A Comparison of the Behavioral Characteristics of Miniature Gas Flow Sensors

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ABSTRACT

This paper presents a comparison of three different designs for a miniature gas flow sensor operating on the thermal transfer principle, the standard silicon nitride membrane device and two plastic designs. The goal of this work is to determine the performance change when the conventional thin silicon nitride membrane is replaced with a thicker but less thermally conductive plastic substrate. The finite element method was used to determine the thermal behavior of the three different designs. Results comparing the temperature difference between the up and down stream sensing wires as a function of flow rate are presented.

Keywords: thermal gas flow sensor, plastic

INTRODUCTION

This paper presents a comparison between different designs for a miniature gas flow sensor operating on the thermal transfer principle for sensing the flow rate of a gas, the standard silicon nitride membrane design and two different designs using a plastic substrate. Previous publications on thermal gas flow sensors include [1, 2, 3]. Several miniature gas flow sensors are on the market (or are just coming to the market). In particular Honeywell [4] and Leister Process Technologies [5] both produce sensors, which have a thin membrane. The work presented here investigates using a plastic substrate instead of a thin silicon membrane in these devices.

The goal of this work is to determine the performance change when the conventional thin silicon nitride membrane is replaced with a thicker but less thermally conductive plastic substrate. One design criterion for a viable plastic design is whether the temperature difference between the up and down stream wires is great enough for measuring the flow rate in the desired range. The motive for pursuing this line of investigation is that silicon nitride membranes are susceptible to breakage from handling and have limits on the operational gas pressure. If it were possible to increase the thickness of the membrane, this would lead to a more robust design.

The finite element method was used to compare the thermal behavior of the three different designs. For the silicon nitride membrane model, experimental data was used to benchmark the accuracy of the computer results. For the different designs, results comparing the temperature difference between the up and down stream wires as a function of the separation distance of the wires and gas flow are presented.

DEVICE DESCRIPTIONS

Three different designs for a flow sensor are studied in this paper, the standard silicon nitride membrane design and two different designs using a plastic substrate. Figure 1 is a photograph of the thermal anemometer developed by Leister Process Technologies that was used in our studies. The three nickel film thermoresistors are structured on top of a thin silicon nitride membrane (0.5 μm thick), supported by a silicon substrate (500 μm thick); gas flows perpendicularly to these thermoresistors. The center wire is used as a heater; the other two wires measure temperature. The principle of hot-wire anemometry is the correlation of flow speed with the measured temperature difference between the up and down stream wires. The silicon device pictured is capable of detecting flows from 0.01 *ml/min* up to 20 *ml/min* with a power consumption of 200 *mW*.

Figure 2 shows a schematic drawing of the silicon flow sensor along with the two plastic designs. The first plastic design (the middle diagram) consists of a solid plastic substrate, 515 *μm* thick. The second plastic design (the bottom diagram) consists of a plastic membrane, 15 *μm* thick, supported by a plastic substrate, 500 *μm* thick. In both cases, three nickel film thermoresistors are deposited on top; the center wire is used for heating and the other two for temperature sensing. In all three designs, a rectangular channel, 0.7 *mm* tall and 2 *mm* wide (out of the page), was modeled above the structure; this channel (not shown in Fig. 2) is used to convey the gas. The heating area, created by the center wire, is in the middle of the devices and is 40 *μm* long (in the horizontal direction) and 1 *mm* wide; the height of the wire was neglected. For the two membrane designs, the membrane area is 1.5 *mm* long and 1 *mm* wide. The enclosed volume beneath the membrane is considered filled with stationary air.

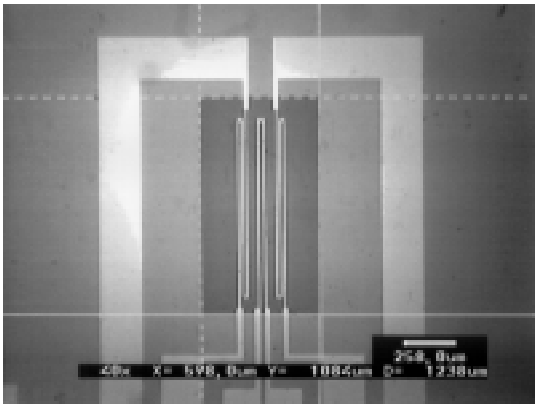

Figure 1: Photomicrograph of the gas flow sensor. The three serpentine thermoresistors are shown on the (dark) membrane region.

FINITE ELEMENT MODEL

The finite element method was used to simulate the behavior of the different devices. The commercially available software package ANSYS 5.4 was used for the analyses. For each device, a three-dimensional model was developed. The element used for these analyses (solid70) is capable of modeling thermal conduction and convection. The final model of each device consisted of over 65,000 nodes. Figure 3 shows a sectioned view of the finite element model for the plastic membrane structure. The rectangular box on the top outlines the location of the channel. For the simulations, constant material properties were used and the values were chosen at 50*°C*, which is the median temperature of the system. Air was chosen as the gas modeled. The values used for the thermal conductivity for silicon, silicon nitride, plastic and air were 150, 20, 0.2 and 0.03 *W/m K*, respectively. The flow profile of the gas at the inlet was considered fully developed and this profile remains unchanged along the length of the channel. The flow profile for the rectangular duct was determined using the equations of Natarajan and Lakshmanan as they were reported by Shah and London [6]. Figure 4 shows the temperature distribution of the device for two different views: side and top view. The heater wire is fixed (by the circuitry of the sensor) at a temperature of 100*°C*. The gas at the inlet and all the walls of the system, except the channel outlet, were considered fixed at an ambient temperature of 0*°C*.

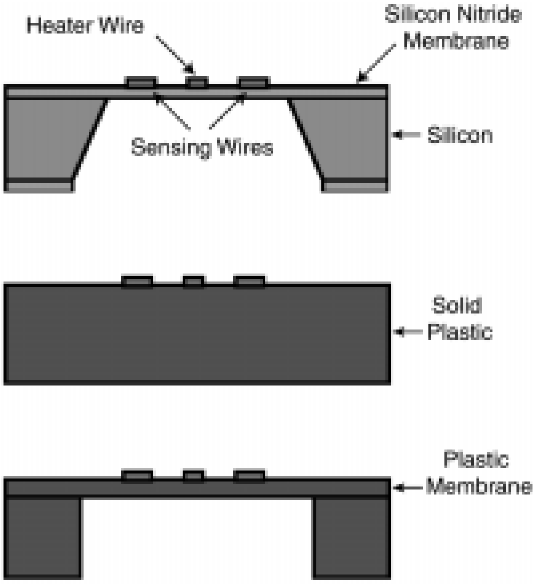

Figure 2: The three different designs investigated: *top*, a silicon nitride membrane; *middle*, a solid plastic substrate; *bottom*, a plastic membrane.

EXPERIMENTAL VERIFICATION

For the silicon nitride flow sensor, the simulation results have been compared with experimental data. This data was obtained by applying a constant current source to the heater wire. At the same time, the resistance of the heating wire was measured. With this data, the dissipated power is known. Using a syringe attached to a linear motor, a constant and known flow was forced through the channel above the membrane. The resistance of the up and down stream wires was measured and, therefore, the change in temperature caused by the gas flow can be determined. By entering the same power and flow into the finite element model, the computed temperature difference between the up and down stream wires can be compared with the experimental data. Figure 5 summarizes the results for two different flow speeds, 5 and 10 *ml/min*. The results of the finite element analyses are slightly lower than the experimental results, but in general, good agreement was found.

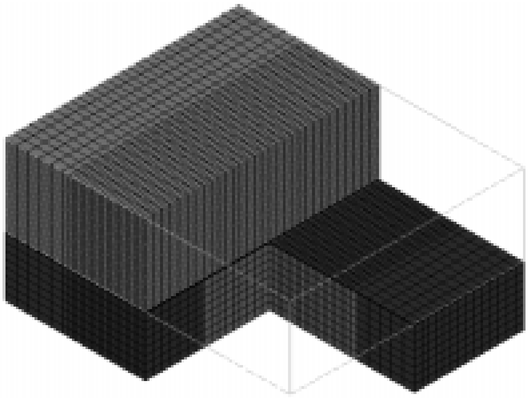

Figure 3: A sectioned view of the finite element model of the plastic membrane structure on the bottom and the gas channel on top.

RESULTS

For the three different geometries described above, the steady state temperature distribution was determined for different flows between 0.25 and 4 *m/s*. Figure 6 shows the temperature difference of the up and down stream wires as a function of the separation distance of the wires. For each flow, there is an optimum separation distance. For the silicon nitride membrane device, this distance varies between 0.7 to 0.5 *mm*; for the plastic membrane device, the variation is larger, ranging from 0.65 to 0.35 *mm*.

Figure 7 shows, for a specific wire separation of 0.6 *mm*, the temperature difference as a function of mean flow speed for the three different designs. All three designs have a linear operating range of approximately 0 to 0.5 *m/s*, after which the curve flattens as predicted by King's law. Sensitivity is defined as the change in the temperature difference divided by the change in mean flow. At low flows the sensitivity of the three different designs are: 40 *K/m/s* for the silicon nitride model, 17 *K/m/s* for the plastic solid, and 54 *K/m/s* for the plastic membrane.

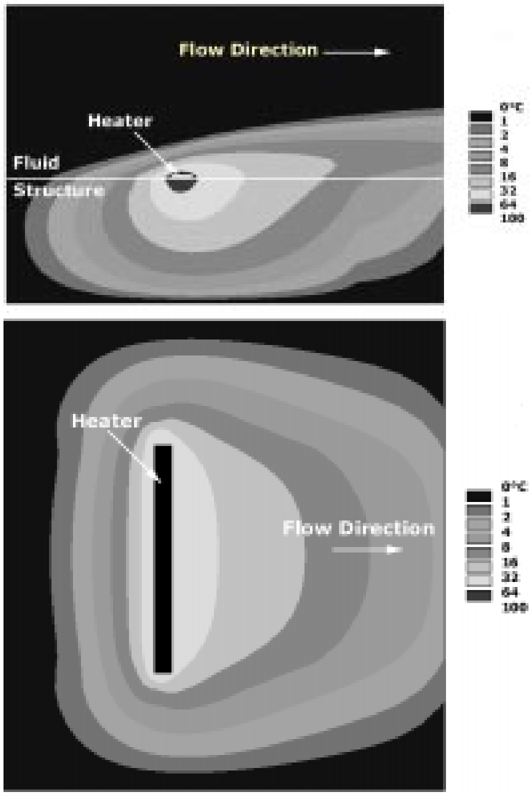

Figure 4: The computed temperature distribution of a plastic membrane device: *top*, side view of a center section of the device; *bottom*, top view of the interface between the fluid and structure. In both cases, the heater wire is fixed at a temperature of 100°C, the ambient temperature is 0°C, and the mean flow speed is 4.0 m/s.

CONCLUSION

The goal of this work was to determine the change in the thermal performance of a miniature gas flow sensor when the conventional thin silicon nitride membrane is replaced by a thicker but less thermally conductive plastic. By examining the sensitivity at low flows for the three different designs, one can determine that the sensitivity of the plastic membrane design is of the same order of magnitude as the traditional silicon nitride membrane design, while the sensitivity of the solid plastic design is much lower. Therefore, from thermal transfer design criteria, a successful thermal flow sensor can be constructed from plastic, if the substrate thickness can be made thin enough.

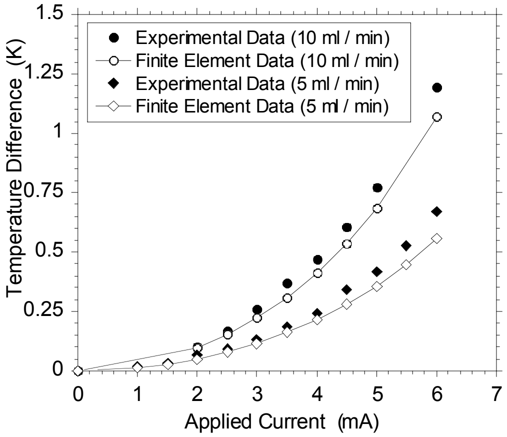

Figure 5: Comparison of the experimental and simulated results for the silicon nitride membrane device for two different flow speeds, 5 and 10 *ml/min*.

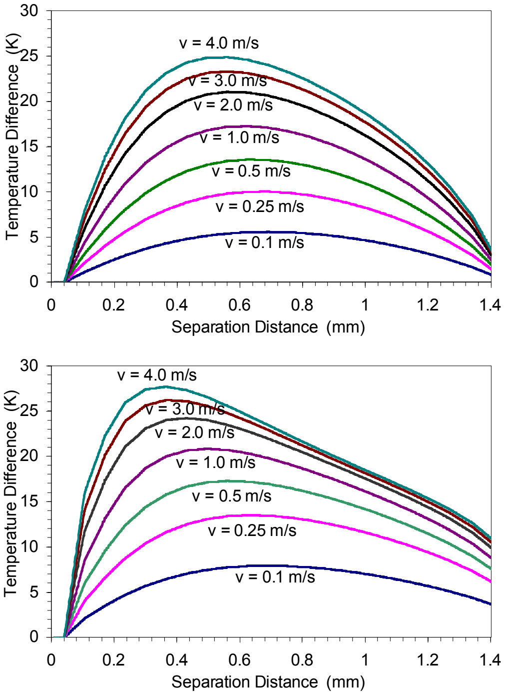

Figure 6: The temperature difference between the up and down stream wires as a function of the separation distance between the wires for different flows: *top*, silicon nitride membrane configuration; *bottom*, plastic membrane configuration.

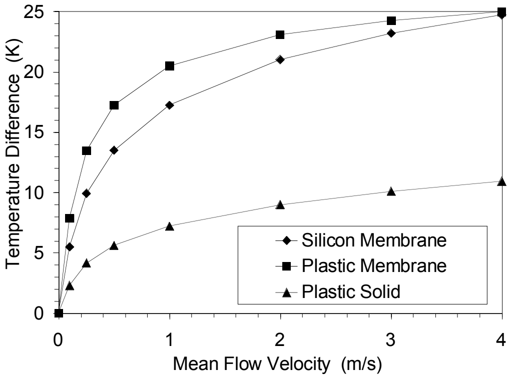

Figure 7: The variation for different flow speeds of the temperature difference between the up and down stream wires for the three different configurations. The wire separation is 0.6 mm and the heater was fixed at 100°C.

REFERENCES

[1] S. F. Trautweiler, "Silicon Hot Film Flow Sensors," Thesis submitted to the Swiss Federal Institute of Technology Zurich, DISS ETH No. 12185, 1997.

[2] Ph. Lerch, O. Dubochet, and Ph. Renaud, "From simple devices to promising microsystem applications," 21st International Conference on Microelectronics, Nug, Yugoslavia, September 14-17, 1997, pp. 59-62.

[3] S. B. Crary, P. Cousseau, D. Armstrong, D. M. Woodcock, O. Dubochet, Ph. Lerch, Ph. Renaud, "Optimal design of computer experiments for the generation of microsystems macromodels using IMSET and non-parametric fitting," 2nd International Conference on Modeling and Simulation of Microsystems, San Juan, Puerto Rico, April 19-21, 1999, pp. 184-189.

[4] Honeywell, MICRO SWITCH Sensing and Control, USA.

[5] Leister Process Technologies, CH-6060 Sarnen, Switzerland.

[6] R. K. Shah, A. L. London, "Laminar Flow Forced Convection in Ducts," Academic Press, New York, 1978, pp. 196-203.