

Rapid communication

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



Eric Gavignet, François Lanzetta\*

FEMTO-ST Institute, Energy Department, UMR 6174, CNRS/UFC/ENSMM/UTBM, University of Franche-Comté, Parc Technologique, 2 Avenue Jean Moulin, 90000 Belfort, France

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### ABSTRACT

We present an experimental characterization of a new vacuum gauge based on a K type micro thermocouple with 25.4  $\mu\text{m}$  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.

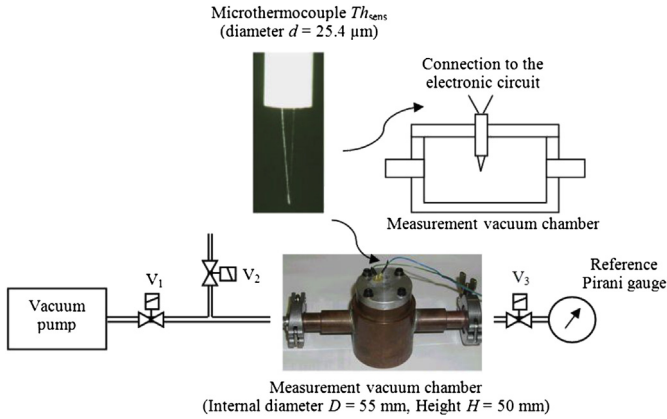
This paper describes the results obtained with a new kind of thermocouple gauge in which the classical arrangement wire and thermocouple is replaced by a simple K type micro thermocouple (Chromel–Alumel with 25.4  $\mu\text{m}$  diameter) heated by an electric current and cooled by the gas (air) for 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  $Th_{\text{sens}}$  (Fig. 1).

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

\* Corresponding author. Tel.: +33 384578224.

E-mail address: [francois.lanzetta@univ-fcomte.fr](mailto:francois.lanzetta@univ-fcomte.fr) (F. Lanzetta).

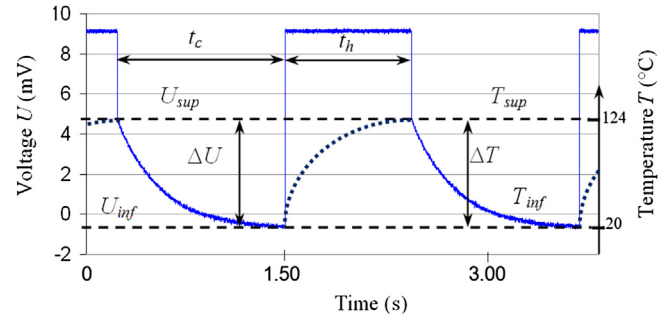


**Fig. 1.** Experimental setup. The vacuum gauge micro thermocouple measures the pressure and the temperature in the volume of the vacuum chamber.

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  $25.4\ \mu\text{m}$  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  $\pm 0.1$  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



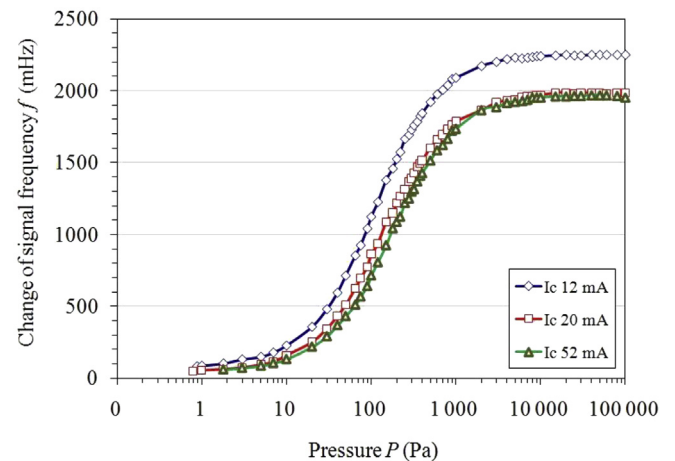
**Fig. 2.** Typical response of the sensor for the vacuum pressure  $P = 100$  Pa. Vacuum gauge = K type thermocouple. Seebeck coefficient =  $40\ \mu\text{V K}^{-1}$ , diameter  $d = 25.4\ \mu\text{m}$ ,  $t_h = 1$  s,  $t_c = 1.25$  s,  $I_c = 31.5$  mA, oscillation frequency  $f = 1/(t_c + t_h) = 444.44$  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 ( $\times 1000$ ) measurement was possible during the heating duration  $t_h$ .

cooling of variable  $t_c$  duration characterize a global relaxation phenomenon at the  $f$  frequency which is function of the pressure  $P$  directly:

$$f = \frac{1}{t_h + t_c} \quad (1)$$

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  $25.4\ \mu\text{m}$ . 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).

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