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Quantitative measurement of gas pressure drop along T-shaped micro channels by interferometry

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Abstract. The study of gas flows in microchannels has received considerably more attention in the literature from a simulation perspective than an experimental. The majority of the experimental work has emphasis on the global measurements at the inlet or exit of the microchannel instead locally along it. In this paper some efforts were made to measure the pressure drop along T-shaped micro channel by using interferometry. The two side channels were served as gas entrances and they were both open to air and the channel outlet was being vacuumed during experiments. A Mach-Zehnder interference microscopy was built for the measurement of gas pressure drop along the mixing channel. Some points along the mixing channel were selected for interferometric measurements. Simulations were first developed in unsteady condition by using Ansys Fluent to verify the nonexistence of transient phenomena of gas flow in the defined condition and then run again in steady condition to get the theoretical pressure drop that was would be used for comparison with experimental results.

1. Introduction

The experimental study on gas flow in microchannels was started 100 years ago, but the indirect measurement such as the pressure or temperature measurement near channel inlets and outlets still remains the most popular methods. The flow visualization in micro scale develops mainly in liquid phase microchannel flows rather than in gas phase [1], for example, the particle-based techniques PIV and LDV well developed in liquid flow has limitation in gaseous flow measurement because of the challenges associated with seeding and particle inertia [1, 2]. Molecular tagging approaches have advantages for velocimetry in gas-phase as it uses molecular tracers instead of particles. The flowing medium is premixed with molecule-seeds that can be turned into long-lifetime tracers upon excitation by photons of an appropriate wavelength [2]. But Molecular tagging methods involving seeding are often undesirable. The molecular seed can be toxic or environmentally hazardous, and it is often difficult to distribute the seeding throughout the flow [3]. So except the flow visualization techniques mentioned above, some totally non-intrusive techniques such as interferometry [4] have still been being developed in microfluidics. Based on some previous work [4, 5], this paper will study gas flow by using micro interferometry.

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Interferometry can be applied to the measurement or visualization of changes in physical properties of transparent objects and such properties include mass density of fluids, electron density of plasma, temperature of fluids, and chemical species concentration in reacting gases and state of stress in solids [6]. The change of the refractive index is due to the change in density of the medium if it is homogeneous. For gases, the phase information is related to many physical properties, for example, temperature, pressure or density. In this paper, the local pressure measurement along microchannels by interferometry will be studied.

2. Experimental

2.1 Principles

If the microchannel together with gases is treated as a phase object and the probing optical rays are assumed to be straight lines. The optical path length difference $\Delta\Phi\,(x, y)$ of a ray traveling in z direction (the direction of depth) through a phase object is given by: [6]

$$\Delta\Phi\,(x,y) = \int [n(x,y,z) - n_0]\, dz \tag{1}$$

n_0 is the refractive index of phase object of the initial holographic exposure, n(x,y,z) is the refractive index distribution at the time of the second exposure.

The phase change $\Delta\delta$ is related to the optical length change by:

$$\Delta\delta = \frac{2\pi}{\lambda}\,\Delta\Phi \tag{2}$$

The equation (1) and (2) show that for one phase change measurement, two refractive index, n_0 and n(x,y,z), are necessary to be determined experimentally, the former is for the reference condition, and the latter is for the real gas flow condition.

2.2 Interferometry setup

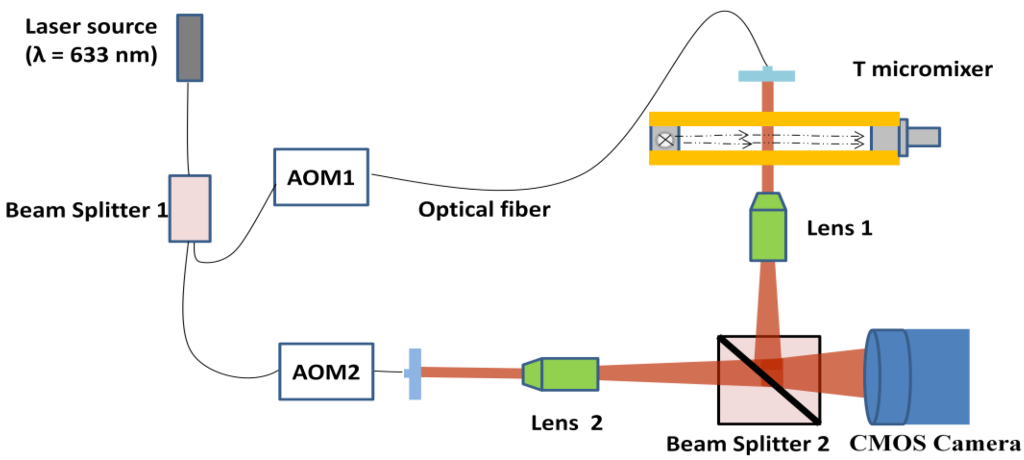

Figure 1. Schematic of the Mach-Zehnder interferometric microscope

Figure 1 shows the Mach-Zehnder interferometric microscope used in this study. A He-Ne laser with a wavelength of 633 nm is connected to the beam splitter 1 (BS1) by optical fibres. Then BS1 splits the laser beam into two laser beams with equal intensity: reference beam and measurement beam. Both beams travel through the acoustic optic modulators (AOM1 or 2) separately. The reference beam goes across the channel sample, and the gas property change can be detected by the phase information at the local measurement point. After magnification by tube lens (Lens1 and Lens2), the two beams recombine again at the beam splitter 2 (BS2). A CMOS camera is put after the recombined beam to acquire the fringes images. The speed of camera is set as 336 f/s that is 4 times of the frequency shift introduced by AOMs.

2.3 Microchannel

The channel used in this work was manufactured in a previous work (patent pending). The channel comprises of three layers: a polymer layer (detailed in Figure1) is sandwiched by two quartz glass plates that give optical access.

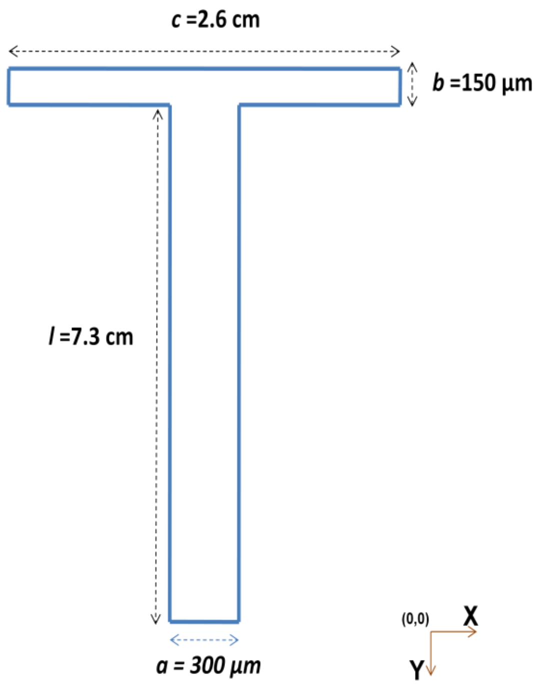

Figure 2. Demonstration of channel polymer layer

From the physical point of view, the local heating of the wall due to the continuous laser could be an issue as it introduces undesirable heat source to the gas flow. It is important to make this influence as small as possible through ensuring: a) avoiding significant laser absorbance by using quartz glasses. The two quartz glass plates with1 mm each have about 90% transmission ratio in the wavelength of 633 nm [7]; b) using lower laser intensity, the laser power used in this work is 35mv, and it is split into two beams, then both beams pass though the optical fibres, attenuating the intensity in the optical fibres. Especially the power suppliers of AOMs can also be used to reduce the output laser intensity; c) Fast measurement: it takes about 1s for 10 measurements. d) Studying pressure drop instead of temperature change. The later simulation results show that in the experimental condition, phase change is not sensitive to temperature change but only to pressure drop. So the laser induced heat is negligible in this work.

The T-mixer has a square section of 300 x 300 μm^2 and a length of 73 mm for the mixing channel and a rectangular section of 150 µm in width x 300 µm in height and a length of 12 mm for each side channel (see Figure 2). Each ending of the channel has a connector that does not have good optical transparency and it occupies roughly 1.3 cm. The analysis near the channel endings is limited.

2.4 Experimental process

Several points along the microchannel were selected for phase change analyse, but each time the interferometric system can only measure the phase information at one location, so it is important to develop a system to keep the gas flow constant, which allows the pressure change measurement in different locations sequentially without changing the experimental condition. The system shown in Figure 3 was developed for this purpose. The two entrance channels are open to air to make the inlet pressure constant at 1atm. A vacuum pump is running during the experiments to keep the outlet pressure stable at around 4000 Pa. A pressure gauge is used to monitor the outlet pressure.

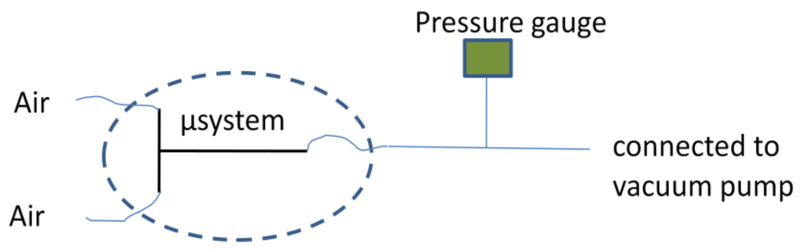

Figure 3. Schema of the gas mass flow control system

2.5 Phase extraction process

There are two methods for phase extraction; one is known as phase stepping where an interferogram is recorded after each known phase step is introduced to the system. The second is the integrating-bucket method, in which the intensity is detected as the phase is shifted continuously [8]. The former is used in this study.

The phase difference between the beams of the interferometer is determined by a measure of the intensity at the interference point for a range of phase shifts, which is introduced by using AOMs in this work. The mathematical expression of the interference of two light waves has already been derived. This can be expressed in terms of the average intensity and the modulation level [9].

$$I_i = I_0(1 + \gamma \cos \delta) \quad (3)$$

From Equation (3) it can be seen that there are three unknowns, hence a minimum of three equations is required to solve for the phase data. By the introduction of a known phase step, α_i, the interference expression becomes:

$$I_i = I_0(1 + \gamma \cos(\delta + \alpha_i)) \quad (4)$$

A four-step method is adopted. By repetition of this process with varied phase steps of multiples of π/2 Equation (4) may be solved. The four steps introduced are α= 0, π /2, π and 3π/2 and result in the three intensity equations (5-8).

$$I_1 = I_0[1 + \gamma \cos(\delta)] \quad (5)$$

$$I_1 = I_0[1 + \gamma \cos(\delta + \pi/2)] \quad (6)$$

$$I_1 = I_0[1 + \gamma \cos(\delta + \pi)] \quad (7)$$

$$I_1 = I_0[1 + \gamma \cos(\delta + 3\pi/2)] \quad (8)$$

Hence, the unknown phase difference in the interference pattern can be retrieved by: [10]

$$\delta = tan^{-1}\frac{(I_4 - I_2)}{(I_1 - I_3)} \tag{9}$$

3. Simulation and calculation

3.1 Simulation with Ansys Fluent

The computational volume was build with GAMBIT. The domain was represented with a grid constructed from hexagonal cells. Along the X - axial direction, the grid had 20 points evenly distributed in the T – junction and 150 points were distributed in each entrance channel with a slightly less clustered tendency towards the inlet. Along the Y - axial direction, the grid had 10 points evenly distributed in the T-junction and 800 points were distributed in the main channel with a slightly less clustered tendency towards the outlet. Along the Z-axial direction (vertical to screen), the grid had 10 points evenly distributed. Then the simulation was performed with Ansys Fluent. The inlet pressures of 100 kPa and the outlet pressure of 4 kPa were taken as the boundary condition.

The possibility of existence of transient flow phenomena for symmetrical 1:1 mixing in T-shaped micro channels with rectangular cross-section was approved in Dreher's work [11] depending on Reynolds numbers. In this case of study, the transient phenomena may introduce pressure or temperature fluctuations that could contribute to significant phase fluctuations at one location, which could make the extracted phase values more scattered even failed. So it was necessary to avoid this happening in this work. Because the T-mixer dimension and the fluids used in Dreher's work were different from ours, the range of Reynolds numbers to get steady flow could be different. For this purpose a simulation with Ansys Fluent was run and the transient calculations were first performed. Some flow points with a distance of 100 μm to the mixing channel wall were selected and their velocities were monitored over time. The time step was set as 1 x 10^{-5} s and the duration correspondent to real experiment was 50 ms. The results show that the velocity fluctuation is less than 0.03% (see Figure 4), which proves the flow in the experiment would be steady flow. Then the simulation was run again under steady condition. The pressure and temperature distribution inside the T micro channel were simulated by using laminar model.

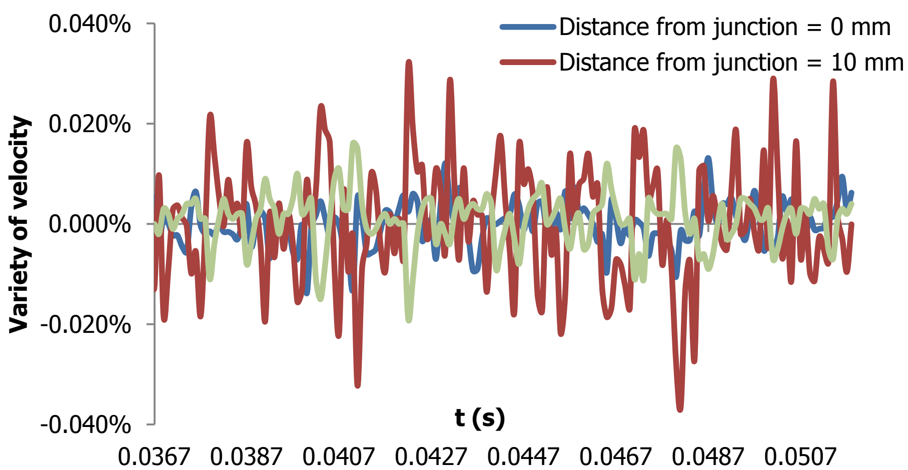

Figure 4. Velocity fluctuation

3.2 Relationship between the refractive index of air and pressure / temperature

The refractive index of air was well studied in Bengte's work [12] and then updated by Birch [13, 14]. It can be expressed as a function of air pressure and temperature by the equations (10) and (11). The agreement between calculation and experiment within an experimental uncertainty can be reduced to 3 x 10^{-8}. In reality, due to the carbon dioxide and humidity content of laboratory air can be very different, so the prediction of air pressure and temperature from the equations (10) and (11) can be expected to have a higher uncertainty than reported in literature.

The value of $(n\text{-}1)_s$, the refractivity of standard air at 1 atmosphere and 15 ℃, is calculated from the dispersion formula which was given as

$$(n-1)_s \times 10^8 = 8342.54 + 2406147(130-\sigma^2)^{-1} + 15998(38.9-\sigma^2)^{-1} \qquad (10)$$

Where σ is the vacuum wavenumber and is expressed in μm^{-1}.

$$(n-1)_{t,p} = \frac{p(n-1)_s}{96095.43} \times \frac{1+10^{-8}(0.601-0.00972t)p}{1+0.0036610t} \qquad (11)$$

Where $(n\text{-}l)_{tp}$ is the refractivity of standard air, the temperature t is expressed in degrees Celsius and the air pressure p in Pascal.

4. Results and discussion

The channel materials were quratz glass and polymers that had low thermal conductivity, but as the temperature could influence the phase change, the simulations with both adiabatic and isothermal boundary conditions were carried out separately. It is believed that the real temperature distribution should be between those found in the two simulations. As the goal of this work was to find the pressure drop along the channel by analyzing phase information obtained, it was expected that the temperature influence could be neglected. Figures 5 and 6 show that in this experimental condition, thermal boundary condition settings have much influence in temperature distribution but not in pressure distribution.

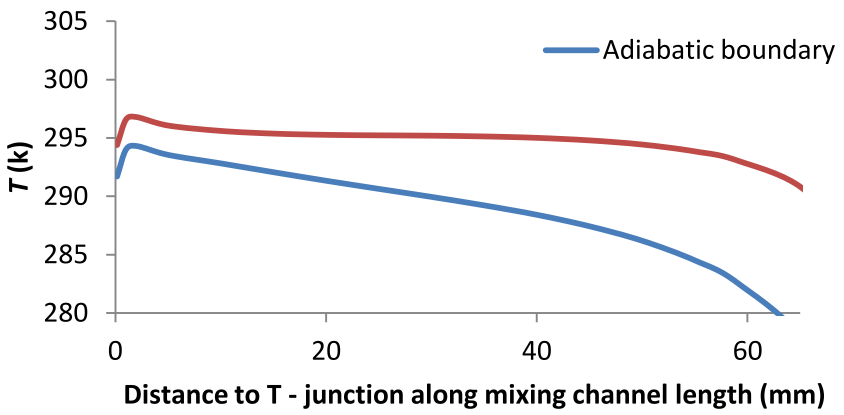

Figure 5. Temperature distributions along mixing channel

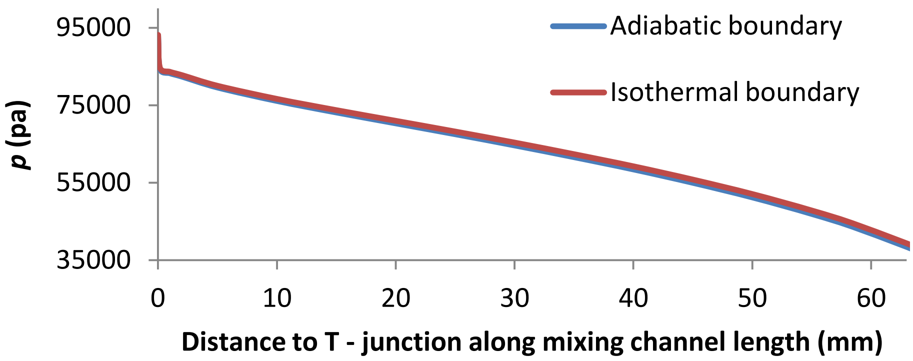

Figure 6. Pressure distributions along mixing channel

From the pressure and temperature distribution curves, the phase change information were calculated and presented in Figure 7. It is noted that for the phase change curve along the mixing channel is almost independent to thermal boundary settings, the same as pressure distribution (see Figure.5) but different from temperature distribution (see Figure. 6). That is, the temperature difference in the two cases does not cause significant phase difference, which indicates the phase analysis will be only the function of pressure in the defined experimental condition, as the contribution to phase change in gas flow are mainly by temperature and pressure change.

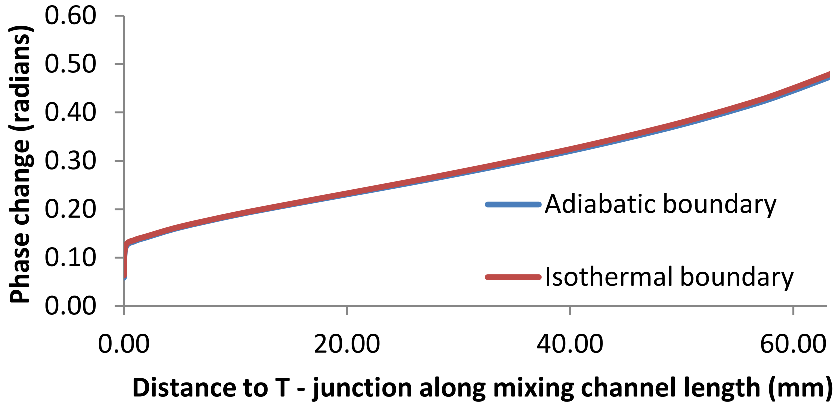

Figure 7. Expected phase change along the mixing channel

In experiments, the phase difference between the reference condition and real flow condition will be measured by interferometry microscope shown in Figure 1, then extracted by the 4 steps methods phase extraction process and finally translated into pressure difference. For reference condition, the pump is shut down and there is no flow inside the micro system, so the air inside the channel has the pressure of 1 atm. The phase change curve (see Figure 7) has a converse tend compared to the pressure drop curve (see figures 5 and 6), for the reason that the air at atmosphere pressure is taken as reference condition, and the pressure in the defined gas flow condition is always below 1atm.

Figure 7 shows that the phase change happening in this work will be between 0.1 and 0.5 radians, compared to the temporal noise of this setup, 0.01 radians, in some areas of the micro channel the phase measurement could be good while it does exist some areas where the phase measurement could have a high deviation.

The noise level is an important factor to limit the use of this technique for gas pressure drop analyse. There exists vibration during the experiments, which introduces temporal noise to the measurement. The optical length fluctuation due to the temporal noise in the present setup is roughly 1 nm. Spatial noise is not very sensitive in this case, because the average value for the measurement at one point is taken instead of analyzing the phase pixel by pixel, the special noise could be averaged out. To reduce noise level in these experiments, there are some solutions, for example, using high speed detectors, increasing gas density or channel dimension, or even performing the experiments in midnight when the laboratory and its surroundings are quiet, etc.

5. Conclusions

The flow studied in this work is a steady flow and there will be no influences on phase measurement due to flow fluctuations. Pressure drop measurement by interferometry in this selected experimental condition is feasible as the phase change is not sensitive to temperature change. But the interferometry technique is sensitive to noise, and the good experimental results can only be expected in some locations of the mixing channel under the defined flow condition.

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