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Sensing elements space design of hot-film sensor array considering thermal crosstalk

Baoyun Sun, Binghe Ma*, Jian Luo*, Boyuan Li, Chengyu Jiang, Jinjun Deng

Key Laboratory of Micro/Nano Systems for Aerospace, Ministry of Education, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China

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ABSTRACT

The flexible hot-film sensor array fabricated on polymer substrate with MEMS technology holds great importance for investigating and controlling flow separation and transition in the applications of fluid mechanics. The principle of these sensors is convective heat transfer from the sensing elements into the fluid. However, the heat dissipated into the fluid through forced convective will possibly has thermal crosstalk on the down-stream sensing elements. For this reason, the optimal space between two adjacent sensing elements needs to be considered in sensor array design. In this paper, FEM (Finite Element Method) simulations were performed to estimate the corresponding temperature distribution in the vicinity of the sensing element. We got the minimum non-thermal crosstalk spaces between two adjacent sensing elements in an array with various shear stress and sensing element working temperature. Moreover, both wind and water tunnel experiments were conducted to study the thermal crosstalk in a sensor array, and experimental results were agreed with the simulation results.

1. Introduction

When a fluid flows over a solid body, viscous effects generate shear stress and skin friction on the surface. Knowledge of such wall shear stress is extremely important in fluid mechanics studies, and its measurement is essential for investigating wall-bound turbulence [1–3] and flow separation [4–7] in aerodynamic/hydrodynamic applications.

In the last several decades, a large number of shear stress measurement devices have been developed, either based on direct or indirect methods [8]. The floating element sensor [9–11] is typically a direct way, which uses a wall shear stress balance. However, most aerodynamic structures are non-planar, and it makes the measurements difficult for the floating element sensor. The flexible hot-film sensor [12–14] is one indirect way for shear stress measurement, fabricated on a flexible substrate, possessing merits of well fit on curved surfaces, and less interference to the flow. Moreover, hot-film sensor array can be fabricated with simple MEMS processes, which can contribute to distributed flow measurement. Thus, it attracts broad attention for flow measurement.

As known, small space among sensing elements contributes to high spatial resolution in a sensor array. However, if the space is too small, the heat dissipates from the upstream sensing elements through forced convective will heat up the fluid, which will result in an increase of dowmstream ambient temperature, finally leads to inaccurate output voltage of downstream sensing elements. To reduce or even eliminate this kind of thermal crosstalk, the appropriate space in a sensor array should be considered.

In this paper, FEM simulations were performed to study temperature distribution around the sensing elements. Besides, the minimum non-thermal crosstalk spaces between two adjacent sensing elements in a sensor array with various shear stress and sensing element working temperature were studied. Finally, wind tunnel and water tunnel experiments were conducted to compare with the simulation results.

2. Theory analysis of heat transfer

The joule heat generated by the sensing element dissipated into the ambient in three modes of heat transfer [15], as shown in Fig. 1, include heat convection (Q_1), heat conduction (Q_2) and heat radiation (Q_3), while the heat radiation can be neglected. The heat convection, as described in Eq. (1), is depends on the heat transfer coefficient h, the surface area A and T–T_{fluid}, the temperature difference between the sensing element and the surrounding fluid.

$$Q_1 = hA(T - T_{fluid}) \quad (1)$$

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* Corresponding authors.
E-mail addresses: mabh@nwpu.edu.cn (B. Ma), luojian1985@gmail.com (J. Luo).

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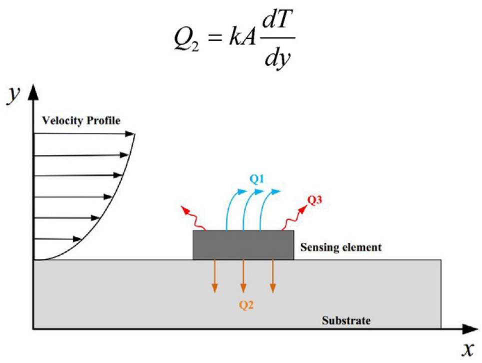

Fig. 1. Three heat transfer modes of the sensing element.

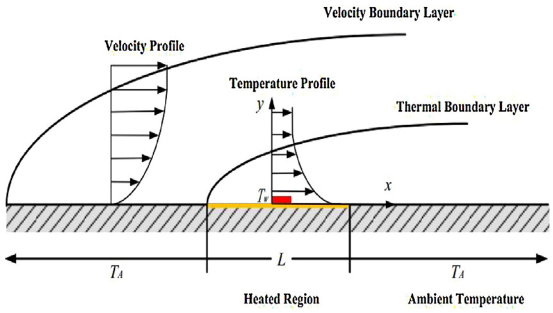

Fig. 2. Schematic view of the hot-film sensor heat transfer model.

The heat conduction Q_2, as described in Eq. (2), is conducted through a sensing element with the cross-section A when having a temperature gradient dT/dy at the sensing element/substrate interface. The ability of conducting the heat is defined by the thermal conductivity k.

$$Q_2 = kA\frac{dT}{dy} \tag{2}$$

The schematic view of the hot-film sensor heat transfer model is shown in Fig. 2. A theory was developed to describe the heat transfer effect of thermal sensors[16]. Forced heat convection in the fluid is governed by Eq. (3), and heat conduction in the substrate is governed by Eq. (4).

$$u\frac{\partial T}{\partial x} = \alpha\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \tag{3}$$

$$k_s t\frac{\partial^2 T_s}{\partial x^2} + k\frac{\partial T}{\partial y}\Big|_{y=0} = 0 \tag{4}$$

Where u is the flow velocity, $\boldsymbol{\alpha}$ is the thermal diffusivity of the fluid, T_s is the substrate temperature, and k_s is the thermal conductivity of the substrate.

If the space among two adjacent sensing elements is big enough, the thermal crosstalk can be minimized and even be neglected. How to evaluate the impact of thermal crosstalk and in what circumstances it can be ignored should be determined. We use the downstream ambient temperature change ΔT to estimate the magnitude of thermal crosstalk.

The resistance change of downstream sensing element ΔR is linear with the downstream ambient temperature change ΔT, as showed in Eq. (5), where R_0 is the sensing element resistance at temperature of 20 °C, α_0 is the temperature coefficient of resistance (TCR) of the sensing element.

$$\Delta R = R_0\alpha_0\Delta T \tag{5}$$

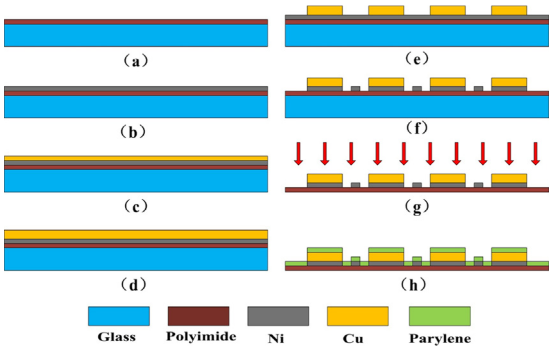

Fig. 3. Fabrication processes of flexible hot-film sensor array.

When the sensor operating in constant current mode, the output voltage change $\boldsymbol{\Delta}V$ is governed by Eq. (6), where I is the drive current.

$$I\Delta R = \Delta V \tag{6}$$

$\boldsymbol{\Delta}T$ can be expressed by Eq. (7), which is derived from Eq. (5) and Eq. (6).

$$\Delta T = \frac{\Delta V}{IR_0\alpha_0} \tag{7}$$

In our calibration experiments, the minimum output voltage change $\Delta V_{\min}$ is 1 mV, I = 50 mA, R_0 = 10 Ω, α_0 = 4000 ppm/ °C. Based on the above parameters, ΔT = 0.5 °C. In other words, if the temperature change of downstream fluid $\Delta T \leq 0.5$ °C due to heat effect from upstream, we considered the thermal crosstalk can be neglected.

3. Fabrication

The fabrication processes of the flexible hot-film sensor array are shown in Fig. 3. A ready-made polyimide (PI) foil in thickness of 50 μm is used as flexible substrate of the sensor. It is affixed onto a glass wafer by using a polydimethylsiloxane (PDMS) adhesive layer (a), which is spun-on the glass wafer and cured in a vacuum oven. The thermal sensing nickel layer is then magnetron sputtered (b) onto the cleaned PI foil. With a sputtered seed layer (c), the copper tracks layer is electroplated (d). Then the tracks and sensing elements are patterned with photolithography and wet-etched (e-f).

In order to improve the TCR and make the sensor's electrical resistance stable, annealing (g) and electrical aging are carried out to eliminate lattice defects in Ni films. The sensor is kept in a high-vacuum furnace, the temperature increased to 400 °C within 120 min and kept constant for 360 min. Then the sensor is applied an electric current of 60 mA in ambient temperature for 480 min.

If the sensor array needs a protective cover e.g. for measurements in water, Parylene C is selected as the protective layer to coat on the sensor (h). One fabricated sensor array with eight parallel thermal sensing elements is shown in Fig. 4, and the distance between each sensing element is 6 mm.

4. Simulation

In the simulation, the computational grids of fluid region and the sensing element are shown in Fig. 5. The minimum grid size in each direction is 0.002 mm, the total number of the grid points is approximately 4,057,900. Geometric configuration of the sensing element is illustrated in Fig. 6, whose length l is 3 mm, width b is 50 μm and thickness h is 1 μm.

Fluid temperature is set to be 20 °C (293.15 K) in our simulations. If the temperature change of downstream fluid $\Delta T \leq 0.5$ °C due to heat effect from upstream, the thermal crosstalk can be