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13. ABSTRACT (Maximum 200 words)

There are two tasks in this grant. The first is to develop a micromachined miniature polysilicon hot-wire anemometers with improved spatial resolution and frequency response. The finished device was a μm-sized polysilicon wire supported by free-standing gold/silicon-nitride beams. These devices have time constants as small as a few μs and, under constant-temperature mode, an unprecedented bandwidth of 1.4 MHz was achieved measured in wind tunnel. The second task is to study gaseous microchannel flows as an effort to understand the basic science of fluid mechanics when the mean-free-path of the gas is about the size of the channel. A micromachined microsystem was developed with a micron-sized flow channel (one μm high) and (4 or 13) distributed pressure sensors. A range of pressure drop up to 20 psi was used and nonlinear pressure distributions were, for the first time, successfully obtained. It was found that surface-gas interaction plays an important role in the flow behavior in microflow systems and that new flow models have to be developed to explain the new phenomena.

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Microsensors For Turbulent Flow Diagnostics

AFOSR Grant F49620-92-J-0424 Amendment P00002

FINAL TECHNICAL REPORT
(7/15/92-4/14/95)

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July 31, 1995

SUMMARY

It was concluded in the MICROFLOWS AND MICRODIAGNOSTICS WORKSHOP (IIT Center, Chicago, Illinois, 1991) and various other diagnostics Workshops that there are great needs for high resolution, non-intrusive diagnostics in experimental turbulence. On the other hand, recent advancement of micromachining has made possible many new microsensors that are small, fast, sensitive, accurate, and mass-producible. As a result, we had proposed to developed, in this project, μm-sized hot-wire (point) anemometers that have much improved spatial resolution and frequency response suitable for turbulent flow study. The hot-wire(point) anemometer was a μm-sized polysilicon thermistor head supported by free-standing gold/silicon-nitride beams so that the overall thermal mass is typically several order of magnitude smaller than the lab-made hot-wire anemometer. In fact, it was found that the time constants of these wires were down to only a few μs. When configured into a constant-temperature circuit, a record bandwidth of 1.4 MHz was achieved. These integrated hot-wire anemometers were extensively tested at UCLA and their practical wind-tunnel performance was confirmed.

In addition, we had also proposed to study gaseous microchannel flows as an effort to understand the basic science of fluid mechanics when the mean-free-path of the gas is about the size of the channel. Two kinds of integrated microflow MEMS microsystems were developed for this part of project. The structure of the flow systems was a micron-sized flow channel with distributed pressure sensors. The feature height of the channel is about one μm and 4-13 pressure sensors were distributed along the channel. Various experimental conditions were tested with a pressure drop

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of 1-20 psi along the channel. Nonlinear pressure distributions were, for the first time, successfully obtained using these systems. It was found that surface-gas interaction plays an important role in the flow behavior in microflow systems and that new flow models have to be developed to explain the new phenomena found here.

1. INTEGRATED POLYSILICON ANEMOMETER

1.1 INTRODUCTION

A hot-wire anemometer is a thermal transducer which is capable of sensing point flow velocity through temperature variation using a heated resistive wire which has a non-zero temperature coefficient of resistance (TCR). When the electrically heated wire is placed in the flow of fluid, the heat is taken away by the flow-induced forced convection. Depending on the operation modes (constant current or constant temperature), either the resistance or the output voltage drop across the wire is a function of the flow velocity.

Conventional hot-wire anemometers have been used for flow velocity measurements for over 80 years. Fig. 1a shows the structure of a typical hot-wire anemometer. A metal wire is welded or soldered to two metal needles which are molded to the probe body. The wire is usually made of platinum or tungsten and is typically 5 μm in diameter and 1mm in length. It has a resistance of 10 - 30 ohms at room temperature and needs 10 - 40 mA of current to operate. These conventional anemometers have to be hand-assembled one by one, thus making it difficult to be arrayed for simultaneous velocity distribution measurement. Also, since the wire diameter is difficult to control with good repeatability, the anemometer probes are essentially not interchangible without recalibrating the whole anemometer system.

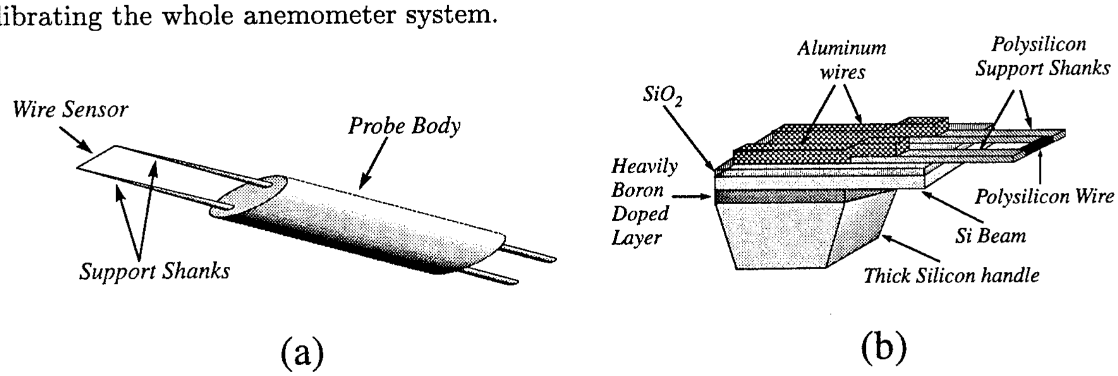

Fig. 1 Hot-wire anemometers: (a) Conventional, (b) Micromachined.

Since the spatial resolution of the anemometers for flow velocity distribution measurement is determined by its dimensions, it is advantageous if the wire size can be further reduced. This would also decrease power comsumption and thermal interference to the flow and increase frequency response. In fact, many anemometer designs have been demonstrated using either surface or bulk micromachining technologies. Interestingly, however, they are either bulk-micromachined chip-sized devices or wires on top of chips. No one really simulates the real feature of a conventional hot-wire anemometer, i.e., a wire thermistor free-standing in space without anything nearby so that best thermal isolation is achieved. As a result, they can not be direct replacements for the conventional hot-wire anemometers. Here, we report our research on a new type of micromachined anemometers that emphasize the real simulation of a hot-wire anemometer but with greatly reduced wire size. This is made possible by combining surface and bulk micromachining technologies. Not only the spatial resolution and device sensitivity are better, the frequency response is also improved by at least one order of magnitude (confirmed from extensive wind tunnel calibration) over the conventional hot-wire anemometers. Optimization of the structural geometry and the material properties has resulted in anemometers with time constant of 2 μs in the constant current mode and a bandwidth of 1.4 MHz in constant temperature mode.

1.2 STRUCTURE

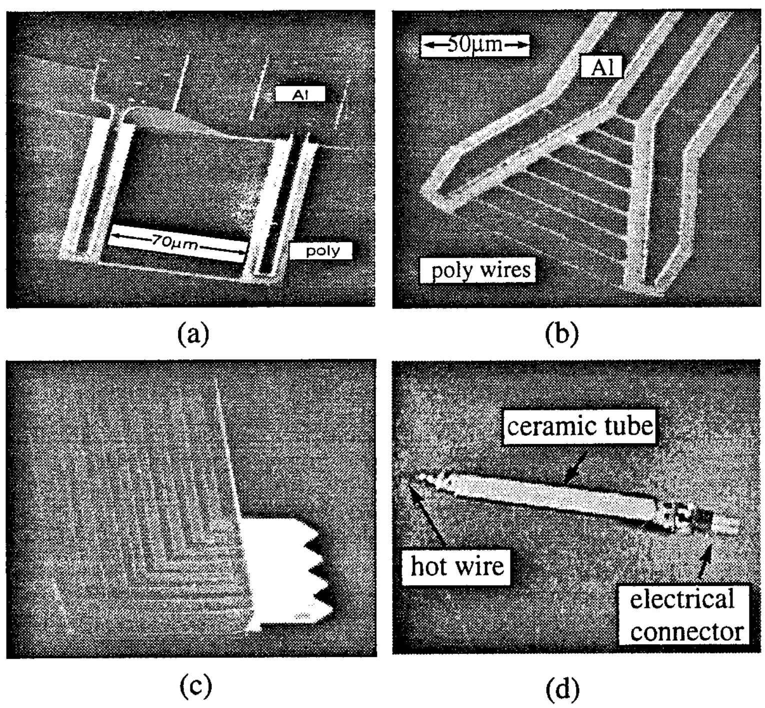

Fig. 2 (a) SEM of a 70 μm long hot wire, (b) a multi-wire probe, (c) an array of hot wires, (d) photograph of a packaged anemometer.

The micromachined anemometer (Fig. 1b) consists of a sensing wire, two parallel support shanks, a silicon beam, and a thick (500 μm) Si handle. The silicon beam acts as the probe body and is 1 mm long, 200 μm wide and 75 μm thick. The two parallel support shanks are 100 μm long, 20 μm wide, and 0.5 μm thick. Various sizes of the sensing wires have been made and they are 10-160 μm long, 1 μm wide, and 0.5 μm thick, and are free standing to optimize the interaction with the flow and to minimize the thermal conduction to the handle. Polysilicon, instead of platinum or tungsten, is used as the sensing and supporting material because of its compatibility with existing micromachining technologies and because of its controllable TCR in the range of -1%/°C to +0.2%/°C depending on the doping concentration. The doping concentration of $10^{18} cm^{-3}$ corresponds to a reproducible TCR of -1%/°C for our polysilicon, with which high thermal sensitivity can be achieved even at low operating temperature. The polysilicon wires can be uniformly doped by high dose boron implantation (type I) or nonuniformly doped by a low dose implantation followed by a high dose implantation with the center part of about 2 μm being masked (type II). Type I poly wires behavior similar to the platinum or tungsten wires. For type II wires, the resistance and the ohmic heating are concentrated at the 2 μm lightly doped center region. The other part of the wire acts only as the electrical conductor and mechanical support[8]. It can be expected that anemometers with this type of wire should have improved frequency response and spatial resolution over the type I wires. Since the lightly doped part is very short, the total resistance of the anemometer is still within a reasonable range (less than 20 kilo-ohms) which can be adequately handled by signal processing circuits. hot wire[1]. Figs. 2b and 2c are SEM's of a multi-wire probe and an array of hot wires which can be easily obtained by just changing the layout design.

The package of the anemometers is a ceramic tube a few centimeter long and 3 mm in diameter (Fig. 2d). The anemometer handle is soldered with electrical cables, placed inside the tube, and then epoxy-fixed. During handling, all mechanical vibrations are avoided so as not to damage the wires.

1.3 CALIBRATION

The micromachined hot-wire anemometers have a resistance of a few kilo-ohms and need less than 3mA to be drived. Compared to the low-resistance, high-current conventional hot wires, this low driving current simplifies the anemometer circuits, especially in the most frequently used constant temperature mode.

The calibration of the micromachined hot-wire anemometers include the measurements of the steady-state characteristics in windtunnel and dynamic responses in still air. It is found that the output voltage change with the wind velocity follows the well-known King's law. The average sensitivities are generally higher than those of conventional hot wires. The steady-state calibration also shows that the short wires have strong pitch angle dependency and basically no yaw angle dependency, and long wires have smaller pitch angle dependency and the same cosine-law yaw angle dependency as the conventional ones. The thermal time constant increases with the wire length for short wires where heat conduction dominates the heat transfer, and remains relatively constant for long wires where heat convection dominates the heat transfer. The smallest time constant is 2 μs for a centrally lightly doped wires and is 8 μs for the uniformly heavily doped wires. When this heavily doped wire with 8 μs time constant is operated in constant temperature mode, a bandwidth of unprecedented 1.4 MHz is realized (Fig. 3).

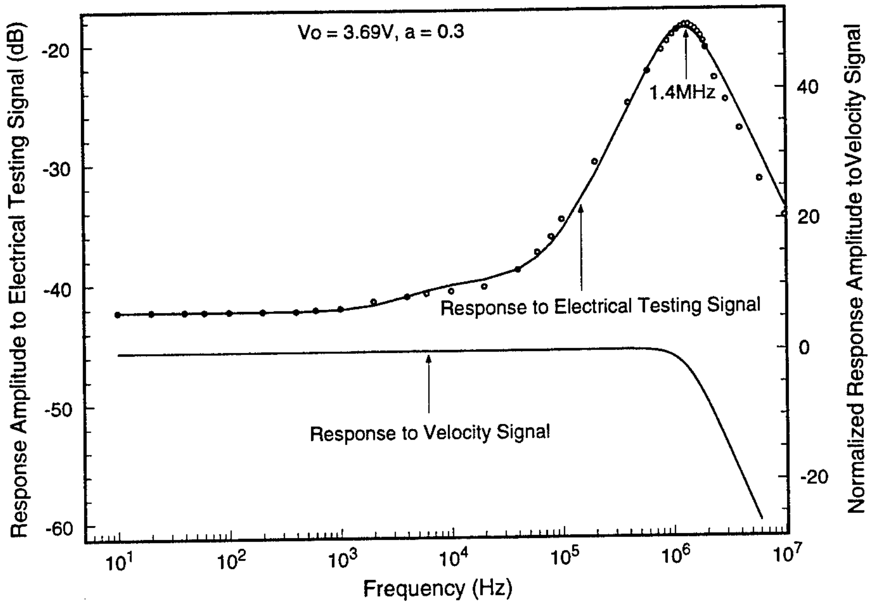

Fig. 3 Frequency responses of a heavily doped micromachined hot wire anemometer in constant temperature mode.

2. MICROCHANNEL GASEOUS FLOW STUDIES

2.1 INTRODUCTION

Studies on fluid flows in micro-scaled capillary tubes can be traced back to Knudsen, 1909. Recently, microflow research emerged again probably because the development of micromachining technology enables fabrication of microflow systems such as micro pumps and heat exchangers. In order to design these devices properly, extensive study on microflows is necessary. Unfortunately, microflow experi- ments inside microstructures are very difficult because of the lack of interface instruments. For example, pressure distribution in micro- channels is one of the most important pieces of information in under- stand microflows, but there has been no reported experimental data on this. Earlier, we reported a preliminary technology to fabricate inte- grated microflow systems. Since then, we have successfully fabricated two microflow MEMS systems and used them to obtain the first ever pressure-distribution data in microchannels, which is reported in the following.

2.2 UNIFORM MICROCHANNEL

Fig. 4 shows an integrated micro- channel/pressure-sensor system with a uniform cross-section

(40 by 1.2 μm^2) microchannel. This 4.5 mm long channel has 13 distributed pressure sensors (including those on the top of the inlet and outlet dia- phragms). Each pressure sensor is connected to the channel through a 5 μm long bridging channel (with a cross section of 2x0.3 μm^2) as shown in Fig. 5. The size of the pressure sensor is 250x250 μm^2. There are 4 polysilicon piezoresistors on the diaphragm forming a Wheatstone-bridge circuit. These systems were made because straight channels are one of the most fundamental flow structures.

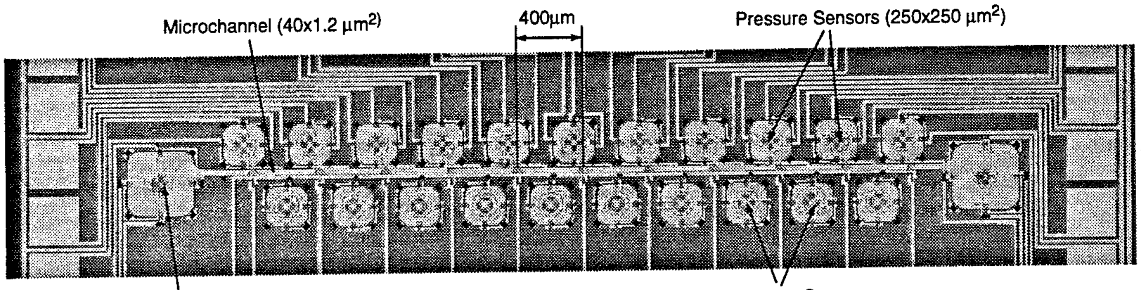

Fig. 4 A microflow system with a uniform microchannel, 4.5 mm long, 40 μm wide and 1.2 μm high.

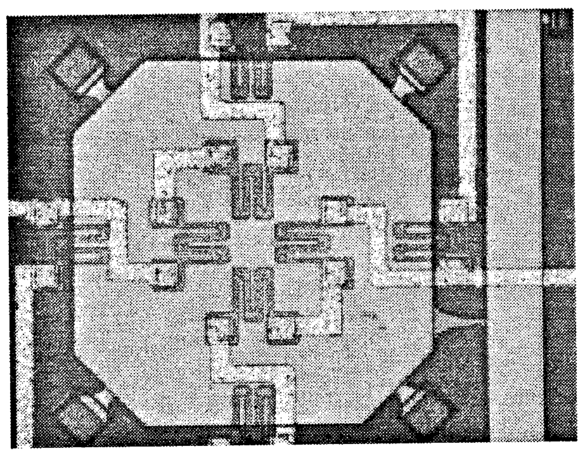

Fig. 5 A pressure sensor connected to the channel.

2.3 NONUNIFORM MICROCHANNEL

Fig. 6. shows the design and the transitions of a non-uniform cross section microchannel system. Basi- cally, the channel has two sections (40 and 100 μm wide respectively) and three transitions between the gas inlet and outlet. Each transition has three pressure senors at its entrance, throat, and exit.

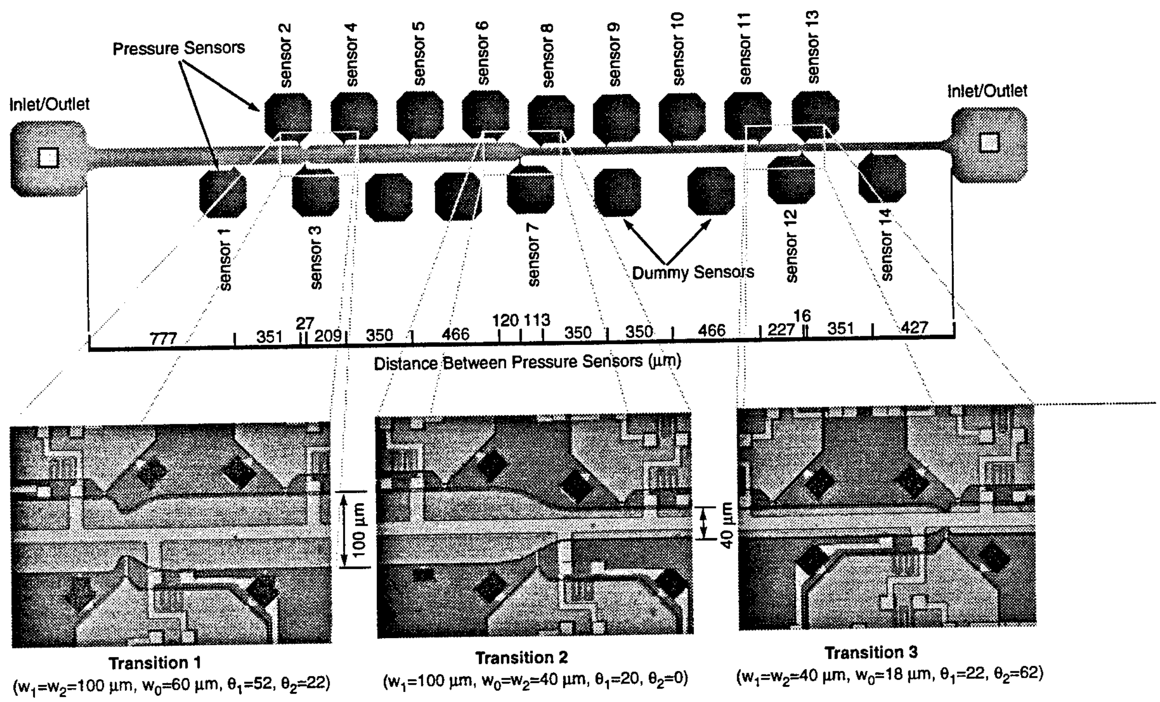

Fig. 6 The transitions in a non-uniform microchannel.

2.4 EXPERIMENTS AND RESULTS

To minimize experimental errors, we first calibrate all pressure sensors using an AC-drive technique. It is found that the output characteristics of these pressure sen- sors can be modeled very well using a linear function with a sensitivity of 0.25 mV/Vpsi, and the accuracy is 0.1 psi or better. Pressure distribution experiments are then carried out using the setup in Fig. 7. An HP3852A data acquisition used to average data over long period of time. Fig. 8 shows the pressure distributions of helium flows in a uniform microchannel. The pressure distribution is clearly not lin- ear. Even more interestingly, the pressure gradients near the inlet and outlet of the channel are smaller than that in the middle. As far as we know, there is no valid theory yet to explain this phenomenon. In our experiments, both helium and nitrogen are used. It is found that the nonlinearity of the pressure distribution changes significantly between them, which should be attributed to Knudsen effects.

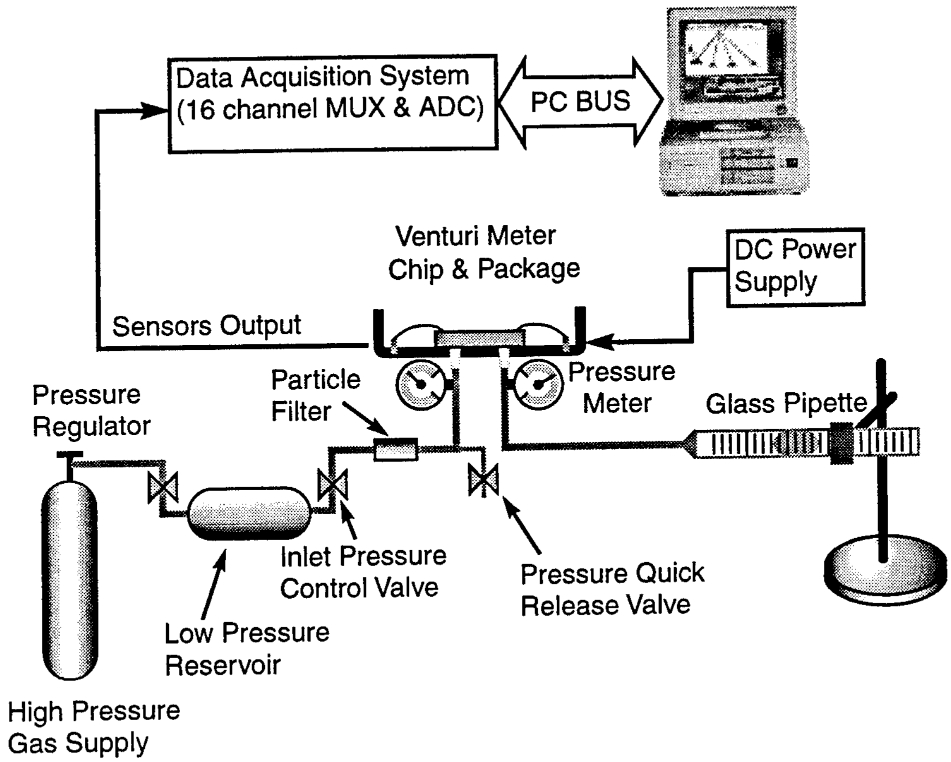

Fig. 7 Schematic of the experimental setup.

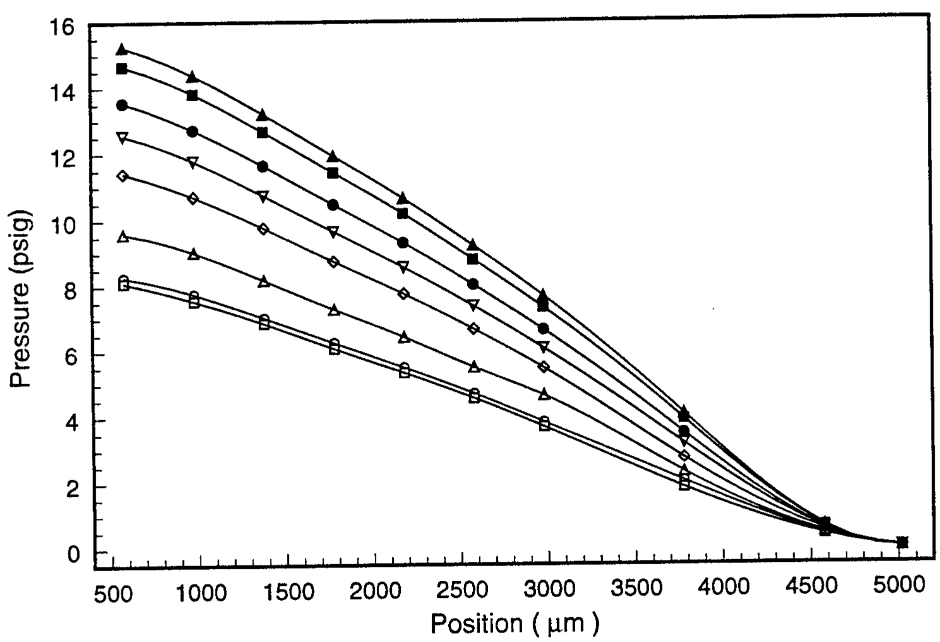

Fig. 8 The pressure distribution in a uniform microchannel.

For microflows in non-uniform channels, more features are found as shown in Fig. 9. There are sudden pressure changes arosss the transi- tions. For example, at transition 1 the pressure drop is about 0.5 psi under an inlet pressure of 20 psig, while at trasition 2 (where channel changes from wide to narrow) the pressure actually increases by more than 1 psi. However, these features become less distinctive at a smaller inlet pressure of 10 psig (see Fig. 9). In general, these pressure changes depend on flow rates (ml/min), which are obtained using a volume-accumulation method (as in Fig. 10). In conclusion, we pro- pose here that it is possible to establish a relation between the pressure change and the flow rate for a specific transition, and it can be used as a new micro flowmeter. This flowmeter in principle is based on vis- cous effects at extremely small Reynolds number (10^{-2}), which is very different from conventional Venturi meters that are based on the inviscid Bernoulli theory.

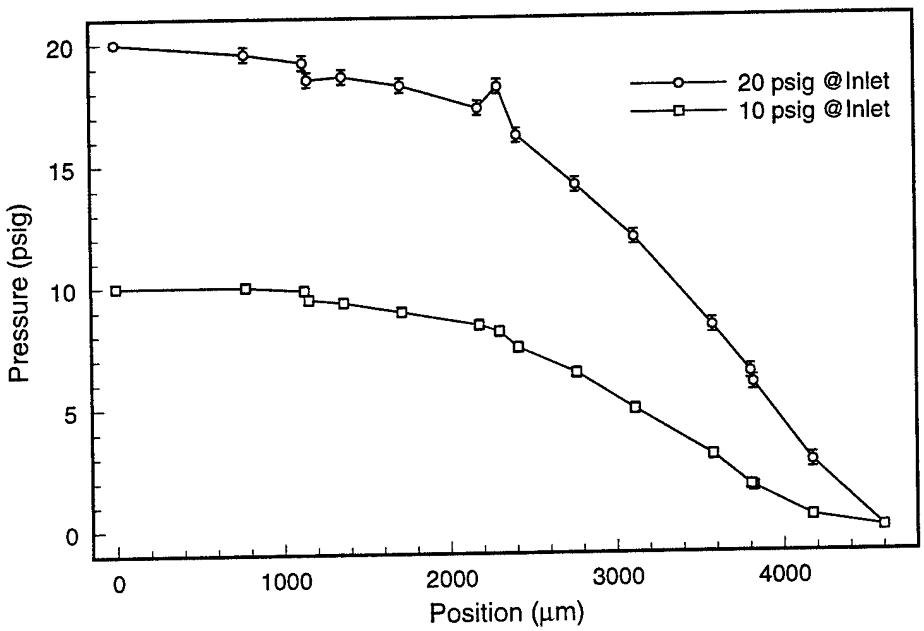

Fig. 9 Pressure distributions in a transition channel as in Fig. 6

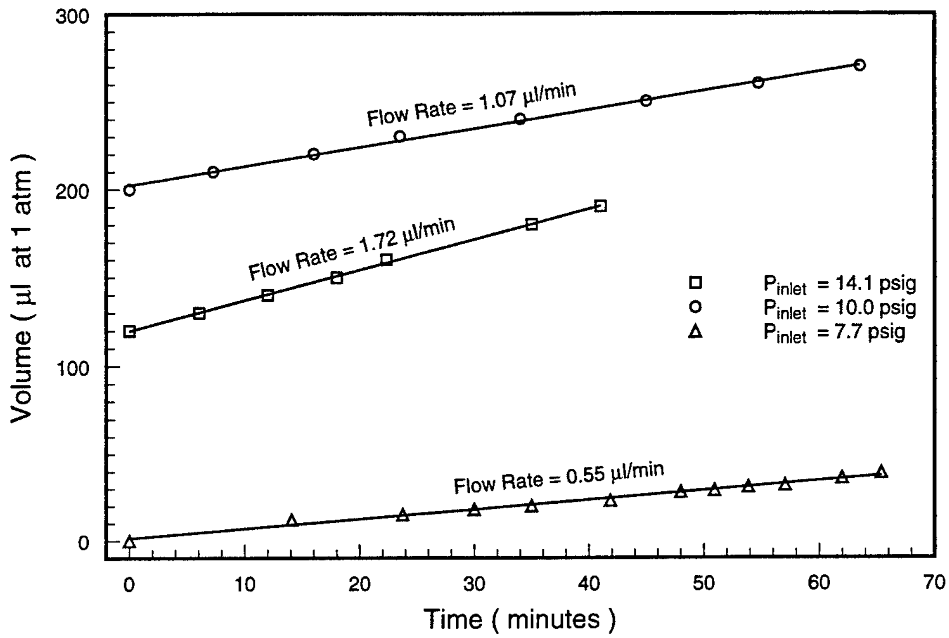

Fig. 10 Measured helium gas flow rates vs. pressure in the uniform microchannel.

3. PERSONNEL

Professor: Yu-Chong Tai

Engineer: Trevor Roper

Ph.D. Student: FuKang Jiang (anemometer), JianQiang Liu (microflow)

4. PUBLICATIONS

[1] F. Jiang, Y. C. Tai, C. H. Ho, W. J. Li, "A Micromachined Polysilicon Hot-Wire Anemometer", *Tech. Digest 1994 Solid-State Sensors and Actuator Workshop*, Hilton Head, SC, June 1994, pp. 264-267.

[2] F. Jiang, Y. C. Tai, C. H. Ho, R. Karan, M. Garstenauer, "Theoretical and Experimental Studies of Micromachined Hot-Wire Anemometers", *Tech. Digest 1994 IEDM*, San Francisco, CA, Dec. 1994, pp. 139-142.

[3] Liu, J. Q., Tai, Y. C., Pong, K. C., and Ho, C. M., "Micromachined Channel/Pressure Sensor Systems For Micro Flow Studies," *Digest, The 7th International Conference on Solid-State Sensors and Actuators, (Transducers'93)*, Yokohama, Japan, pp. 995-998, 1993.

[4] J. Liu, Y.C. Tai, K.C. Pong and C.M. Ho, "MEMS for Pressure Distribution Studies of Gaseous Flows in Microchannels," *Proceedings, IEEE Micro Electro mechanical Systems Meeting (MEMS'95)*, Amsterdam, Netherlands, Jan. 29-Feb. 2, 1995.