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CHARACTERISTICS OF ON-WALL IN-TUBE FLEXIBLE THERMAL FLOW SENSOR AT WRAP PIPE CONDITION

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Abstract: We previously proposed a novel type of on-wall in-tube thermal flexible sensor, and confirmed that it can measure the flow-rate in both hydraulically developing and fully-developed conditions [1]. This time, we investigated another outstanding advantage, i.e. the sensor is able to measure the flow-rate at axially asymmetric flow condition, and found that the sensor is applicable for the measurement of the flow-rate in bent tube condition.

Keywords: Thermal flow sensor, Flexible structure, Asymmetric flow

1. INTRODUCTION

Flow rate detection is important in industrial fields and laboratory studies, and various flow sensor structures have been developed to satisfy measurement requirements. Gas piping is frequently coiled in actual applications to decrease the volume it occupies (Fig. 1(a)) [2]. In this case, the flow-velocity distribution becomes asymmetrical in the axial direction. The commonly used commercial flow sensor detects the flow rate at a point in the center of a tube (Fig. 1(b)). Therefore, the sensor needs to be a certain distance away from the end of the bent section of tube to obtain an axially symmetrical flow-velocity distribution [3-5].

The proposed sensor is fabricated on a flexible polyimide film and mounted on the surface of the tube's inner wall to form a ring-shaped structure (Figs. 1(c) and 1(d)). It can measure the flow rate in both hydraulically developing and fully developed conditions because a steady flow rate is developed near the surface of pipe [1]. In addition, the ring-shaped sensing structure averages the various flow rates in distorted flow conditions (this means that the sensor output is independent of the axial symmetry of the flow distribution). In this paper, we evaluate the performance of the ring-shaped sensor under various bent-tube conditions in order to apply it to flow-rate measurement in a coiled pipe.

2. DETECTION PRINCIPLE

A schematic view of the on-wall in-tube flexible thermal flow sensor is shown in Fig. 1(d). Flow rate was measured from the change in resistance of the heater in constant-current mode. In this section, we describe the detection principle of our thermal sensor.

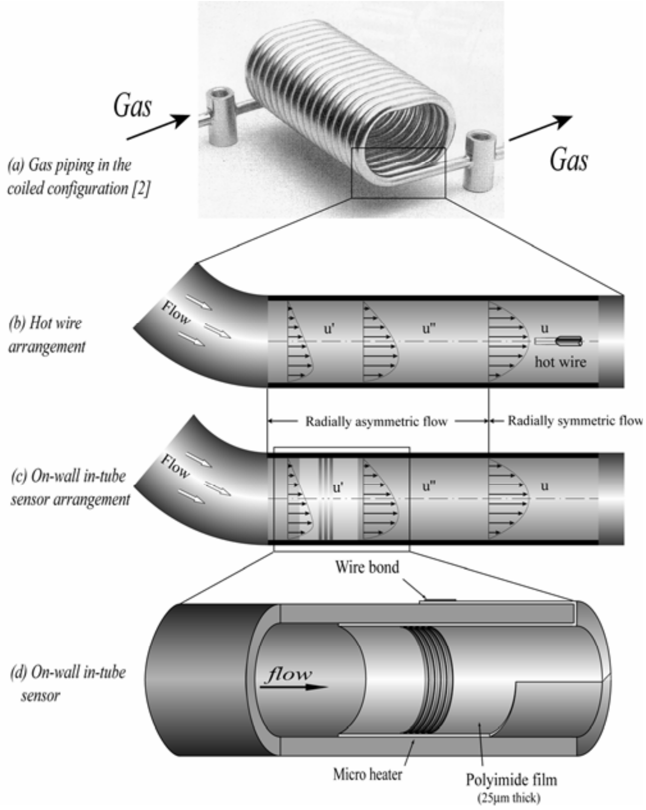


Figure 1. Conceptual diagrams of flow development in a bent tube.

The heat transferred from the heater element placed in the tube to the surrounding medium can be broken down into thermal conduction, thermal radiation, and thermal convection. The values of the conduction and radiation terms are much smaller than that of the convection term in our device. Therefore, thermal convection from the heater to the gas environment dominates the overall heat transfer. As a result, the heat transfer can be written simply as

$$P \approx h_{conv.} \cdot A \cdot \left(T_s - T_{in}\right) \tag{1}$$

where h_{conv} is the heat-transfer coefficient ($W \cdot K^{-1} \cdot m^{-2}$) from the heater to the gases in the tube, T_{in} and T_s are the temperatures (K) of the gas in the tube and of the heater surface, respectively, and A is the total area of the heating element (m^2). The heat-transfer coefficient can be expressed by an empirical formula showing the relationship between the heat-transfer coefficient and the flow velocity:

$$h_{conv.} = a + bu^n \tag{2}$$

where u is the mean velocity of the gas in the tube, a and b are constants, and n is a geometric factor. The relationship between the heater's electrical resistance R and its temperature T_s is given by

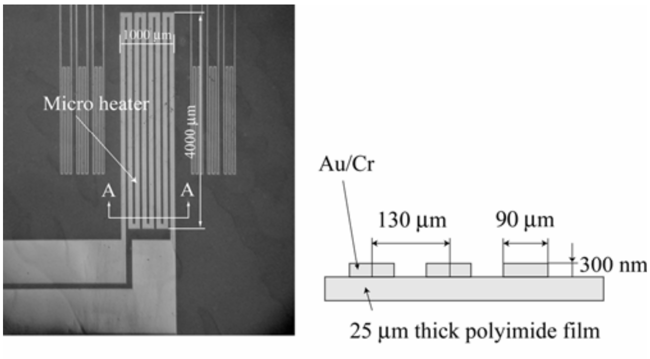
$$R_s = R_0\left[1 + \alpha\left(T_s - T_0\right)\right] \tag{3}$$

where T_0 is the ambient temperature, R_0 is the resistance of the heater at T_0, and α is the temperature coefficient of resistance. Using the power equation $P = I^2 R_s$, we can write

$$I^2 \cdot R_0\left[1 + \alpha\left(T_s - T_0\right)\right] \approx \left(a + bu^n\right) \cdot A \cdot \left(T_s - T_{in}\right) \tag{4}$$

In the present study, current I is constant (constant current mode), and T_0 is equal to T_{in}. From equations (1)–(4), we can derive the relationship between the variation in heater temperature and the gas velocity as

$$(T_s - T_0) \propto (c + du^{-n}) \tag{5}$$



(a) Top view (b) cross-section A-A

Figure 2. Microheater deposited on polyimide film.

where c and d are constants. As shown in equation (3), the variation in heater temperature (T_s-T_o) is proportional to the change in the resistance of the heater (R_s/R_o), which means that the resistance change is proportional to the mean gas velocity to the power $-n$ (i.e. the resistance ratio decreases as the gas velocity increases):

$$\frac{R_s}{R_0} \propto \left(c + du^{-n}\right) \tag{6}$$

The sensor detects the gas velocity, i.e. the flow rate in the tube, by measuring the change in resistance of the heating element.

3. FABRICATION

We fabricated the sensor element using polymer-MEMS technologies. We used 25-µm-thick polyimide film as a substrate. We deposited a thin Au/Cr film about 300 nm thick by sputtering and patterned it using a lift-off process to form the heater. The total size of the heater element was 1.0 x 4.0 mm^2 (Fig. 2). The width and interval of the heating lines were 90 and 40 µm, respectively. We mounted the flexible sensor on the inner wall of a tube to form a ring-shaped structure. We used a transparent flexible silicone tube to make it easier to change the bending conditions of the tube. The inner diameter of the tube was 3 mm. The assembled on-wall in-tube flexible thermal flow sensor is shown in Fig. 3.

4. EXPERIMENT

The experimental setup for evaluating the sensor under various tube bending conditions is shown in Fig. 3. We made a platform having several different angled grooves to simplify the

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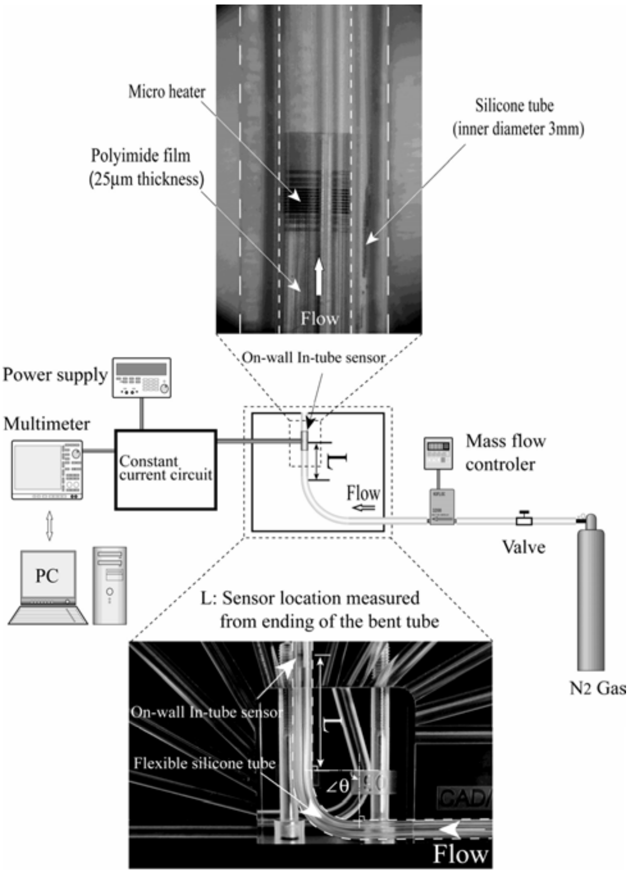

Figure 3. Experimental setup for flow rate measurement.

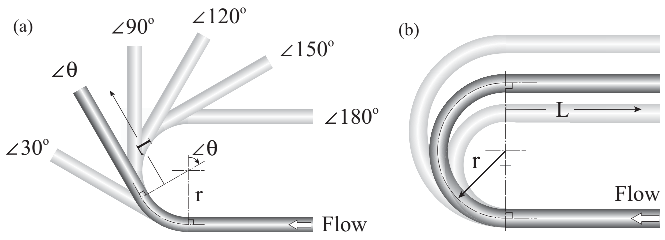

Figure 4. Bending angle (a) and curvature radius (b) used in the experiment. L: location of sensor measured from the end of the curve.

setting of the bending angle and radius of curvature of the flexible silicone tube. The experimental parameters—the bending angle *θ*, the radius of curvature *r*, and the distance from the end of tube's curve *L*—are schematically shown in Fig. 4.

The electrical resistance of the sensor's heater depends on the flow rate, as shown in equation (6). We first investigated the relationship between the resistance change and the flow rate in a straight tube. The results are shown by the dotted line in Fig. 5 (applied current: 55 mA). The normalized value of resistance, R/R_o, was used to show the amount of change clearly. The relationship can be expressed simply as $R/R_0 = 0.77 + 0.14u^{-0.3}$, so we concluded that the heat convection from the heater to the gas dominates the overall heat transfer, as described in section 2.

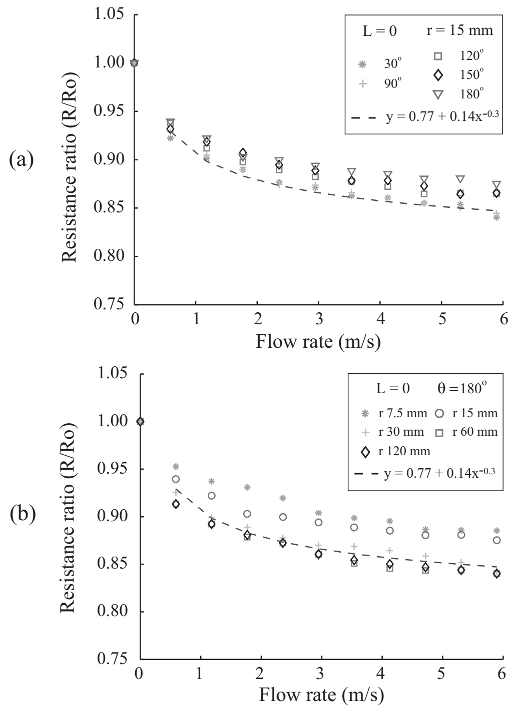

*Figure 5. Change in resistance versus flow rate for various bending angle, **θ**, (a) and curvature radius, r, at L=0D (b).*

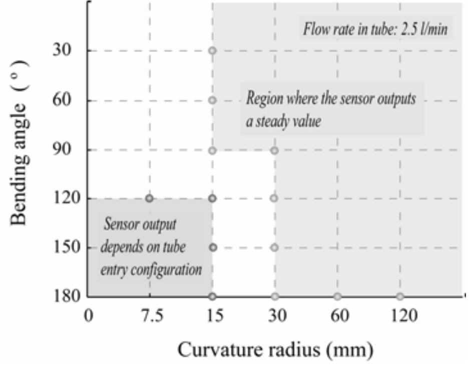

Figure 6. Steady sensor output.

We then evaluated the changes in sensor output versus the flow rate for various bending angle and curvature radius (Fig. 6). The sensor was placed at the end of the curve (*L=0D*). The resistance changes versus flow rate were almost the same as those obtained in the straight tube under the conditions of $\theta \leq 90°$ or $r \geq 30$ mm. The region where the sensor output was independent of both the angle and curvature radius at the end of curve is shown in Fig. 6.

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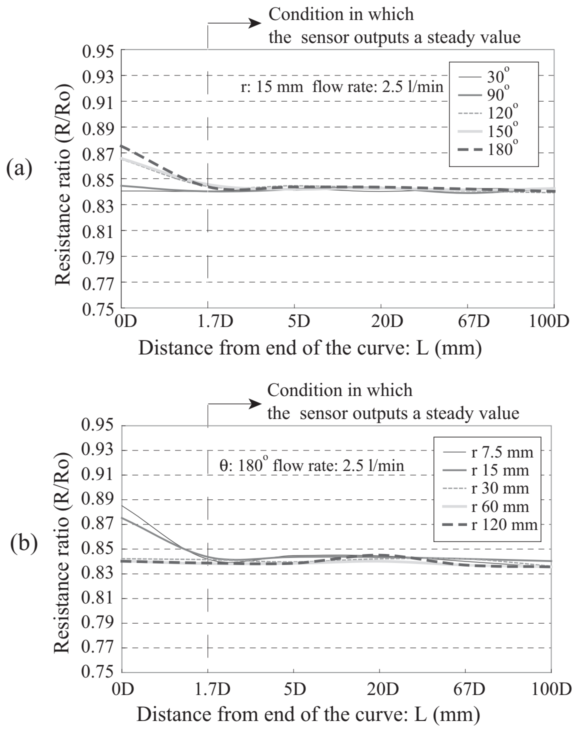

Figure 7. Change in resistance versus flow rate for various distances from the end of the curve (L) for various bending angle, θ, (a) and curvature radius, r (b).

The above results indicate that the sensor output depends on the bending angle and the curvature radius. We therefore investigated the effect of the distance between the end of curve and the sensor position under the conditions of 30° ≤ θ ≤ 180° at r = 15 mm and 7.5 mm ≤ r ≤ 120 mm at θ = 180° because the secondary flow gradually disappeared as a result of the gas viscosity as distance L increased. The flow rate was 2.5 l/min. As shown in Fig. 7, the sensor output was constant at L=1.7D and above (D: inner diameter of the 3-mm tube). This result means that our sensor can measure the gas flow rate independent of the tube configuration if it is placed at a location more than 1.7D downstream from the end of the curve.

5. CONCLUSION

We investigated the characteristics of an on-wall in-tube thermal flexible flow sensor under a radially asymmetric flow condition in a curved tube. The results are summarized as follows.

(1) The electrical resistance of the heater element decreased with increasing flow rate when the current was constant. This indicates that heat convection from the heater to the gas dominates the overall heat transfer.

(2) For tube configurations of $r \geq 15$ mm with $\theta \leq 90°$ or $r \geq 30$ mm with $\theta > 90°$, the change in resistance of the sensor versus flow rate at the end of the tube's curve ($L = 0$ mm) were the same as those in a straight tube. This means that the sensor can measure the gas flow rate stably at the end of the curve when the tube has one of these configurations.

(3) The sensor's resistance change became constant irrespective of θ and r when the distance from the end of the curve to the sensor position (L) was over 1.7D even if the tube configuration was unfavorable for flow-rate measurement at the end of the curve ($\theta \geq 120°$ and $r \leq 15$ mm).

From these results, we conclude that this on-wall in-tube flexible thermal flow sensor with a ring-shaped sensing structure can average the circumferentially nonuniform velocity distribution in a curve and is highly suitable for measuring the gas flow rate in the radially asymmetric flow condition in a curved tube.

REFERENCES

[1] Z. Y. Tan, M. Shikida, M. Hirota, and K. Sato, Characteristics of on-wall in-tube thermal flexible mass-flow sensors, Proc. 19th Int. Conf. on Micro Electro Mechanical Systems (MEMS 2006), 622-625, 2006.

[2] J. P. Holman, Heat Transfer Ninth Edition, McGraw-Hill Higher Education, pp 520, 2002

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

[4] J. Chen, J. Zou, and J. Liu, A Surface Micromachined, Out-of-Plane Anemometer, IEEE International Conference on Micro Electro Mechanical Systems 2002 15th, 332-335 IEEE, 2002.

[5] 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, 361-363, 1985.