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Technical Note

Study of the sensitivity of a thermal flow sensor

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ABSTRACT

The sensitivity of a thermal flow sensor is investigated in this study. A simple numerical model for analyzing heat transfer phenomena in the thermal flow sensor is presented. In order to validate the proposed model, experimental investigations are performed. Based on the results from the validated model, a correlation that predicts the sensitivity of the thermal flow sensor is presented. From the correlation, the manner in which the heat loss, the positions of the temperature sensors, the input power, and the heater length affect the sensitivity of the thermal flow sensor is investigated.

1. Introduction

The measurement and control of flow is critical in many engineering applications, including semiconductor manufacturing processes, chemical processes, and MEMS devices. The most widely used flow sensor is a thermal flow sensor, which has the advantage of a small size, a short response time, and low power consumption [1]. The thermal flow sensor typically consists of upstream and downstream temperature sensors and a heater located between the two temperature sensors as shown in Fig. 1(a). The mass flow rate is sensed via the temperature difference caused by the heat transfer interaction between a heated sensor and a fluid stream, as shown in Fig. 1(a) [2,3].

As shown in Fig. 1(b), the sensitivity of a thermal flow sensor is defined as the derivative of the temperature difference with respect to the mass flow rate at a zero flow rate. In other words, the sensitivity is given as the following equation:

$$S = \left.\frac{\partial(T_t(x = L_s) - T_t(x = -L_s))}{\partial \dot{m}}\right|_{\dot{m}=0} \quad (1)$$

As the sensitivity decreases, the ratio of the temperature difference to the mass flow rate decreases. If this temperature difference becomes smaller than the resolution of the temperature sensors, the thermal flow sensor cannot be used to measure the mass flow rate. Therefore, sensitivity is a critical parameter in the design of a thermal flow sensor. A number of researchers have studied the sensitivity of thermal flow sensors. Lammerink et al. [4] presented parameters that affect the sensitivity of a thermal flow sensor using simple 1-D modeling. Sabate et al. [5], Roh et al. [6], and Kim and Kim [7] experimentally showed the effects of the positions of temperature sensors and/or the heater power on the sensitivity of the thermal flow sensor. However, their results were limited to a qualitative evaluation. There is no reliable data or correlation by which it is possible to predict the sensitivity in the design of thermal flow sensors quantitatively.

The present study contends with the sensitivity of a thermal flow sensor. In it, a simple numerical model of a thermal flow sensor is presented. In order to validate the proposed model, experimental investigations are performed. Based on the results from the validated model, a correlation that predicts the sensitivity of a thermal flow sensor is presented. From the correlation, the manner in which the heat loss, the positions of temperature sensors, the input power, and the heater length affect the sensitivity of the thermal flow sensor is investigated.

2. Simple numerical model

To analyze heat transfer phenomena in a thermal flow sensor, the physical domain of the thermal flow sensor is divided into two regions: a sensor tube region and an inner fluid region. The energy balance for each region is represented by

$$k_t A_t \frac{d^2 T_t}{dx^2} + h_i P(T_f - T_t) - \frac{1}{R_r}(T_t - T_{amb}) + q' = 0 \quad (2)$$

$$k_f A_f \frac{d^2 T_f}{dx^2} - \dot{m} C_f \frac{dT_f}{dx} + h_i P(T_t - T_f) = 0 \quad (3)$$

where T_s, T_f, A, h_i, P, R_r, and q' are the tube temperature, inner fluid temperature, cross-sectional area, interstitial heat transfer coefficient, wetted perimeter of the tube, thermal resistance per unit length for radial heat loss, and heat flux per unit length supplied from the heater, respectively [8]. The first term on the left side of Eq. (2) is the axial conduction term, and the second term represents the thermal interaction between the sensor tube and the fluid. The third term denotes the radial heat loss from the outer wall of the tube to the surrounding area. Similarly, Eq. (3) consists of a conduction term in the axial direction, the enthalpy change term of the

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Nomenclature

A	cross-sectional area, m^2
C	heat capacity, J/kg K
h_i	interstitial heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	distance from the center of the thermal flow sensor to the end of the channel, m
L_h	distance from the center of the thermal flow sensor to the end of the heater, m
L_s	distance from the center of the thermal flow sensor to the temperature sensor, m
$\dot{m}$	mass flow rate of the fluid, kg/s
P	wetted perimeter of the tube, m
q'	heat flux per unit length supplied from the heater, W/m
R_r	thermal resistance per unit length for radial heat loss, m K/W
S	sensitivity of the thermal flow sensor, °C/(kg/s)
T	temperature, °C
x	axial coordinate

Subscripts

amb	ambient
f	fluid
t	tube

fluid, and the thermal interaction term. Boundary conditions are given as follows:

$$T_t(x=-L) = T_f(x=-L) = T_{amb} \tag{4}$$

$$T'_t(x\to\infty) = T'_f(x\to\infty) = 0 \tag{5}$$

Governing equations are solved using the control-volume-based finite difference method. A power law scheme is used for discretization of the conduction and convection terms. Discretization equations are calculated using the ADI method. All numerical data in this paper were obtained using the numerical model presented in this section.

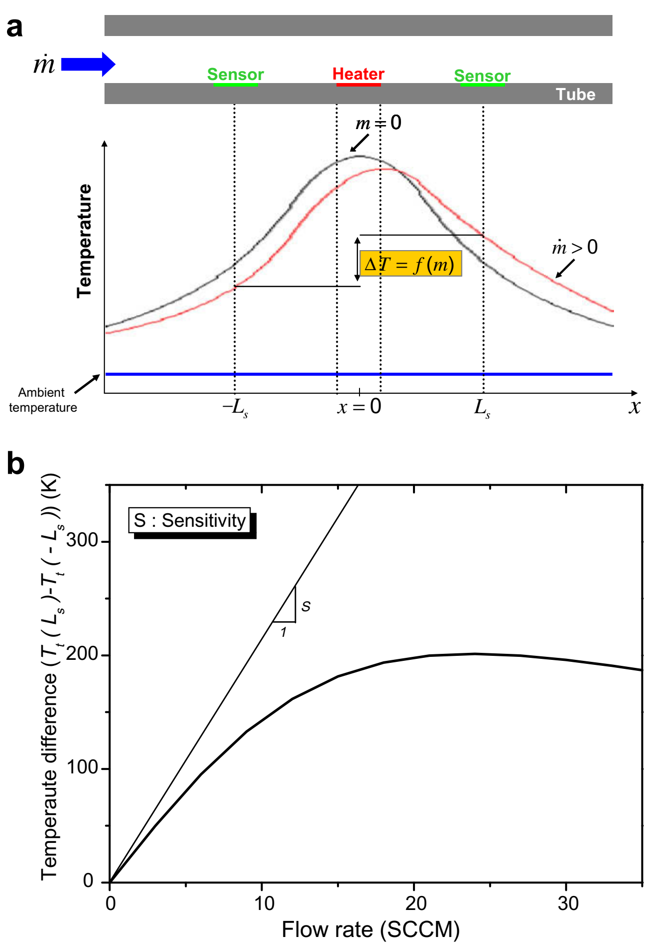

Fig. 1. Operating principle of the thermal flow sensor. (a) Schematic layout of the thermal flow sensor. (b) Typical output of the thermal flow sensor (not in scale).

3. Experimental validation

An experimental investigation was performed to validate the proposed numerical model. A thermal flow sensor was manufactured through simple microfabrication processes. Thin-film thermocouples and a heater were fabricated on a quartz wafer in sputtering processes. The heater consisted of nichrome and the thin-film thermocouples have compositions that are identical to those of standard K-type thermocouples. A channel consisted of PDMS (polydimethylsiloxane). The quartz wafer and the PDMS channel were bonded by using air plasma. Fig. 2 shows the thermal flow sensor. Detailed fabrication processes are explained in Ref. [7]. As flow sensors are generally calibrated with nitrogen gas, nitrogen gas was used as the operating fluid in this experiment. The purity

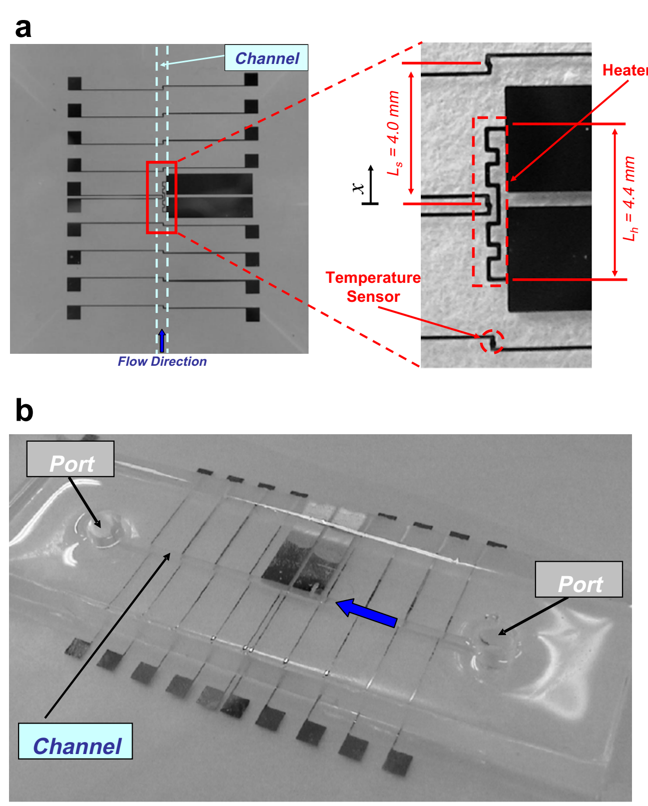

Fig. 2. Thermal flow sensor [7]. (a) Thin-film thermocouples and a heater deposited onto a quartz wafer. (b) The thermal flow sensor integrated with a PDMS channel.