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Dynamic operation of a micro-thermocouple sensor as a vacuum gauge

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A B S T R A C T

We present an experimental characterization of a new vacuum gauge based on a K type micro thermocouple with 25.4 μm diameter. This sensor is intended for the simultaneous measurement of the temperature and pressure in the ranges extending from 293 K to 400 K and 10^{-1} Pa to 10^5 Pa respectively. The paper gives an investigation of the micro-thermocouple vacuum gauge signal for the oscillating heating and cooling processes. The operation of the sensor is based on the analysis of the frequency of the oscillating signal obtained from an electric Joule heating of fixed duration and a cooling of variable duration depending on gas pressure in the vacuum chamber volume. The frequency of the signal oscillation is a function of the gas pressure in the system. Due to its low thermal inertia (time constant of 30 ms), this gauge gives two pieces of information simultaneously: the temperature and the pressure of the gas. Experiments are conducted with dry air.

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Vacuum gauges are devices for measuring gas pressures below atmospheric pressure. In many cases the pressure indication depends on the nature of the gas. For instruments with indirect pressure measurement, the pressure is determined as a function of a pressure-dependent property (thermal conductivity, ionization probability, electrical conductivity) of the gas that are proportional to the number density of particles and thus to the pressure. The vacuum gauges with gas-dependent pressure reading include the ionization vacuum gauge, the viscosity gauge and the thermal conductivity vacuum gauge [1–11]. Thermocouple gauges belong to the class of vacuum gauges which rely on the thermal transport qualities of gases. The thermocouple gauge uses the thermal conductivity property of gases, by incorporating a wire filament which is heated by a constant source of power. Attached to this filament is a thermocouple, which measures the temperature of the wire. At high pressures, the large number of gas molecules striking the heated wire carries energy away and cools the wire. At low pressures, the smaller number of gas molecules striking the wire cause less cooling, and thus a higher temperature. The thermocouple output voltage responds to these temperature changes to give an indication of pressure: low gas pressure gives high filament temperature which gives high thermocouple output voltage; high gas pressure gives low filament temperature which gives low thermocouple output voltage. The meter measuring the thermocouple voltage is calibrated in pressure units to give a direct indication of pressure. At pressures below about 10^{-1} Pa, the heat loss from the filament is primarily through radiation since the density of gas molecules is so low. Since the heat loss due to radiation is constant, the resulting temperature corresponds to the “zero” reading on the meter. The thermocouple gauge is a simple, rugged device which is very useful at rough vacuum pressures.

This paper describes the results obtained with a new kind of thermocouple gauge in which the classical arrangement wire and thermocouple is replaced by a simple K type micro thermocouple (Chromel–Alumel with 25.4 μm diameter) heated by an electric current and cooled by the gas (air) for the simultaneous measurements of the temperature and the pressure in the range extending from 10^{-1} Pa–10^5 Pa. The Chromel–Alumel thermocouple is recommended for use in clean oxidizing atmospheres and it is the thermocouple most widely used in industrial applications. Type K thermocouples generally work in most applications because they are nickel based and have good corrosion resistance.

The experimental setup is composed of a vacuum pump, a measurement chamber and the micro thermocouple Th_{sens} (Fig. 1).

The vacuum measurement chamber is a copper cylinder of 55 mm internal diameter and 50 mm height. It represents a 90 cm^3 internal volume approximately (without the volumes of the two

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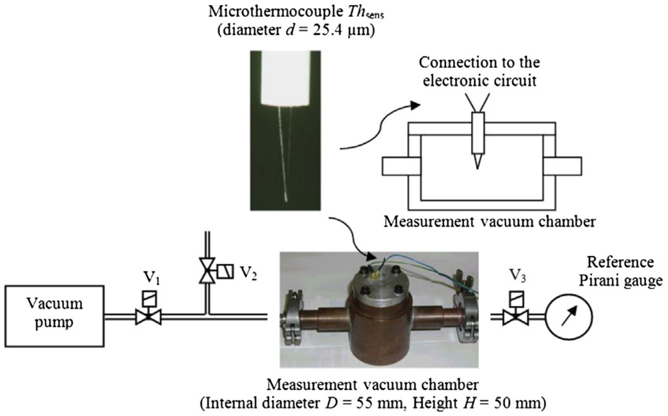

Fig. 1. Experimental setup. The vacuum gauge micro thermocouple measures the pressure and the temperature in the volume of the vacuum chamber.

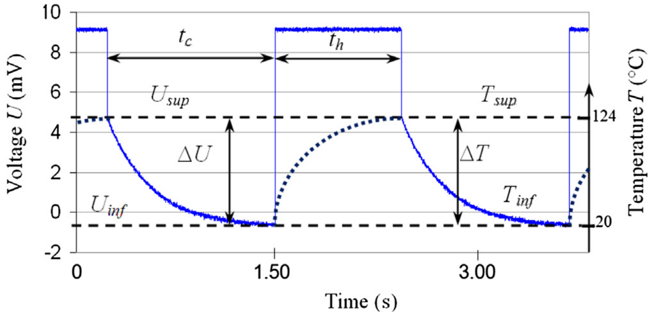

Fig. 2. Typical response of the sensor for the vacuum pressure $P = 100$ Pa. Vacuum gauge = K type thermocouple. Seebeck coefficient = 40 μV K^{-1}, diameter $d = 25.4$ μm, $t_h = 1$ s, $t_c = 1.25$ s, $I_c = 31.5$ mA, oscillation frequency $f = 1/(t_c + t_h) = 444.44$ mHz, $\Delta U = U_{sup} - U_{inf} = 5.2$ mV, $\Delta T = T_{sup} - T_{inf} = 104$ °C. The dashed curve (.......) corresponds to the rise in temperature that would follow the thermocouple if the amplified voltage (×1000) measurement was possible during the heating duration t_h.

connecting tubes). The system is pumped by a mechanical vacuum pump down to the pressure of 1 Pa. The V_1 valve isolates the pump from the calibrating chamber. The high-sensitivity leak valve V_2 connected to the atmospheric pressure is used to adjust the working pressure in the chamber. In a first step, the V_2 valve is closed while the chamber is pumped down from atmospheric pressure to a primary vacuum (10^{-1} Pa). Then, the V_1 valve is closed and the second V_2 valve is opened in order to admit the gas into the calibration chamber. The absolute pressure range obtained with this method is thus of 10^{-1} Pa–10^5 Pa. The sensitive probe Th_{sens} is placed in the vacuum measurement chamber and the static pressure is measured by a Pirani vacuum gauge (type Thermovac TM 20) located next to the V_3 valve after the measurement vacuum chamber and is used in our experiments as a reference pressure gauge. The micro thermocouple probe is realized in our Laboratory. It consists of two Chromel and Alumel wires with 25.4 μm diameter inserted in a ceramic double bore insulator with length and external diameter depending on the experimentation [12]. Aside from the low heat capacity effect, another consequence is that the cross-sectional area of the wire itself can be used to calculate time constants.

The dynamic operation of the micro-thermocouple sensor as vacuum gauge consists in heating a micro thermocouple with an electric current by Joule effect during a constant phase and letting it cool during a second phase, which depends on the pressure existing inside a vacuum chamber volume. An electronic command ensures the succession of these two processes and it becomes possible to connect the pressure information to the obtained signal frequency. The sensor is then used as a vacuum gauge. Moreover, at the end of the cooling phase, the signal value corresponds to the local temperature of the fluid and this method presents thus the advantage to measure the two local thermodynamic parameters, the pressure and the temperature, with one probe only.

Fig. 2 presents the transient response of the micro-thermocouple placed in the vacuum measurement chamber. At the end of the heating period t_h, the temperature of the Th_{sens} micro-thermocouple tends to that of the fluid temperature T_f. A temperature calibration apparatus (AOIP PHP 601) is used to calibrate the thermocouple with a global static temperature accuracy of ±0.1 K in the temperature range 293 K–400 K. The time t_c necessary to the sensor during the cooling phase to reach the temperature T_f is not constant and depends on the fluid pressure P directly. During this time, the wires of the thermocouple exchange heat with the environment under the static pressure P to be determined. The action of the fluid is then traceable only during this cooling phase. The heating of constant t_h duration and the cooling of variable t_c duration characterize a global relaxation phenomenon at the f frequency which is function of the pressure P directly:

$$f = \frac{1}{t_h + t_c} \tag{1}$$

Therefore, each frequency measurement f corresponds to a pressure P of the fluid (air) given by the reference Pirani gauge in the range 0.1 Pa–10^5 Pa.

Figs. 3 and 4 represent the frequency variations of the micro-thermocouple gauge as a function of the static pressure (air) in the vacuum measurement chamber for a K type micro-thermocouple of diameter 25.4 μm. The two different cases present the same behavior. Each experimental curve is composed by three parts corresponding to the quality of energy transfer between the sensor and the gas which is pressure-dependent [13]. First, from 0.1 Pa to about 10 Pa, the sensor response is independent of the pressure and no significant variations are observed. For this vacuum range, heat transfer occurs by radiation because of the small amount of gas inside the volume. The mean free path of the gas molecules is larger than the dimension (internal diameter of the chamber) of the chamber. The wire cannot exchange heat with surroundings and its temperature increases so that it cannot be cooled: the oscillation frequency f (Hz) does not vary. The second part corresponds to the range between 10 Pa and 400 Pa. This zone

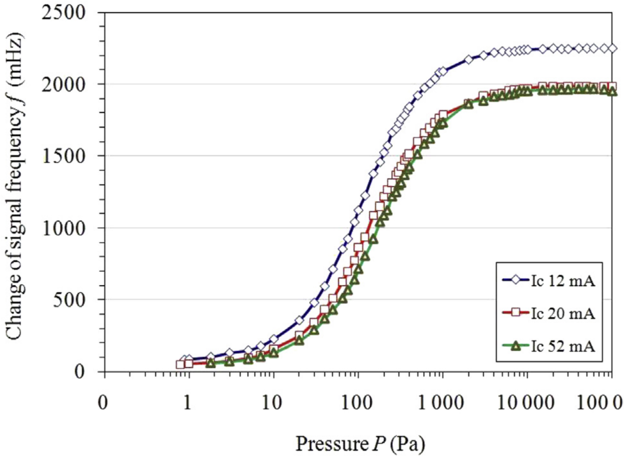

Fig. 3. Experimental variations of the signal frequency versus pressure for different current intensities (Heating time fixed at $t_h = 0.4$ s).

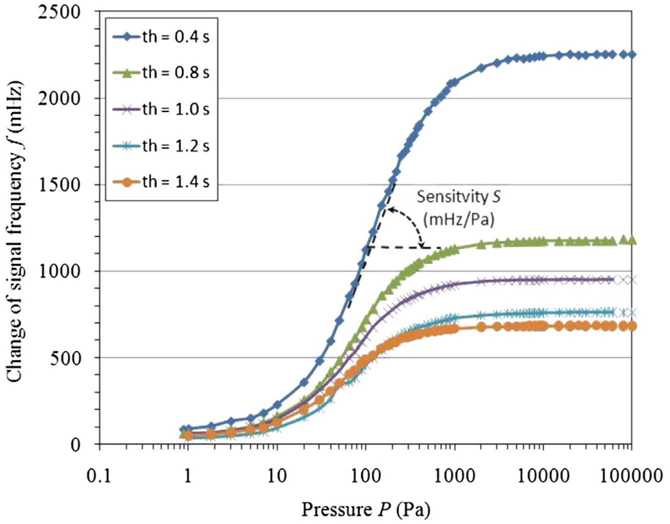

Fig. 4. Experimental variations of the signal frequency f versus pressure P for different heating durations t_h (Current intensity $I_c = 12$ mA).

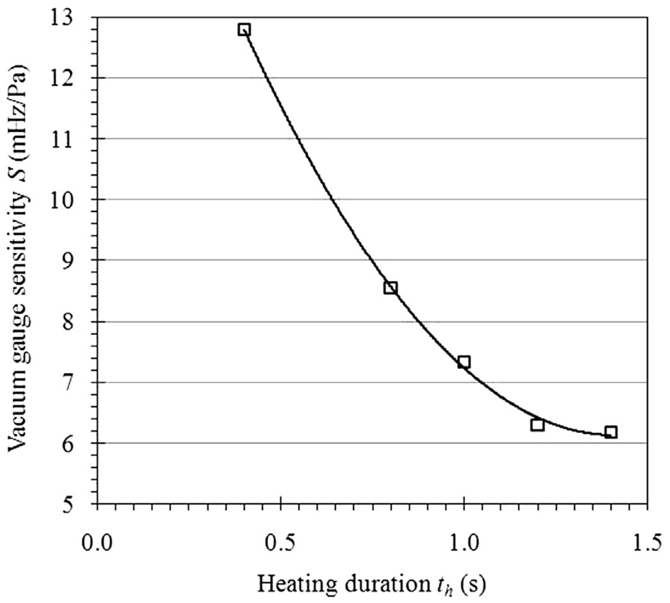

Fig. 5. Vacuum sensitivity S function of the heating duration t_h (Current intensity $I_c = 12$ mA).

corresponds to the best functioning of the sensor where its sensitivity S (mHz/Pa) is maximal. The frequency response of the sensor is linearly dependent of the pressure. The heat generated by Joule effect in the junction is evacuated by heat conduction and convection in the gas until reaching the saturation zone, beyond 400 Pa. The third part is above 400 Pa. The heat transfers by Joule effect do not increase sufficiently the wires temperature because the intensity of the heat convection which cools the wires. Then, the temperature difference between the gas and the wires is no longer sufficient to start the frequency oscillation. In this third part, the sensor response is independent of the pressure.

Three heating current intensities ($I_c = 12$, 20 and 52 mA) are considered for the same heating duration t_h of 0.4 s (Fig. 3). The behavior of the vacuum gauge is the same for the three cases but the 12 mA curve gives the best performances above 10 Pa. At saturation level, from 10^3 Pa to 10^5 Pa, a sensitivity frequency difference is 250 mHz/Pa between the 12 mA curve and the 20 mA and 52 mA curves. It was demonstrated that, when the current intensity increases, the wires are no longer able to dissipate the heat accumulated.

Five heating durations t_h (0.4, 0.8, 1.0, 1.2 and 1.4 s) are applied to the sensor for a current intensity I_c of 12 mA (Fig. 4). An examination of the effects of heating durations on gauge calibration shows a serious spread on the behavior of the sensor. The performance of the gauge (oscillation frequency f) decreases with the heating duration t_h. If the heating duration is 3 times longer (from 0.4 s to 1.2 s), the frequency is divided by 3.3 from the 10^3 Pa–10^5 Pa range. The more the heating duration increases the more heat is accumulated in the gauge's volume and the heat evacuated to the surroundings decreases.

The parametrical study shows that, in the linear zone (Fig. 4), the sensor sensitivity S decreases strongly when the heating duration t_h increases (Fig. 5). From 0.4 s to 1.2 s heating durations, the sensitivity S is divided by 2 (between 30 and 300 Pa). The best sensitivity S of 12.8 mHz/Pa is obtained in the pressure range of 30–300 Pa for the experiment with the lowest heating duration $t_h = 0.4$ s. It is noticed that the heating duration must be less than the time constant of the micro-thermocouple. If not, the temperature would be compensated. The micro-thermocouple presents a time constant of 30 ms corresponding to a cut-off frequency of 5 Hz at atmospheric pressure [12]. In an experimental study with Pirani sensors, Jitshin showed that the time constant of the resistive wire decreases when the vacuum increases [9]. We demonstrated the same result with a micro-thermocouple [14]. So, the time constant of our vacuum gauge is lower than 30 ms in vacuum conditions.

Table 1 presents the change of frequency measurement uncertainties for the experimental results given in Fig. 4. For each current I, the uncertainty grows with the pressure but it presents small values in the pressure range where the micro-thermocouple is sensitive (between 100 and 1000 Pa). The frequency versus pressure curve presents the lowest relative uncertainties $\Delta f/f$ for the current $I = 12$ mA in the pressure range 10^2 Pa–10^3 Pa.

The purpose of this work is to realize a vacuum gauge for use in dry air. Based on the hot wire anemometer principle and using a micro thermocouple of 25.4 μm diameter, this gauge presents a

Table 1

Change of frequency measurement uncertainties. For each current I, the uncertainties are calculated on the basis of five measurements for each pressure point. The Pirani gauge gives the reference pressure.

Reference pressure with the Pirani gauge P (Pa)	Frequency measurement f (mHz)					
	Current $I = 12$ mA	$\Delta f/f$ (%)	Current $I = 20$ mA	$\Delta f/f$ (%)	Current $I = 52$ mA	$\Delta f/f$ (%)
1	87.2 ± 0.4	0.45	51.5 ± 0.7	1.40	58.1 ± 0.6	1.03
10	227.2 ± 1.8	0.79	158.3 ± 1.2	0.75	131.6 ± 1.4	1.06
10^2	1123.6 ± 3.2	0.28	862.1 ± 5.2	0.60	714.3 ± 6.5	0.91
10^3	2092.0 ± 5.8	0.27	1785.7 ± 6.8	0.38	1736.1 ± 7.2	0.41
10^4	2242.1 ± 6.1	0.27	1968.5 ± 7.5	0.38	1953.1 ± 8.1	0.42
10^5	2252.2 ± 9.3	0.41	1984.1 ± 8.7	0.44	1953.2 ± 9.2	0.47

weak response time (cut-off frequency of 5 Hz) and it is inert. The local temperature information of the sensor can be deduced from the relaxation cooling period while the signal frequency allows to access to the vacuum pressure information. At the end of the heating period t_h the temperature of the Th_{sens} micro thermocouple tends to that of the fluid temperature T_f. The experimental characterization has shown that the optimum functioning is obtained with low heating duration. The measuring range is 10^{-1} Pa–10^5 Pa and the pressure sensitivity is good between 5 and 10 Pa and 2–3 kPa. The best sensitivity in air is obtained for values of heating current I_c of 12 mA and heating duration t_h of 40 ms. It has been established that the sensor has a the best sensitivity S of 12.8 mHz/Pa for vacuum in the range 30 Pa–300 Pa and measures pressures up to 10^5 Pa.

The developed sensor is still a prototype and several modifications may be taken into account to improve its performance. This sensor was used with dry air and it needs calibration for various gases. Heating time, current intensity and wire diameters are fundamental parameters in the sensor behavior and need to be optimized for the future sensor development. Moreover, the fact that micromachining techniques are not used for the sensor realization presents the advantage to introduce the probe in different places in a microsystem and to establish local measurements. Finally, miniaturization of the probe will be continued in testing of other thermocouples diameters like 12.7 and 7.6 μm for a K type and 5.3, 1.27 or 0.53 μm for a S type (Platinum–Platinum with 13% Rhodium).

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