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A dynamic thermal flow sensor for simultaneous measurement of thermal conductivity and flow velocity of gases

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ABSTRACT

Through finite element modeling and experiments, we describe individual influences of gas flow velocity (v) and thermal conductivity (λ) on temperature amplitude and phase measurements from a dynamic MEMS thermal flow sensor that employs AC heating at 200 Hz. We further describe the relationships among the temperature phase, time-of-flight, and time-of-diffusion proposing a new boundary layer definition based on the existing flow and thermal boundary layer theories. The sensor has five primary thermistors made of amorphous germanium for high sensitivity. Four of these are symmetrically distributed around four central heater elements on a thermally isolating diaphragm where the fifth is in the center. Simulations and experimental results show that phase shifts (time lags) of temperature between thermistors primarily depend on λ, and negligibly on v below a velocity limit. Simulation results also suggest that the influences of density (ρ) and specific heat capacity (c_P) on these phase shifts are relatively small or even negligible. Thus, λ can be accurately determined independent of the flow velocity for gases of similar $\rho \cdot c_P$ product, up to 1 m/s under the set flow boundary conditions. Hence, simultaneous determination of thermal conductivity and flow velocity is expected to be feasible with this sensor under these circumstances, which, in turn, allows medium-independent flow sensing for a such selected set of gases. Experimental results show that the measurement resolution and maximum inaccuracy of λ within the prescribed flow conditions are approximately equal to 2.445% and 3.18 + 4.20% (nonlinearity + velocity dependence) of the actual thermal conductivity, respectively.

1. Introduction

Thermal flow sensors are widely used in various applications for both liquids and gases. They operate by heating the fluid at one location and relating the convective cooling to the flow velocity (v) by measuring temperature at one or more locations along the flow path [1]. The rate and magnitude of temperature change at any sensor location depend also on density (ρ), specific heat capacity at constant pressure (c_P), and thermal conductivity (λ) of the fluid, which can be a pure gas or a mixture of gases. Because of that, such sensors must be calibrated for each fluid or compensated if the thermal properties of the fluid are known [2]. Ideally, compensation can also be made in a dynamic manner, i.e., during the measurement. This is especially beneficial if the fluid properties are time-dependent, which might result from an absolute temperature or pressure change or from a change in the composition of a gas mixture. In this particular case, the time-dependence of the fluid properties should be already known or the properties should be measured simultaneously with the flow. In this way, velocity of the flow can be accurately measured regardless of the fluid and fluctuations in its thermal properties. Such a sensor which enables simultaneous determination of thermal properties and flow velocity can be called medium-independent flow sensor.

Previous attempts to develop a medium-independent flow sensor have been reported based on combined temperature difference and time-of-flight measurements [3,4], and distributed temperature sensing across and along a multi-section microfluidic flow channel [5]. Disadvantages of these methods include the need for complicated data extraction methods based on neural networks [3,4] and on temperature profile measurements across microbridges [5], exhaustive measurements from many thermistor elements, and fabrication of a relatively complicated microsensor [5]. Although the sensor proposed by van Baar [5] is capable of delivering all the relevant thermal properties (ρ, c_P, λ) and flow information (v, η), where η is the dynamic viscosity, its fully

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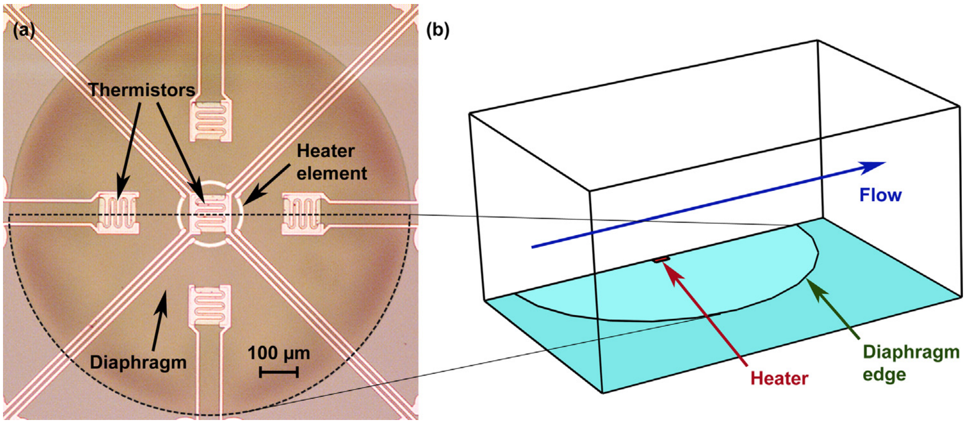

Fig. 1. (a) Magnified view of the sensor diaphragm with 5 thermistors, 4 heater elements, and corresponding metal connections and (b) an illustration of the axisymmetric simulation model.

integrated functionality as a medium-independent flow sensor has neither been demonstrated nor proven yet. Another proposed sensor measures the temperature frequency response by sweeping a range of heating frequencies [6] and uses it to extract thermal conductivity and thermal diffusivity provided that the flow velocity is known. Conversely, this sensor can also measure flow velocity provided that the thermal properties are known [6]. Both of these features require parameter fits using the derived analytical model. Since it requires the knowledge of either flow velocity or fluid properties, it cannot be regarded as a medium-independent flow sensor.

Here, we report on a different approach to thermal flow sensing that has several potential advantages. It is expected to enable the measurement of both flow rate and thermal conductivity of fluid using a simpler method and an easy-to-fabricate sensor. An optimized MEMS thermal flow sensor with low power consumption has been developed at IMTEK [7]. The proposed sensor employs four small heaters and five thermistors symmetrically placed around the heaters. This sensor is used with sinusoidal AC heating at 200 Hz, which provides additional information such as temperature amplitude and phase from each thermistor. This design alone is clearly not capable of extracting all necessary fluid and flow information (ρ, c_P, λ, v) required for a medium-independent flow sensor. Nevertheless, it is expected to perform as a medium-independent flow sensor for special applications where the fluids of concern are a set of gases having very similar $\rho \cdot c_P$ product. An example to such gases are noble gases. Additionally, it would be possible to extract thermal diffusivity (α) besides λ and v for such selected sets of gases with known $\rho \cdot c_P$ product.

Although AC heating-sensing method resembles the methods used by Lammerink and van Kuijk [3,4], sensor topography and data extraction methods distinguish our sensor widely from theirs. In our work, the high frequency heating method ($f > 100$ Hz) provides flow velocity independence for the temperature phase, which does not exist in their works. Thermal conductivity of the fluid can be extracted through the velocity-independent temperature phase. The extracted thermal conductivity information could be used to simultaneously correct the temperature amplitude signals to obtain medium-independent flow measurements for gases of similar $\rho \cdot c_P$ product. A similar case is shown by Reyes et al. [8]. Furthermore, temperature phase could serve for the determination of fluid concentrations in binary homogeneous fluid mixtures in stationary state [9] or within flows as proposed in this paper.

AC heating has also been used by many sensors for different purposes. It is a feature of the well-established thermal property measurement techniques: transient hot-wire method and the 2ω, 3ω methods, but flow-free media are considered in these works [10,11]. Contrarily, application of AC heating in thermal flow sensors has usually been a requirement of the chosen application and sensor type, but not a need for additional thermal property measurement [12–24].

In this work, we present the variation of temperature amplitude and phase with v and λ of the flowing fluid by means of finite element simulations (Section 6) [25]. Findings from simulations are supported by measurements (Section 7). These characteristics are shown for the first time together for a high heating frequency applied to a diaphragm-type MEMS thermal flow sensor. We further propose and define a new boundary layer based on the existing theories in flow and thermal domains (Section 5). Using this definition, the relationships among the temperature phase, time-of-flight, and time-of-diffusion are semi-quantitatively described.

2. Design features and fabrication

The sensor is composed of four arc-like central heater elements and five thermistors patterned on a 1.4 µm thick, 1 mm wide SiN_x–SiO_x diaphragm (Fig. 1(a)). The central thermistor measures approximately the heater temperature while the other four are symmetrically distributed around the heaters. Heater elements are made of chromium whereas the electrical leads are of titanium and gold to have an effective heating in the center. Highly sensitive, amorphous germanium thermistors are used, whose resolution is in the order of 100 µK [26,27] and have a temperature coefficient of resistance in the range of 2–3%/K at room temperature. This resolution enables us to operate the sensor with a low temperature rise so that the thermal properties of fluids remain approximately constant. All heater elements and thermistors are passivated by SiN_x–SiO_x thin films. The choice of diaphragm material and thickness provides a higher sensitivity to the fluid flow and to its properties and enables low power consumption.

The fabrication process is shown in Fig. 2 [25]. First, 400 nm thick wet silicon oxide is grown on a double-side-polished silicon wafer. Following that, 110 nm LPCVD nitride is deposited on both sides. Then, 500 nm low-stress PECVD nitride and 5 µm PECVD oxide are deposited on the front and the back sides, respectively. Next, 50 nm Cr, 300 nm α-Ge, and 200–100–20 nm Ti–Au–Ti layers are sequentially deposited and structured on the front side. As for the passivation layer, a low-stress PECVD nitride layer of 400 nm thickness is deposited at low temperature. The electrically insulating layers on the contact pads on the front side are structured with RIE. In order to release the diaphragm, SiN_x–SiO_x etch mask on the back side is structured and underlying silicon is etched with DRIE through the wafer. Thermal oxide and LPCVD nitride layers function as etch stop for DRIE.