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THICK-FILM THERMALLY EXCITED RESONATOR FOR MASS FLOW MEASUREMENT

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Abstract: This paper illustrates the design and the development of a thick-film mass flow sensor based on the frequency shift of a resonating ceramic structure. The mechanical oscillator realized uses a measurement principle of thermoanemometric type. The sensor can measure mass flows up to 15 x 10^4 sccm (sccm: 10 sccm = 0.17 mg/s), with high sensitivity. Here we report on the first prototype consisting of a beam 0.254 mm thick , 4 mm large and 17 mm long, in which the temperature variations induced by flow, affect the resonance frequency. Predicted and measured values for the shift of the resonance frequency agree well. At the first flexural mode of vibration of 3.5 kHz and at an average temperature rise of the substrate of 100 ° C, a frequency change of 500 Hz in the mass flow range from zero to 15 x 10^4 sccm can be measured. Indications are proposed for reducing the time response and increasing the sensitivity.

Keywords: thick-film sensors, mass flow measurement, PZT resonators

1 INTRODUCTION

Flow phenomena have a direct practical significance in many industrial, technical and everyday situations: in meteorology (wind velocity and direction), civil engineering (wind forces on building), transport and process industry (fluidic transport of media, combustion, vehicle performance), environmental sciences (dispersion of pollution), biomedical (respiration and blood flow), and indoor climate control (ventilation and air conditioning). Two typical examples of the many possible flow-measurements problems are:

(a) Flow velocity measurement: the flow velocity is a vectorial quantity, which describes the local situation in a flow field. When the direction of the flow is known, a measurement of the magnitude of the flow is sufficient. In other cases a directionally sensitive measurement may be required to determine the different velocity components.

(b) Fluidic transport rate: in the case where the flow is confined to a restricted space (pipe or channel) the total amount of fluid (mass or volume) passing through it per unit of time is to be determined.

In case (b) the best option to measure the mass flow of a gas is to make use of the ability of the gas to transport heat by forced convection [1,2]. Moreover, the specific heat of gases, usually of the order of magnitude of 10^3 J(kg°C)$^{-1}$, is virtually independent of ambient condition [3].
Due to this preliminary observations (and making use of a three-dimensional heat transfer model [4]), the possibilities to use a resonating structure for mass flow measurement within a 3 cm dia. channel is investigated. The principle under consideration is of thermoanemometric type. Besides the general advantages of resonant sensors (i.e. stability and semi-digital output [5]) resonating beam sensor have high sensitivity to planar stress. With the latter that can translated into a frequency shift with high resolution. Our aim is to develop a low cost mass flow sensor for mass flow till to 15 x 10^4 sccm operating at temperature elevation of 100 °C with high demands in term of cost, repeatability and sensitivity.
In this paper the operation principle and the fabrication method in thick-film technology are illustrated together with the experimental results.

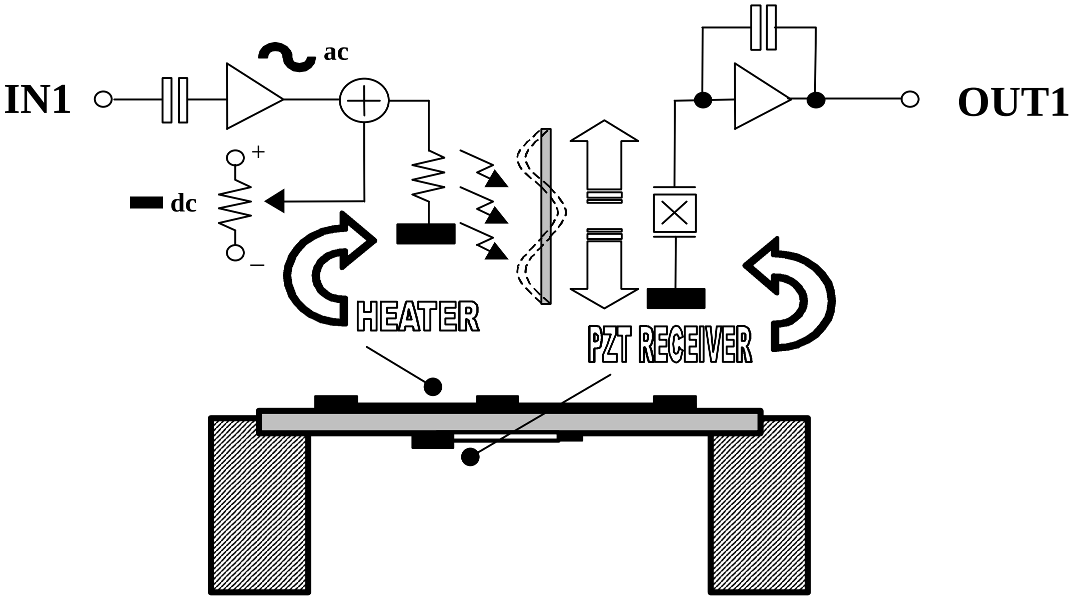

Figure 1. Principe of operation: central thick-film nickel resistor for thermal excitation of the bending vibration; PZT film in the opposite side to reveal the vibrations.

2 PRINCIPLE OF OPERATION OF THE SENSOR

The operation principle of the mechanical oscillator is presented in fig. 1. By applying a d.c. voltage across the centre resistor, a distribuited static heat is generated. The fluid passes across (up and down) the ceramic beam heated by the electrical power, the heat is transferred to the fluid and the resulting average temperature elevation of the beam become dependent on the cooling effect of the passing fluid.

For the forced vibration of the beam, is induced by thermal excitation and piezoelectric detection. For the excitation, an ac voltage (IN1) is superimposed on a dc voltage applied to the centre resistor described above. The dynamic component of the generated heat leads to a periodic thermal expansion of the upper surface of the substrate, thereby inducing a bending mode vibration. In the opposite side of the beam, a piezoelectric sensor is installed to detect the vibration of the mechanical support.

Using the resistor as heat generator with a superimposed dynamic signal and the piezoelectric element as the output we have obtained an electro-thermo-mechanical oscillator [5].

The heater (divided into two-balanced resistive parts) can be also used as flow direction detector. Seeing that the sensor sensitivity closely agree with the fluid temperature, the resistor, used as actuator, can be exploited to measure the initial environmental condition (injecting low currents to avoid self-heating effects).

The resonance frequency of the beam depends on the geometric-constitutive chacteristics of the beam and on the planar stress condition. The temperature elevation of the beam relative to the support causes a compressive planar thermal stress, thereby decreasing the resonance frequency. Cooling the substrate by the mass flow causes an increase of the frequency. This frequency change is now the measurand.

3 THE SENSOR MANUFACTURING IN THICK-FILM TECHNOLOGY

The fabrication method involves the standard thick-film procedures on 96% alumina substrate [7,8]. The planar resistor adopted for the heating processes, for the flow direction detection and for the fluid temperature level is based on an air fired nickel conductor (with a nominal resistance of 250 Ω). The fired nickel film (25 μm thick) has a high positive temperature coefficient of resistance ($\cong$ 5000 ppm/°C).

The vibration detector has a structure of a plane capacitor cosisting of a ferroelectric layers as dielectric and two conductive plates based on Pd/Ag material (Heareus C1214), as armatures. In order to achieve adeguate piezoelectric characteristics, after the firing processes (at a peak temperature of about 950°C) the layers were subjected to a poling step by applying a dc electric field of 2.5 MV/m at 180°C for 20 minutes. The field was then removed when the layers were cooled down to room temperature. These procedures set up the piezoelectric activity of the layers. In fig. 2 is shown a photograph of the electro-thermo-mechanical oscillator. The beam dimensions are 4 x 17 x 0.254 mm respectively. The ferroelectric active layer (on the right) and the thermal actuator/sensor (on the left) are well distinguishable.

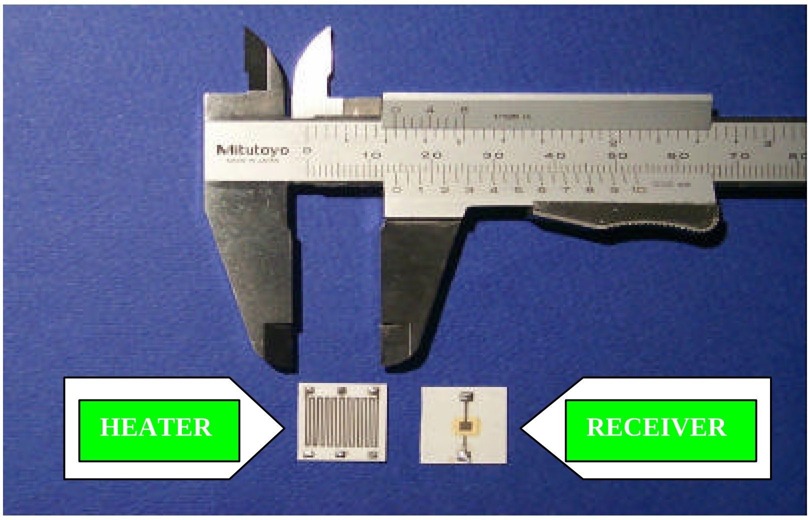

Figure 2. Photograph of the thick-film electro-thermo-mechanical oscillator.

4 EXPERIMENTAL RESULTS OF THE THICK-FILM PROTOTYPE

4.1 Experimental set-up

Figure 3 shows the experimental set-up for testing the sensor. A controlled gas flow (air) is passed across the heated beam though a stainless steel channel with 30 mm dia. For the vibration of the beam, the ac output voltage of the hp 4194 A gain-phase analyzer is amplified, and superimposed on the output voltage of a dc source. This is then translated into a current signal and it is applied over the excitation resistor at the centre of the ceramic substrate. Via a charge amplifier the vibration receiver output is connected to the analyzer. By sweeping the excitation frequency, the analyzer measures the transfer of this two-port electro-thermo-mechanical device. From this, the resonance frequency is determined, which is now a function of the static heat generated on the beam, and of the cooling effect of the airflow.

4.2 Experimental results

Fig. 4 shows a transfer function example (gain-phase behavior) of the two-port electro-thermo-mechanical oscillator in the case of zero mass flow (resonance frequency of about 3500 Hz) and 9 x 10^4 sccm flow (resonance frequency of about 3900 Hz). A Q factor of about 70 can be found.

Fig. 5 (a) presents the results for the measured and predicted (by a complex model [9,10,11]) resonance frequency of the thick-film prototype vs. the mass flow. The results obtained agree qualitatively well with the predicted values (the deviations are probably caused by the uncorrect modelization of the beam clamping condition and the uncertanaity of the beam thickness and of the material properties as well as by omitting the heat dissipation on the nylon support). It can be observed that the frequency shift with increasing mass flow is quite liner in the range till 8 x 10^4 sccm. This leads a sensitivity of about 37Hz/10^3sccm.

Fig. 5 (b) presents the results of the measured and predicted average temperatrure elevation of ceramic substrate vs. the mass flow. The chosen temperature elevation of the ceramic substrate is of about 100 °C in worst case (this value is limited by the Curie temperature of the PZT receiver and the support operative temperature).

Repetitive tests have shown a sensor repeatability of about 0.6 % FS together with an hysteresys not greater than 0.9 % FS. For different cases the measured time response of the sensor (in the case of 40 °C step) is within 25 seconds.

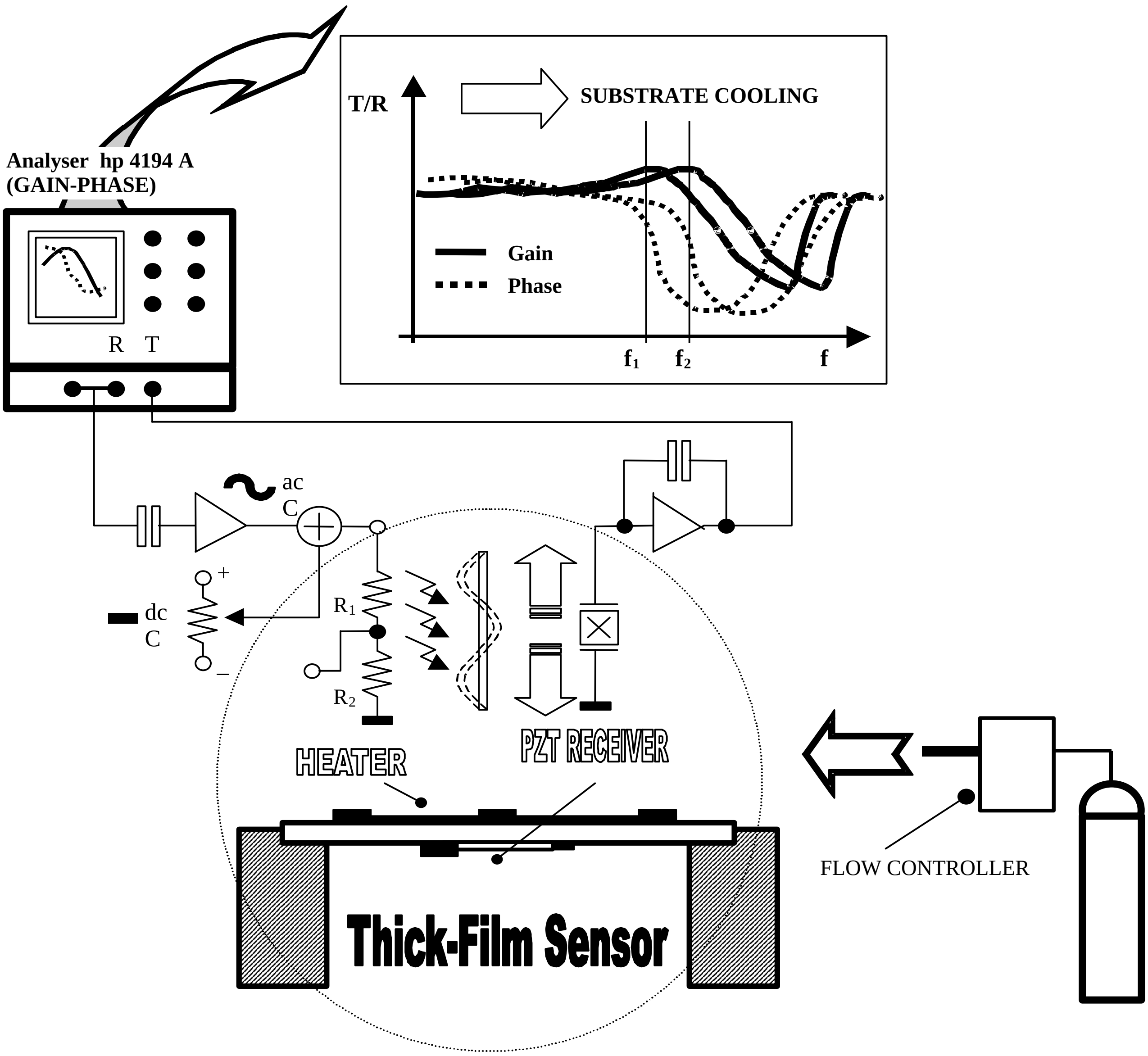

Figure 3. Experimental set-up.

4.3 Discussion

The sensitivity of the resonance frequency to a temperature elevation of the substrate is quite high. The sensitivity can be increased further by using thinner beam substrate (however, a lower limit of 150 µm cannot be overpassed to avoid problems during printing and firing processes) and by decreasing the thermal loss by conduction to the support (e.g. using shortest edges in thermal contact with the support).

The resonance frequency proved to be very stable with respect to small change in ambient condition. However, when the sensor is operating at a low temperature elevation (15-30 °C), a small change in the temperature of the incoming gas may cause a relatively significant frequency shift. The coefficient of thermal conductivity of gases is largely dependent with temperature, pressure and type of gas [3]. A reference measurement will be required to compensate for such undesired effects [4].

5 CONCLUSION

The possibility of mass flow measurements using a resonant beam has been presented. The fabrication of the first prototype consisting of an alumina 96% substrate, with standard thick-film technology for excitation and detection, is relatively simple. The experimental and theoretical results for this bridge prototype agree quite well. The sensitivity of the resonance frequency to a temperature elevation is very high. Repetability and hysteresys are both within1 % FS.

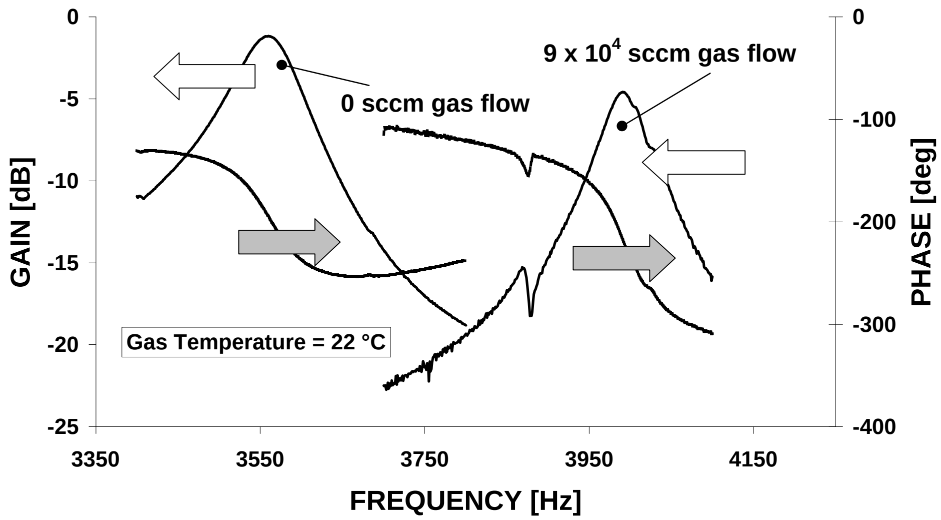

Figure 4. Gain-Phase curves obtained in the case of 0 sccm and 9 x 10^4 sccm flow respectively.

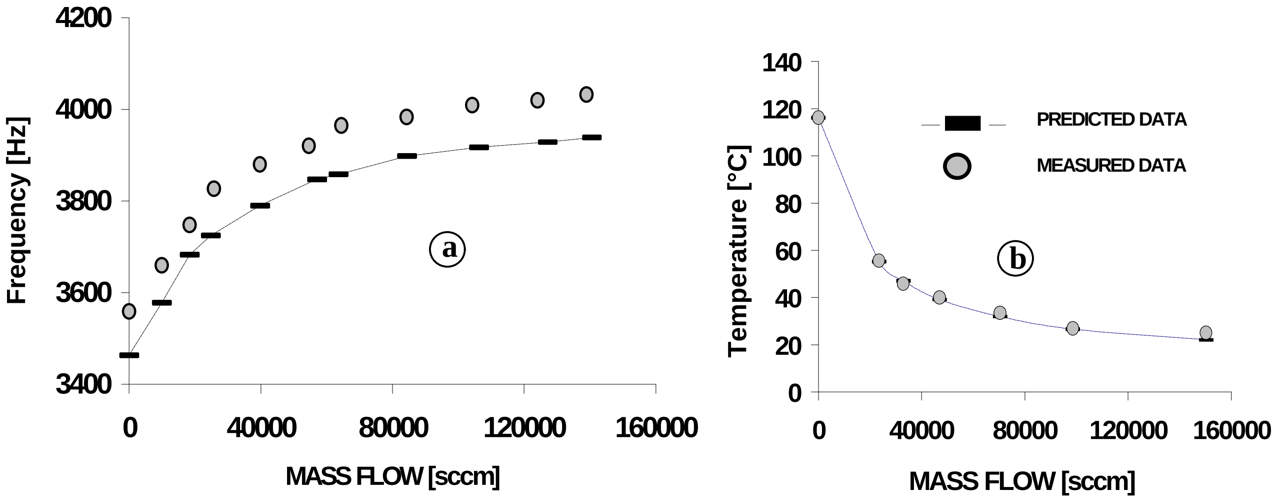

Figure 5. Experimental and theoretical results: (a) measured resonance frequency and predicted resonance frequency (b) measured average temperature elevation of the ceramic substrate and predicted values.

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