CHARACTERISTICS OF ON-WALL IN-TUBE THERMAL FLEXIBLE MASS-FLOW SENSORS

Z.Y. Tan[1], *M. Shikida*[2], *M. Hirota*[1], *and K. Sato*[1]
[1]Department of Micro-Nano Systems Engineering, Nagoya University, JAPAN
[2]EcoTopia Science Institute, Nagoya University, JAPAN

ABSTRACT

We developed a wall-mounted in-tube thermal flexible sensor for measuring mass flow that can measure the flow rate in both hydraulically developing and fully-developed regions. The flexible structure was achieved by using polymer MEMS technologies. It has high linearity with a TCR of $0.0026K^{-1}$, and a steady maximum value for the response time is reached within 7μs. The measuring distance from the tube entrance is 8.3D (D = inner diameter of tube). This is much shorter than 64D, the theoretically calculated distance necessary for the formation of a fully-developed flow condition.

1. INTRODUCTION

Mass flow rate is currently an important parameter in many fields, such as the automotive (fuel and tail gas flows), medical applications (blood flow and respiration rate), and domestic climate control (water and ventilation flows) fields. Therefore, there is a need for mass flow sensors that maintain structural stability under high gaseous velocities and that have a high degree of accuracy, a fast response, low power consumption, and a low cost.

To satisfy these demands, many mass flow sensors have been developed. The most common sensors and structures are hot-wire anemometers and sensor-bridge suspended in the center of flow channel structures [1-2]. These devices detect the flow rate at a point in the center of a tube. Therefore, they have the following essential drawbacks.

1. The flow velocity at the center of tube depends on the flow condition (distance from the entrance), as shown in Fig. 1(a). Therefore, a sensor has to be used in the hydraulically fully-developed flow region to obtain a constant value. This means that it needs to be a certain distance from the tube entrance.
2. In the case of axially asymmetric flow input, the sensor also needs to be a certain distance from the tube entrance to obtain an axially symmetrical flow velocity distribution, as shown in Fig. 1(b).
3. The sensor output also depends on the radial position in the tube, because of the flow velocity distribution. This is true even in a fully-developed flow condition.

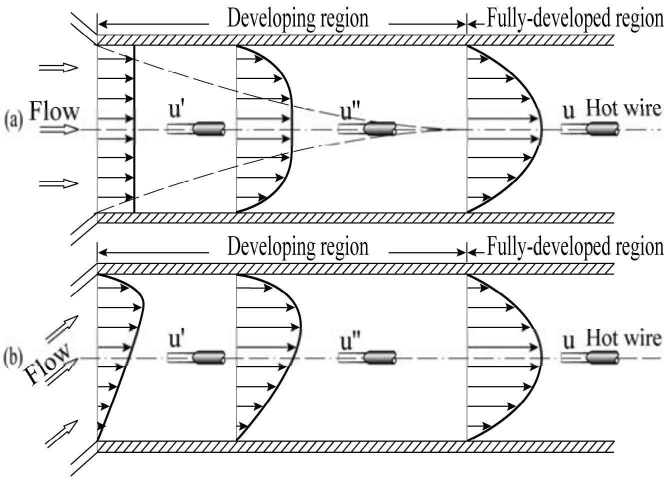

Figure 1: Conceptual diagrams of flow development and hot wire arrangements in a circular tube for various entry configurations. (a) The straight pipe; (b) The 45-angle bend.

We developed a flexible thermal mass flow sensor using polyimide film as the substrate and thermal insulation and mounted it on the inner wall of a glass tube. This sensor is able to measure mass flow rate in both hydraulically developing and fully-developed regions.

2. DESIGN AND FABRICATION

Figure 2 shows the proposed wall-mounted in-tube thermal flexible sensor. The sensor is fabricated on a flexible polyimide film (Fig. 3) and mounted on the inner wall of a tube to form a ring-shaped sensor structure (Fig. 4).

Because of the low thermal conductivity of the polyimide film and the wall-mounted structure, thermal energy from the heater is transferred to fluid effectively with little heat loss. This ensures the sensor's quick response to a transient change of the flow rate and low power consumption. Moreover, the output from the sensor can be insensitive to the velocity distribution in the core region of the tube because heat transfer from the wall-mounted heater is dominated by the flow near the wall. As a result, the flow rate can even be measured in the hydraulically developing region of the tube, which shortens the distance from the entrance required by the sensor. The sensor's output is also insensitive to the axially symmetrical property of velocity distribution because its ring shape enables it to average the peripherally non-uniform heat transfer rates in distorted flow conditions.

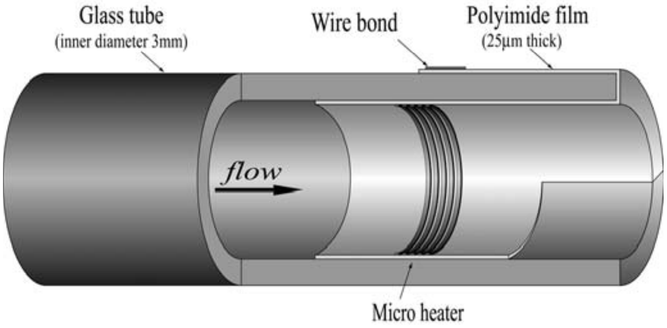

Figure 2: Schematic cross-sectional view of the thermal sensor.

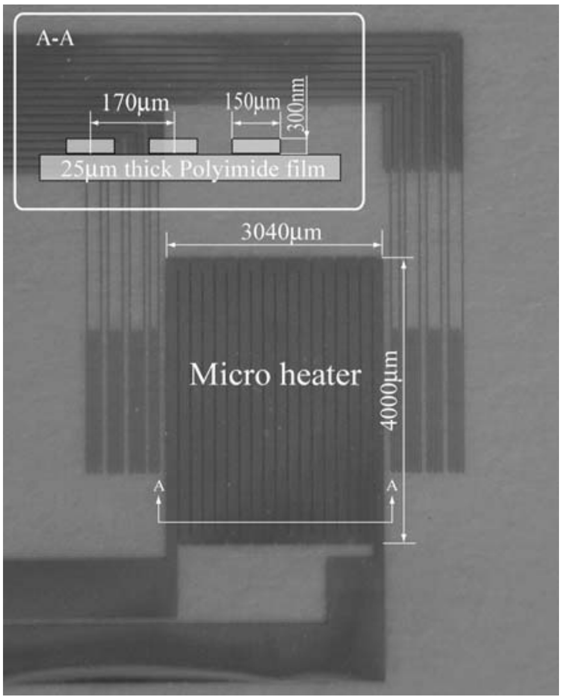

Figure 3: Photograph of the thermal sensor chip.

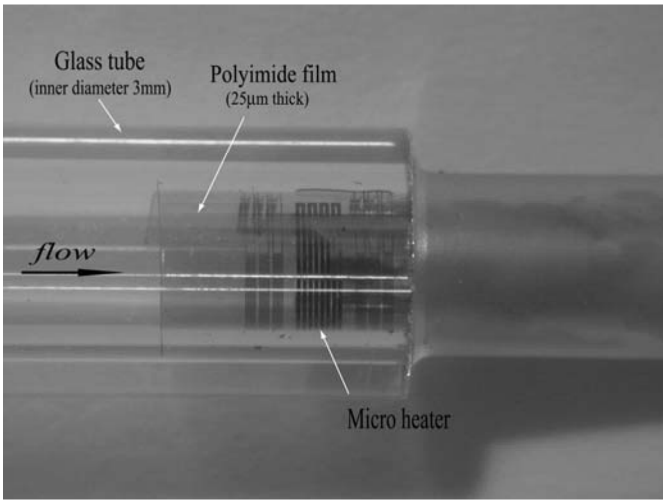

Figure 4: Photograph of the thermal sensor mounted on an inner-wall surface of the glass tube.

We fabricated the flexible sensor using polymer MEMS technologies. We used 25-μm-thick polyimide film as a substrate. We deposited a 300-nm Au/Cr film on the substrate by sputtering and patterned it by lift-off processes to form a heater. The fabrication process is very simple and thus suitable for low cost mass production.

These merits of this sensor were examined experimentally and encouraging results were obtained.

3. RESULTS

We first examined the heater characteristics. The temperature coefficient of resistance (TCR) shows high linearity with a value of $0.0026K^{-1}$. The flow rate can be measured from the resistance change of the heater to the gas velocity under constant current , as shown in Fig. 5.

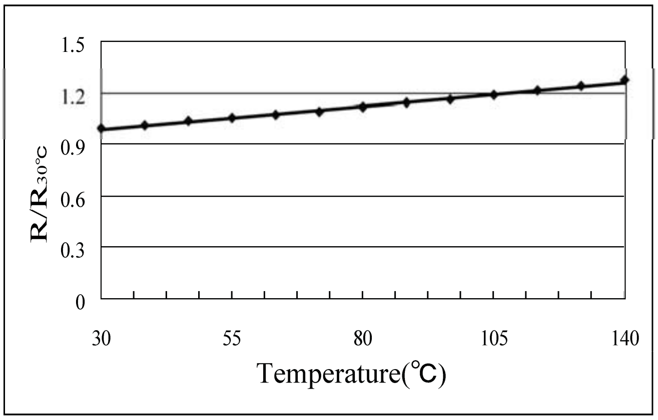

Figure 5: The resistance changes of the thermal sensor to temperature.

The response of the heater to a pulsed voltage change is shown in Fig. 6. For a pulsed voltage of ±2.5V/50μs, a steady maximum value was reached within 7μs. This result demonstrates the sensor's quick response to a transient change of the flow rate.

Figure 7 shows the experimental setup for measuring mass flow rate. The rate was measured using the resistance change of the heater under constant current.

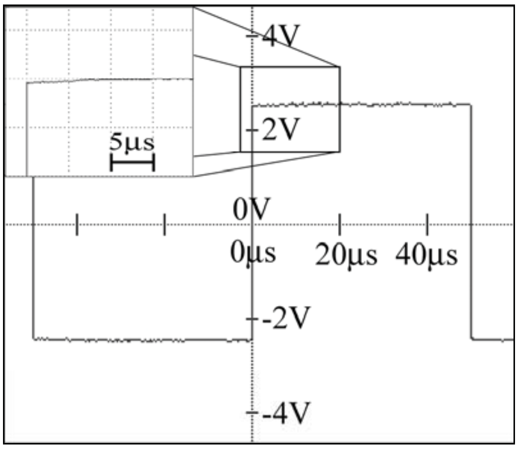

Figure 6: The response time of the thermal sensor.

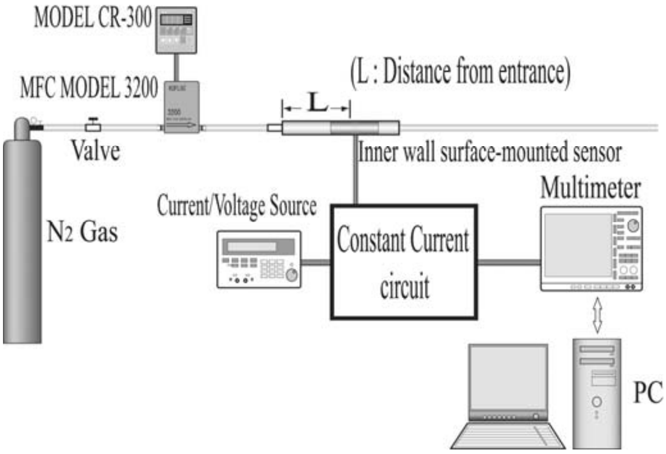

Figure 7: The experimental setup for flow-rate measurement.

Figure 8 shows the relationship between the resistance change of the sensor and the flow rate under constant current. We find the more power consumption (larger currents), the higher sensitivity, but low power consumption is also an important feature for a thermal sensor. In our experiment, a satisfactory level of sensitivity up to 2.75l/min was obtained with a low power consumption of 150mW.

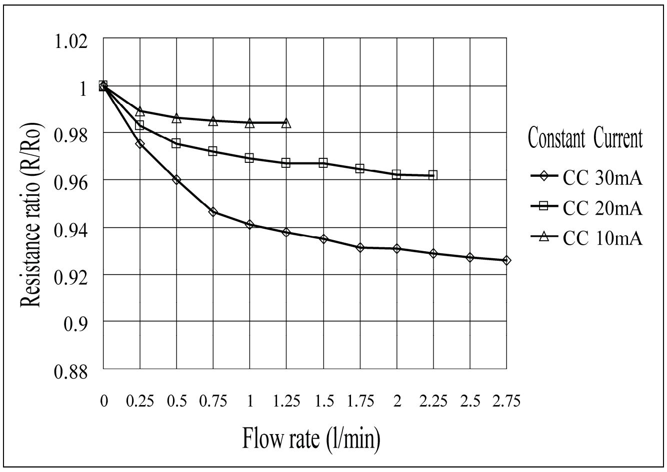

Figure 8: The result of mass flow rate measurement in constant-current mode. Relationship between flow rate and resistance ratio of sensor.

Ro: the resistance of sensor at zero flow (u=0).

We also examined the influence of distance from the tube entrance on the sensor's output. Figures 9-10 show the resistance of the heater to the flow rate for various distances of the sensor from the tube entrance (L). We obtained that the results lie on the same curves at L = 8.3D or over (D = inner diameter of tube). We calculated the distance necessary for the formation of a fully-developed flow condition by using an equation reported elsewhere [3].

$$\frac{x}{D} = \frac{\mathrm{Re}}{20} \tag{1}$$

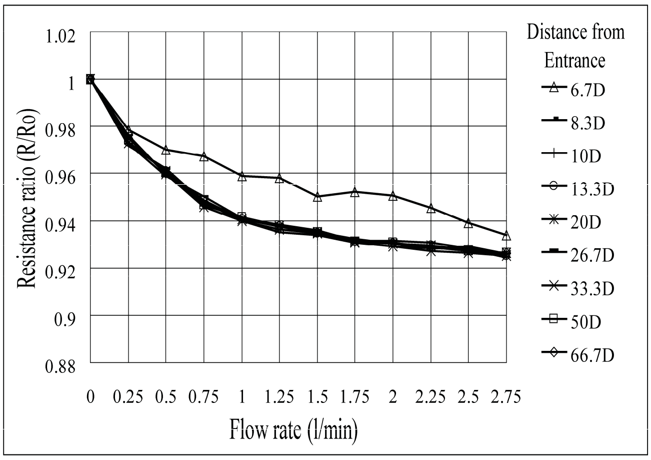

Figure 9: The result of mass flow rate measurement at different position from the entrance of a circular tube. Ro: the resistance of sensor at zero flow (u=0).

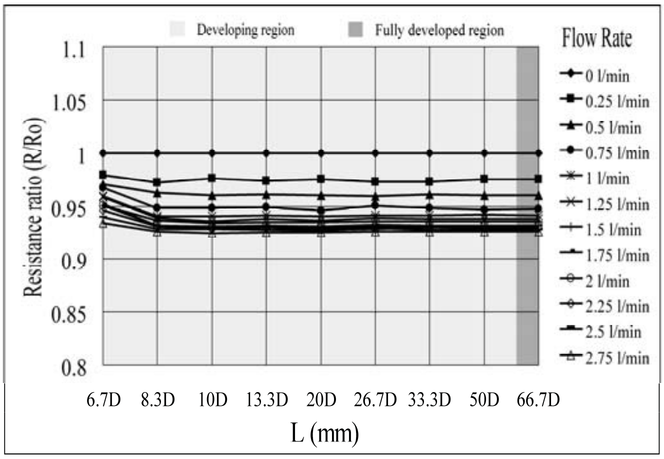

Figure 10: Variation of resistance ratio of sensor to entry length of a circular tube.
Ro: the resistance of sensor at zero flow (u=0).

We obtained a value of 64D from the equation in case of our conditions using Re (Reynolds number) of 1280 (at the maximum flow rate of 2.75 l/min) and D of 3mm. This value is 8 times larger than that of our experimental results. This means that the sensor is able to measure flow rate in both hydraulically developing and fully-developed regions and is able to shorten the distance necessary from the tube entrance.

4. CONCLUSION

We developed a wall-mounted in-tube thermal flexible sensor for measuring mass flow. The good thermal insulation properties and the ring-shaped sensing structure enable high sensitivity and a very short response time of 7μs. The TCR shows high linearity with a value of $0.0026K^{-1}$. The distance from the tube entrance is 8.3D, which is 8 times shorter than the theoretically calculated distance of 64D necessary for the formation of a fully-developed flow condition. Because of these good characteristics, our thermal sensor can be applied in many areas.

5. ACKNOWLEDGEMENTS

It was supported by the 21st COE Program (Micro- and Nano-Mechatronics for Information-based Society).

REFERENCES

[1] H.H. Bruun, *Hot-Wire Anemometry*, Oxford University Press, 1995.

[2] K. Petersen and J. Brown, "High-Precision, High-Performance Mass-Flow Sensor with Integrated Laminar Flow Micro-Channels," *Rec. of the 3rd Int. Conf. on Solid-State Sensors and Actuators*, pp.361-363, 1985.

[3] W.M. Kays and M.E. Crawford, *Convective Heat and Mass Transfer*, McGraw-Hill, 1980.