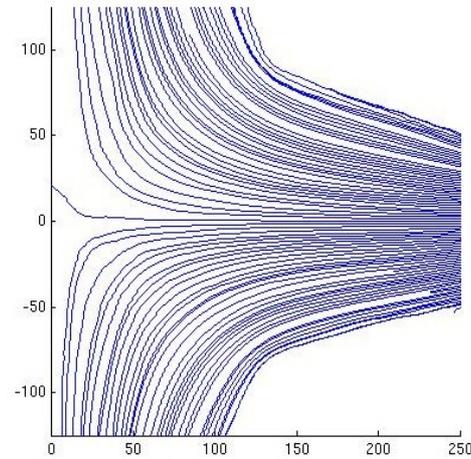*Figure 6: Particle Image Velocimetry measurement of the flow at the junction.*

Figure 7: Streamlines of the flow at the junction.

Image Velocimetry to determine the flow rates through both exits and the position of the stagnation point. The channel is widening slightly before the actual junction, this is caused by the etching process. The PIV results in figure 6 and 7 show that the stagnation point is in the center of the junction and the flow splits equally to both exits. The particles are migrating due to the thermal gradient and the profile of the particle concentration is plotted in figure 8 for different times. The stationary solution of the transport equation (de Groot 1951) incorporating thermophoresis is a exponential distribution in temperature T:

$$c = c_0 \exp[-S_T(T - T_0)]$$

Where c is the weight fraction concentration and S_T the Soret coefficient which is defined as the ratio of the thermal diffusion coefficient and the normal diffusion coefficient. The experiment matches the solution for $S_T = 1.3$ 1/K which compares well to literature values for Polystyrene in water (Schimpf and Semenov 2005). Particles have migrated to the cold side of the channel and locally the concentration is 5 times higher than the initial concentration. 83% Of the particles are in the cold half. Actual measurements of the particles separating to exit C have not yet been performed.
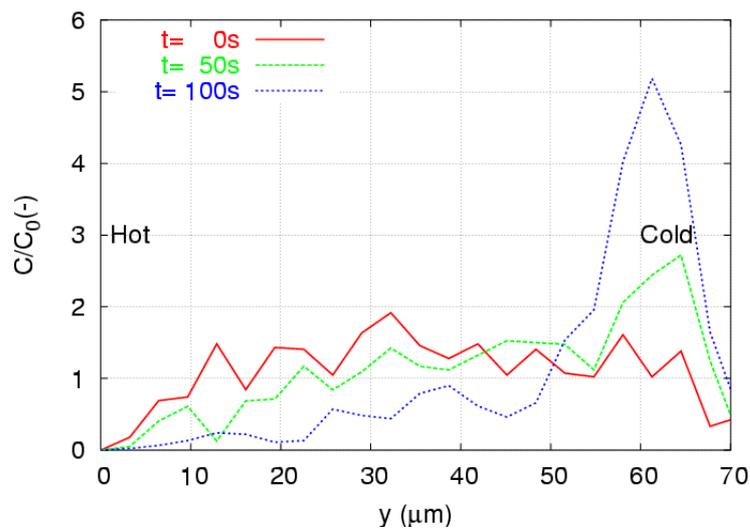

Figure 8: Particle concentrations at different times, normalised with the global concentration.

5.Conclusions and Outlook

Micro Laser Induced Fluorescence has been presented to measure temperature with high resolution, as well as measurement of fluid temperature based on the Brownian motion of particles.

Thermophoresis has been shown to work in micro channels, increasing concentration of 490nm particles five fold due to a small temperature difference. It may be used to increase DNA concentrations near sensors or to separate sub-micron particles without the need for high voltages on chip. The micro thermophoretic chip can be used as a laboratory for investigating thermophoresis. It could be used to test the validity of two explanations for particle thermophoresis in liquids; thermal expansion of the liquid (Bielenberg and Brenner 2005) and surface energy (Sememov 2003).

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