A novel vacuum pressure sensor using a thermoelectric device

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We present the proof-of-concept of a new vacuum pressure sensor based on a new operating principle. The new sensor is formed by the simple combination of a thermoelectric (TE) module that is contacted at both sides by a bent copper plate. The vacuum pressure is related to the change in the thermal contact resistance that exists between the outer ceramic surfaces of the TE module and the copper plate, since heat transfer through the ceramic/copper interface is found to be influenced by the amount of air present in the interface gaps (vacuum pressure). The variations of the thermal contact resistance produce a change of the TE module voltage when a fixed current is applied to it. By monitoring this voltage simultaneously to the response of a commercial pressure sensor at different vacuum pressures inside a vacuum chamber, a calibration equation was identified, which enables obtaining the vacuum pressure from the voltage signal. Random errors lower than 10% were found in the 0.1 to 250 mbar range, which is the pressure range that the sensor can properly sense. This new device is inexpensive, simple to fabricate and integrate, and benefits from the high stability of TE modules.

Keywords: Vacuum gauge, Peltier device, thermoelectric module, thermal contact resistance.

I. INTRODUCTION

A thermoelectric (TE) device, also known as a TE module or Peltier device, can generate a temperature difference across it when current is applied to it (Peltier effect). In addition, the device voltage at open circuit is proportional to the temperature difference across the TE materials (Seebeck effect). TE modules are formed by alternated p-type and n-type semiconductor legs electrically connected in series and thermally in parallel [1,2]. This assembly of TE legs is sandwiched by two electrically insulating plates (typically a ceramic material).

Due to the Seebeck effect, TE devices are affected by the thermal process occurring in their surroundings. This offers the possibility to sense thermal phenomena by the direct use of electrical signals. Taking advantage of this feature different applications of TE devices can be encountered in the literature, such as their use as thermal conductivity and thermal diffusivity sensors [3,4], as devices able to measure the convection heat transfer coefficient (h) [5], the emissivity (ε) [6], and also the thermal contact resistance [7]. Related to our study on the thermal contact resistance [7], it can be seen from electrical impedance measurements performed to a commercial TE device (Fig. 1) that the thermal contact resistance between the TE device and copper blocks is hugely influenced by variations in the air pressure (vacuum level). When the module was sandwiched between two copper blocks without using a thermal interface material (TIM), the size of the semicircle response obtained experienced a huge increase, which was only due to the variation of the air pressure (see measurements from the contacted system in Fig. 1).

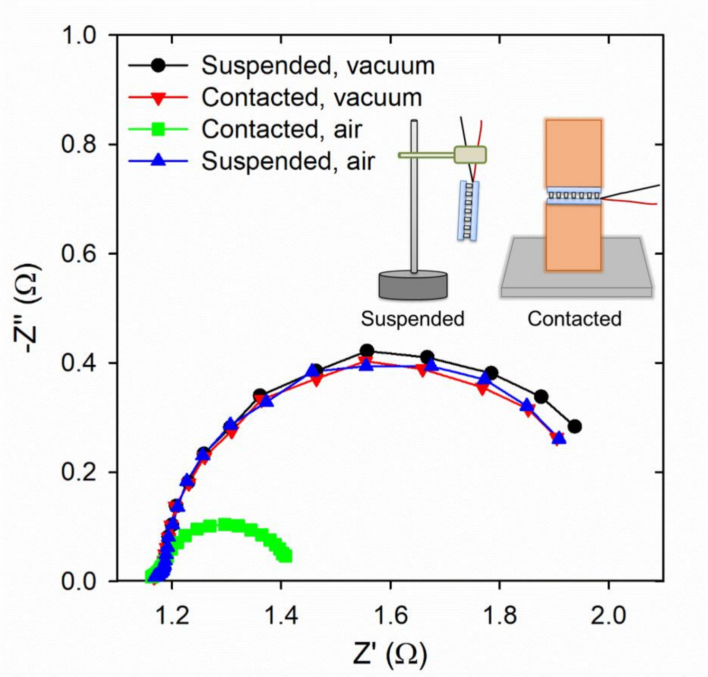

Fig. 1. Impedance spectroscopy measurements, at ambient pressure and in vacuum (<10^{-3} mbar), of a thermoelectric device under two different conditions: suspended and contacted by copper blocks, as schematically shown in the inset.

Remarkably, the response found in vacuum was nearly the same as that from the module suspended in air, i.e. without being in contact with any solid at all, which highlights the poor heat conduction through the copper-TE device thermal contact when no TIM is present. In addition, it is evidenced that the air filling the gaps in the thermal contact is the parameter governing the heat transfer through the interface. A further increase in the semicircle response with respect to the TE module measured suspended in air can be also observed when the module was measured suspended in vacuum, which indicates the low heat losses from the TE device produced by the natural convection.

These observations point to the possibility of fabricating a vacuum pressure sensor based on a thermal contact created on a TE device, which represents a novel operating principle with respect to the existing technologies, such as the Pirani [8] and the thermopile sensors [9]. In both established technologies, a piece of material (typically a plate or a wire) is heated up by and electrical current (Joule effect) and the temperature that it reaches is recorded. The temperature rise in these technologies is governed by convection losses, which depend on the vacuum pressure of the gas present in the surroundings of the heated piece. In addition to these two common vacuum sensors, other type of sensors have been developed which are capable to determine the vacuum pressure by a change in electrical capacity [10] or the amount of ionized gas [11,12], even though they are more complex and not typically used [13].

Furthermore, there are other sensors that measure the vacuum pressure using a thermocouple as a heater and temperature sensor simultaneously [14,15], or the signal of a micro-thermocouple or TE device with oscillating heating and cooling processes [4,16]. However, none of them have a thermal contact as their key part and are not based on thermal changes occurring by the amount of gas enclosed in the thermal contact.

The main objective of this work is to demonstrate the proof-of-concept of a novel vacuum pressure sensor which is based on the changes experienced in the electrical signals of a TE module thermally contacted by a solid at both sides. The variations of the electrical signals are produced by changes in the amount of gas (vacuum pressure) present in the gaps of the thermal contact resistance at the TE module/metal interfaces. First, the fundamental of the operating principle of the new vacuum sensor is explained. Then, the concept is proved experimentally by fabricating the sensor and testing its voltage variations at different vacuum pressures in a vacuum chamber.

II. OPERATING PRINCIPLE

The voltage difference across a TE module is given by [17],

$$V = R_{\Omega} I + S \Delta T \tag{1}$$

Where R_{Ω} is the total ohmic resistance of the TE module (accounting for the electrical resistance of wires, contacts, and semiconductor materials), I is the electric current applied to it, S the module Seebeck coefficient, and $\Delta T = T(L) - T(0)$ the temperature difference between the ends of the TE legs, being L the length of the TE legs (see Fig. 2). Both R_{Ω} and S are module's properties, which are temperature dependent and hence can be considered constants if no significant changes occur in the ambient temperature. Under this assumption and if a constant current is supplied to the TE module, only changes in ΔT will affect the TE device voltage, as stated in Eq. (1).

If a TE module is thermally contacted at both sides by a bent copper plate without any thermal interface material (as shown in Fig. 2 and Fig. 3), plenty of air gaps will be present in the thermal contact interfaces (see inset of Fig. 2). Note that at the thermal contact between two solids the real contact area may be as low as 1-2% of the total area [18]. When the module is suspended in air and a constant current is applied under constant ambient temperature, its ΔT significantly depends on the thermal contact resistance at the ceramic plates/copper interfaces, as schematically shown in Fig. 2. The constant current flow produces the ΔT due to the Peltier effect, i.e. heat is removed at one end of the legs and released at the other. For an infinite thermal contact resistance, the ΔT will be the highest possible, since the Peltier heat removed/released at the junctions will not be evacuated through the copper plate (dotted line case of Fig. 2). However, if the thermal contact resistance is decreased, heat is able to cross the interface and hence to be extracted through the copper plate, reducing the ΔT (dashed line case of Fig. 2). For an ideal contact (no thermal contact resistance), all the heat reaching the interface will be extracted and thus could not be maintained in the TE device, consequently the temperatures at the Cu-TE module interfaces do not change and are similar to the situation without current flow (solid line case in Fig. 2).

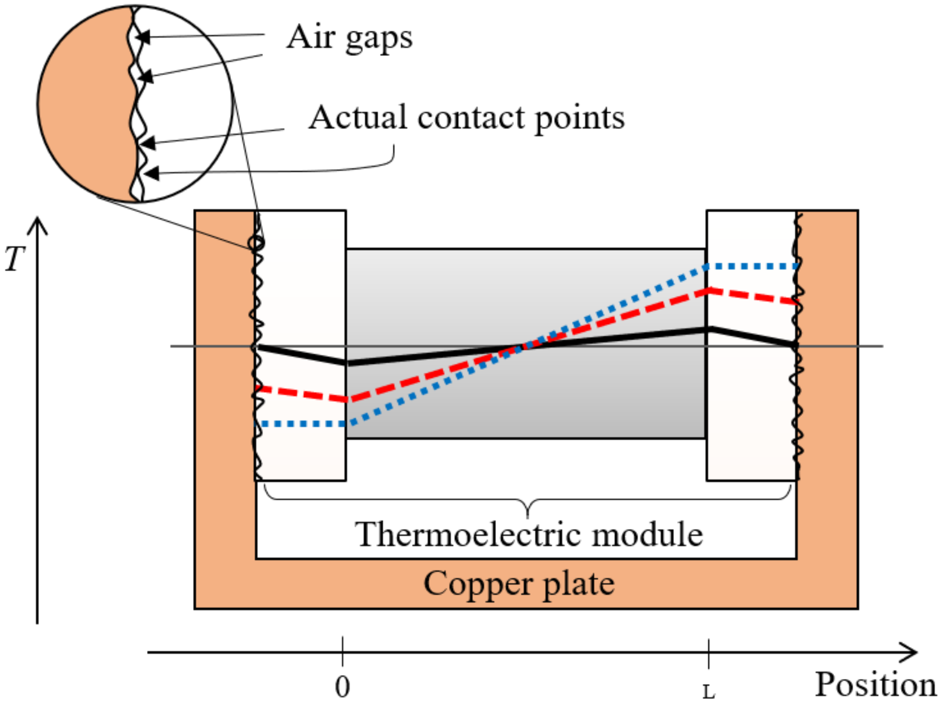

Fig. 2. Schematic view of the temperature profiles obtained in a TE module contacted by a bent copper plate when a constant current is applied. For simplicity, the TE module is represented by only one leg. The profiles when current is not applied (thin grey horizontal line), for an ideal perfect contact (black solid line), for a real contact (dashed line), and for an infinite thermal contact resistance (dotted line) are indicated. Temperature in the copper plate is always the same as the initial. The inset shows a schematic view of the air gaps and the real contact points in the thermal contact.

Note that the fact of having the bent copper plate provokes that the temperature in this plate do not change in any of the cases, since due to its high thermal conductivity and the symmetry of the system, the same amount of heat added at the hot side, is quickly cancelled by the same amount of heat removed at the cold side. Under the conditions described, and as observed in Fig. 1, changes in the voltage (and thus in ΔT) are only possible if the amount of air is varied in the air gaps (variations in the vacuum pressure), which offers the possibility to link this parameter to the vacuum pressure.

III. EXPERIMENTAL PROOF-OF-CONCEPT

In order to experimentally proof the concept of the new vacuum pressure sensor, a copper plate of 10 mm x 20 mm x 0.3 mm dimensions was slightly polished with 400 grit size silicon carbide sandpaper (Ref. 30-5208-012, Buehler) and carefully bent manually in order to thermally contact the two outer ceramic surfaces of a commercial 7 mm x 7 mm Bi-Te TE module (Interm, ref. CBM87), as shown in Fig. 3. In order to ensure a suitable and homogeneous thermal contact along the whole contact area several steps were followed as shown in Fig. 4. First, the copper bar was bent while being held by a metallic bar or screw of similar height to that of the TE module at the middle. Once the bending is completed, the distance between the copper plate ends should be somewhat smaller than that of the TE module. This is to generate some over pressure once the module is introduced inside the bent copper plate which is the final step.Fig. 4

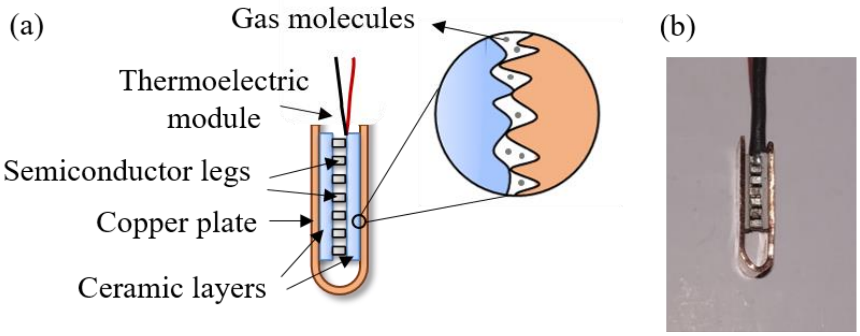

Fig. 3. (a) Schematic view and (b) real picture of the side view of the TE module with the bent copper sheet contacted.

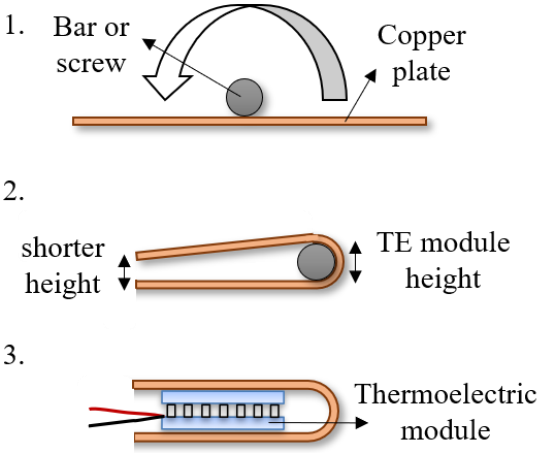

Fig. 4. Steps followed to fabricate the vacuum sensor.

The fabricated sensor was suspended inside a cubic vacuum chamber of 400 mm side. A PGSTAT30 potentiostat (Metrohm Autolab B. V.) controlled by Nova 1.11 software was used to apply a 50 mA constant current to the module and measure its voltage. It should be noted that any other power source able to apply a constant current and a multimeter to measure the voltage might be used. Cables for the measurement of the electrical signals were inserted through a feedthrough in the vacuum chamber. Simultaneously to the voltage measurement, the vacuum pressure of the chamber was registered using a commercial pressure sensor (Pfeiffer, ref. PKR 251) directly installed at one of the vacuum chamber walls. Different vacuum pressure levels were achieved in the chamber using a high vacuum pump unit (Pfeiffer, HiCube 80 Eco).

Before varying the pressure of the vacuum chamber, the 50 mA constant current was applied to the TE device, and it was waited until a steady state value of the voltage signal was reached. The small constant current value was used to avoid significant Joule effect, which may increase the temperature of the TE legs and change their TE properties. Once the steady state was reached, the vacuum pump was activated and the voltage of the TE module was measured simultaneously to the vacuum pressure from the commercial sensor. The pressure change was instantaneously followed by the voltage. The experiment was repeated three times. Results are shown in Fig. 5. It can be observed that the device voltage shows a significant change from ambient pressure up to 0.1 mbar. However, at pressure levels lower than 0.1 mbar the voltage response shows no significant change. A good repeatability between the three experiments performed was also observed.

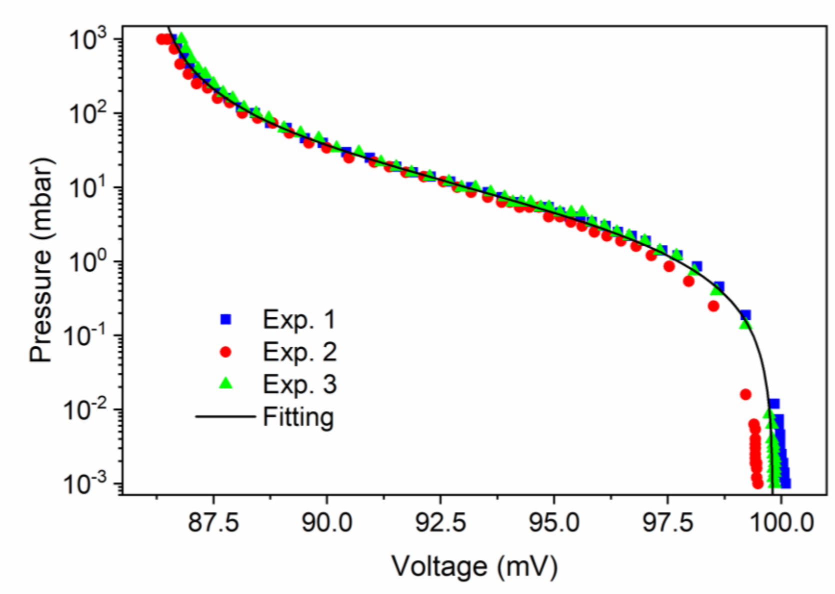

Fig. 5. Measured voltage of the TE module at different values of vacuum pressure for three different experiments. A calibration curve (solid line) obtained by a fitting to all the points of the three experiments is als shown.

A fitting to all the points from the three experiments was performed using MATLAB, leading to the equation,

$$P = \left(\frac{0.0762}{V - 0.0862} - 5.58\right)^{\frac{1}{0.734}} \tag{2}$$

where P is the vacuum pressure (given in mbar units), and V is given in V. The errors of the four fitted parameters obtained from the fitting can be found in Table 1. All of them are lower than 2%, proving the suitability of Eq. (2), which can be used to determine the vacuum pressure from a measured voltage value of the new vacuum pressure sensor.

Table 1. Errors from the different parameters obtained from the fitting to the $P = \left(\frac{b}{V-a} - c\right)^{\frac{1}{d}}$ equation.

Parameter	**Error (%)**
a	0.08
b	1.79
c	1.99
d	1.43

In order to calculate the total combined random error u_c in the determination of P, which is the combined error taking into account all the contributions from the errors from the four fitted parameters (Table 1), the following equation was used [19],

$$u_c{}^2 = \sum_{i=1}^{N} \left(\frac{\partial P}{\partial x_i}\right)^2 u(x_i) + 2\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial P}{\partial x_i}\frac{\partial P}{\partial x_j} u\left(x_i, x_j\right), \tag{3}$$

where N is the number of fitting parameters (4 in our case), x_i=a, b, c, or d and $u(x_i)$ denote the fitting parameters and their associated uncertainties (shown in Table 1), respectively. Finally, $u(x_i,x_j)$ is the uncertainty of the interdependent fitted parameters, which is directly obtained from the non-diagonal elements of the symmetric covariance matrix. This matrix was provided by the fitting procedure, which was perfomed using Origin 2018 software.

The total combined random error can be seen in Fig. 6 for the pressure range where significant variations of voltage occur with pressure. The error adopts different values at different pressures due to the non-linearity of the response. It shows values lower than 10% from approximately 0.1 to 250 mbar, which can be considered the useful pressure range for practical pressure measurements by the novel sensor.

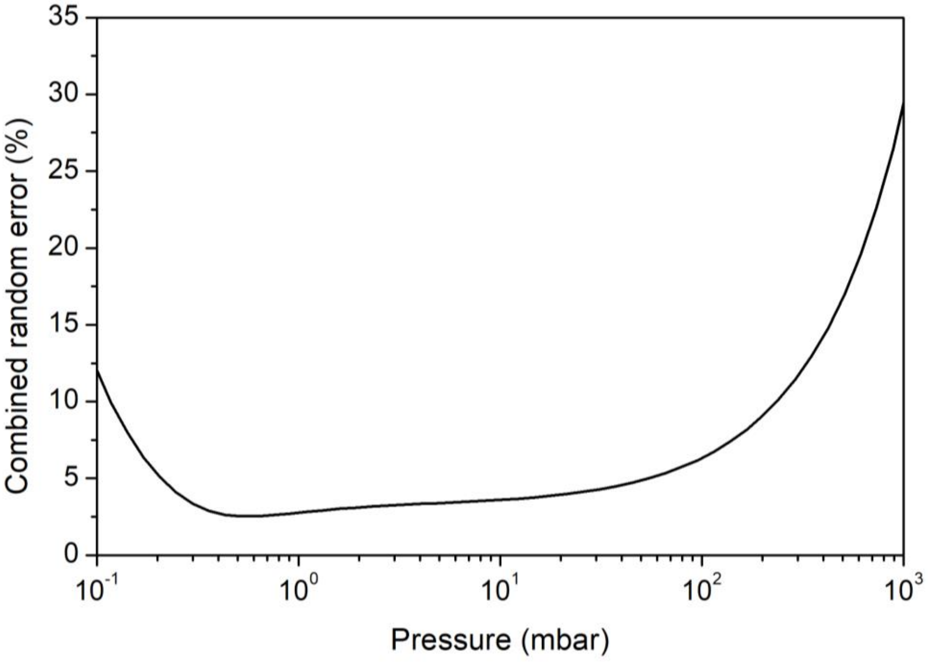

Fig. 6. Combined random error at different pressure values for the novel vacuum pressure sensor.

It should be noted that the obtained calibration curve [Eq. (2)] is only valid at the temperature at which the experiments were performed (25.0 ± 1.5 °C), since the TE properties of the TE module change with significant temperature variations as previously discussed. In any case, the calibration can be repeated at different temperatures and obtain the fitting parameters as a function of temperature for a precise measurement at any operational temperature. On the other hand, the shape and dimensions of the interface gaps were not controlled during sensor fabrication, consequently, a methodology to control this should be developed to ensure repeatability, or all the fabricated devices should undergo an individual calibration.

Finally, we would like to remark the several advantages of the novel sensor, such as low cost (around 35 €, which is the approximate price of the TE module and the copper plate), simple fabrication (it only involves the gentle polishing of the copper plate and its bending to contact the device outer ceramic surfaces apart from the fabrication of the device), and easy integration (only requires the application of a fixed current and registering a voltage).

IV. CONCLUSIONS

The proof-of-concept of a new vacuum pressure sensor based on a thermoelectric module has been demonstrated. The sensor relies on a new operating principle in which the vacuum pressure is measured from the change in the thermal contact resistance that exists between the outer ceramic surfaces of the module and a thermally contacted metallic solid, since heat transfer through the ceramic/metal interface is influenced by the amount of gas present in the interface gaps (vacuum pressure). The variations of the thermal contact resistance produce a change of the thermoelectric module voltage when a fixed current is applied to it under constant ambient temperature. The sensor is built by simply contacting both sides of the thermoelectric device by a bent copper plate. The voltage of the new sensor and the vacuum pressure, measured using a commercial sensor, were simultaneously recorded several times. A good repeatability between experiments was found, and a calibration equation, able to provide the vacuum pressure from the thermoelectric device voltage reading, was obtained. Total combined random errors lower than 10% were obtained from 0.1 to 250 mbar, which is the pressure range that the sensor can properly sense. This new device is inexpensive, simple to fabricate and integrate, and benefits from the high stability of TE modules.

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