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Vacuum 75 (2004) 169–176
VACUUM
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Dynamical behaviour of the Pirani sensor

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Received 30 September 2003; received in revised form 2 February 2004; accepted 16 February 2004

Abstract

The conventional Pirani gauge has poor performance at atmospheric pressures since here the stationary thermal conductivity of gases saturates. In contrast, the heat capacity of the gas does not saturate. It is accessible by a pulsed operation of the wire. The present paper gives an investigation of the Pirani gauge signal for the non-stationary heating and cooling processes. As follows from the experimental data and theoretical estimates, at atmospheric pressure a substantial amount of energy is stored in the gas, much more than in the wire. However, the energy of the gas has only a rather small effect on heating and cooling rates. The reasons for this behaviour are the strong heat losses due to the thermal conductivity of the gas, the rather weak thermal coupling between the wire and surrounding gas as well as the smallness of the average temperature elevation of the gas over ambient. Nevertheless, the effect of the heat capacity of the gas on the rates is sufficiently strong to provide a usable measuring signal. The pulsed operation of the wire and the recording of the time-dependent signal can be accomplished by a smart controller. Such an instrument would provide a substantially improved performance of the Pirani sensor at pressures above 100 mbar.

Keywords: Vacuum measurement; Pirani gauge; Pulsed operation; Heat capacity

1. Introduction

Pressures in the range of about 10^{-3}–10^{2} mbar are conveniently monitored in vacuum technology by the Pirani gauge [1] which is based on the thermal conductivity of the gas. Developed almost 100 years ago, this gauge employs a simply built sensor and offers a wide measuring range covering several pressure decades. The sensor is similar to a light bulb, it typically consists of a thin wire (diameter $d_i \approx 10\,\mu$m) mounted in a cylindrical housing (diameter $d_a \approx 10$ mm), as shown in Fig. 1. The wire is heated by an electrical current. In the stationary case, the electrical heating power applied to the wire is in equilibrium with the heat transport from the hot wire to the cold surroundings by the gas. Since the heat transport increases monotonously with increasing gas pressure, the heating power provides the signal for the pressure measurement.

A substantial improvement of vacuum gauges with a Pirani sensor resulted from the electronic control of the wire heating [2]. A servo loop controls the heating power in such a way that the wire temperature is kept constant, independent of heat losses and thus of gas pressure. The

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0042-207X/$ - see front matter © 2004 Published by Elsevier Ltd.
doi:10.1016/j.vacuum.2004.02.002

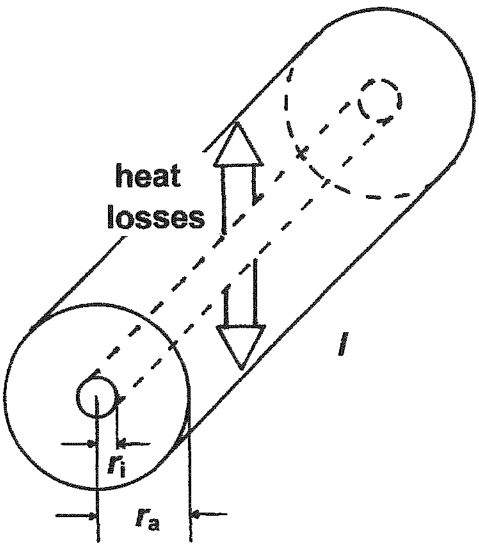

Fig. 1. Schematic drawing of the typical Pirani sensor with a thin heated wire (filament) mounted in a cylindrical housing.

advantages of this measure are a substantial extension of the usable measuring range and a faster response of the gauge signal to pressure changes. The wire temperature is derived from its electrical resistance, since for pure metals the resistivity increases (almost) linearly with temperature. A thorough investigation of the physical and technical properties of the thermal conductivity gauge has been performed by Ubisch [3]. More recently, our group has published a treatment on the metrological properties of the Pirani sensor [4]. To summarise the situation, the measuring performance of the Pirani sensor in the stationary operating mode is well understood today.

A basic problem of the thermal conductivity gauge is its poor performance at pressures above some 100 mbar. This problem stems from the saturation of the thermal conductivity of the gas when the mean free path of the molecules becomes smaller than the wire diameter. A few years ago, the idea of a pulsed Pirani gauge was published [5]. In the pulsed operating mode, the heating and cooling of the wire which is affected by the surrounding gas can be monitored. The corresponding rates depend on both the thermal conductivity of the gas and the heat capacity of wire and gas. Since at high pressures the heat capacity of the gas is comparatively large and directly proportional to pressure, an evaluation of heating and cooling rates is expected to yield improved measuring performance here. To our best knowledge, this idea has not been thoroughly investigated so far.

Recently, a pulsed Pirani gauge has been marketed by the German company Thyracont [6]. The company documents do not provide conclusive information on its physical principle and only hint to the thermal conductivity being important and not to the heat capacity. The measuring characteristics of this gauge (Fig. 4 in Ref. [6]) show a strong saturation towards atmospheric pressure which indicates that the heat capacity of the gas plays no significant role in the gauge characteristics.

The subject of the present work is a thorough investigation of the pulsed Pirani gauge, and in particular, the influence of the heat capacity of the gas on measurable signals. For this purpose, a typical Pirani sensor was built. Heating and cooling processes of the sensor were measured via the wire temperature. Model calculations were performed to explain the experimental data. In the following text, the gauge will be described by the term “hot filament gauge” according to its operation or by “Pirani sensor” according to its inventor, in order to avoid the term “thermal conductivity gauge”.

2. Pirani-sensor operated in a stationary mode

In this section, the stationary operation of the Pirani sensor is considered. The wire is heated by the electronic controller in such a way that its electrical resistance is kept at a constant set value. Thus its temperature is constant, independent of pressure. The heating power supplied to the wire is lost to the surroundings by the thermal conductivity of the gas. There are also minor heat losses at the mounting of the wire and by thermal radiation. The Pirani sensor used has the following parameters (Fig. 1):

- material of wire: tungsten,
- diameter of wire: $d_i = 2r_i = 10\,\mu\text{m}$,

by [8]

$$\tau_D = \frac{1}{23} d_a^2 \frac{\rho_{gas} c_{gas}}{\lambda_{gas}}. \quad (8)$$

For gas at 20°C, 1 bar we have: specific heat capacity $c_{gas} = 1005\,\mathrm{J\,kg^{-1}\,K^{-1}}$, density $\rho_{gas} = 1.2\,\mathrm{kg\,m^{-3}}$, thermal conductivity $\lambda_G = 0.025\,\mathrm{W\,m^{-1}\,K^{-1}}$. Furthermore for our sensor: diameter of housing: $d_a = 16\,\mathrm{mm}$. Thus, we get the time constant:

- τ_D=0.5 s at 1000 mbar,
- τ_D=0.05 s at 100 mbar,
- τ_D=0.005 s at 10 mbar.

4. Heating process of the Pirani sensor

Now the heating of the Pirani sensor in pulsed operation will be considered. Before the pulse, no voltage is applied to the wire so that its temperature ϑ_a (after some waiting) is at ambient. Then a voltage is applied to the wire (indirectly via the Wheatstone bridge including the wire) resulting in heating of the wire. The operating electronics monitors the wire resistance. When the resistance reaches a pre-set value (i.e. the wire temperature reaches the corresponding pre-set value ϑ_i), the heating is switched off, i.e. the pulse is terminated.

The heating power supplied to the wire is spent for two processes: first, for heating the wire itself from ambient to pre-set temperature, and second, for partial heating and heat transfer by the surrounding gas. In order to investigate the dynamics of the heating experimentally, the heating power P_{heat} can be varied as shown schematically in Fig. 2. For high heating power (Fig. 2 top), almost all the heating power is used for heating the wire itself. The heat losses from the wire by the gas, which are zero at the start of the pulse and reach the maximum value P_{stat} at the end of the pulse, only play a minor role. The wire quickly reaches its pre-set temperature and the pulse duration is short. For medium heating power (Fig. 2 middle), the supplied power is consumed in similar fractions in heating the wire and heat losses. The pulse then becomes longer. For a heating power which is only a little bit larger than the thermal heat losses P_{stat} at the pre-set temperature (Fig. 2 bottom), with increasing temperature the fraction used for overcoming the heat losses increases steadily and the power for heating the wire decreases almost to zero. As a consequence, the pulse duration becomes quite long. Independent of the pulse length, the energy E_{wire} required for heating the wire is always the same (light shadowed area in Fig. 2).

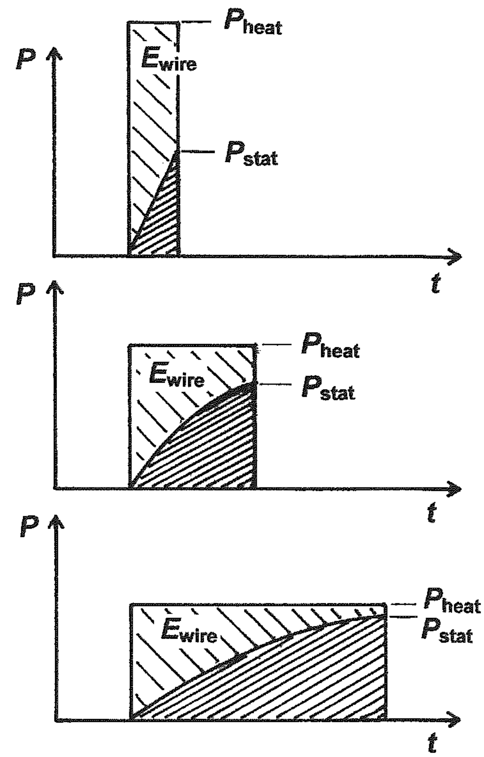

Fig. 2. Separation of the electrical heating power P_{heat} supplied to the wire into its components used for heating the wire itself and for compensating the heat losses by transfer to the gas during a pulse (schematic drawing). Top: heating power large as compared to the losses. Middle: mean heating power. Bottom: heating power only slightly larger than heat losses.

The equation for the heat balance during the heating process can be easily formulated. It is assumed that the heat losses from the wire are proportional to its temperature elevation over ambient. This assumption is valid when the thermal coupling of the gas to the wire occurs without significant delay. It is fulfilled at least at

- length of wire: $l = 38\,\text{mm}$,
- diameter of housing: $d_a = 2r_a = 16\,\text{mm}$.

Since the wire consists of a pure metal, its resistance $R(\vartheta)$ increases (almost) linearly with Celsius temperature ϑ:

$$R(\vartheta) = R(0°\text{C})(1 + \alpha_0\vartheta_i). \tag{1}$$

Here, α_0 denotes the linear temperature coefficient at 0°C, i.e. for tungsten $\alpha_0 = 4.5 \times 10^{-3}\,°\text{C}^{-1}$ [7]. When the wire is not heated, it has ambient temperature ϑ_a and its resistance $R(\vartheta_a)$ is small, i.e. $R(\vartheta_a) = 34.2\,\Omega$. When the wire is heated to its stationary operating temperature ϑ, its resistance is larger, i.e. $R(\vartheta_i) = 46.9\,\Omega$. Thus, we have the data:

- ambient temperature: $\vartheta_a = 20°\text{C}$,
- operating temperature of wire: $\vartheta_i = 110°\text{C}$.

The energy E_{wire} required to heat the wire from initial ambient temperature ϑ_a to its stationary pre-set operating temperature ϑ_i is given by

$$E_{wire} = c_{wire} m_{wire}(\vartheta_i - \vartheta_a). \tag{2}$$

With the material constants of tungsten, specific heat capacity $c_{wire} = 133\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$, density $\rho_{wire} = 19250\,\text{kg}\,\text{m}^{-3}$, and the dimensions of the wire given already above, one calculates a mass of the wire $m_{wire} = 5.8 \times 10^{-8}\,\text{kg}$ and heating energy of

$$E_{wire} = 6.8 \times 10^{-4}\,\text{J}. \tag{3}$$

The gas within the Pirani sensor has a temperature profile, where the temperature decrease radially from the hot wire at the axis to the cold housing at the outside. In case of a cylindrical geometry (Fig. 1) the stationary temperature profile $\vartheta(r)$ as function of radius has (approximately) logarithmic shape [4]:

$$\vartheta(r) = \vartheta_i + (\vartheta_a - \vartheta_i)\frac{\ln(r/r_i)}{\ln(r_a/r_i)}. \tag{4}$$

The mean temperature $\bar{\vartheta}_{gas}$ of the gas, i.e. the average over the volume can be obtained by integrating Eq. (4) over the volume:

$$V = \pi(r_a^2 - r_i^2)l$$

$$\bar{\vartheta}_{gas} = \frac{1}{V}\int_{r_i}^{r_a} \mathrm{d}r 2\pi r l \vartheta(r) = \vartheta_a + \frac{\vartheta_i - \vartheta_a}{2\ln(r_a/r_i)}. \tag{5}$$

In the calculation of the integral in Eq. (5) the well-fulfilled approximation $r_a \gg r_i$ was made to get a simple final formula. With the known mean gas temperature, the energy for heating the gas inside the housing can be calculated:

$$E_{gas} = c_{gas} \times \rho_{gas} \times V_{gas} \times (\bar{\vartheta}_{gas} - \vartheta_a). \tag{6}$$

Eqs. (5) and (6) are now evaluated for our Pirani sensor. The gas is assumed to be air at atmospheric pressure which has a specific heat capacity at constant pressure $c_{gas} = 1005\,\text{J}\,\text{kg}^{-1}\,\text{K}^{-1}$ and a density at 20°C, 1 bar of $\rho_{gas} = 1.19\,\text{kg} \times \text{m}^{-3}$. One gets a mean gas temperature $\bar{\vartheta}_{gas} = 26.0°\text{C}$. This value is much smaller than the wire temperature ϑ_i and only somewhat larger than ambient temperature ϑ_a. This is plausible if one remembers the logarithmic temperature profile of the gas: Only a small region around the wire has a really elevated temperature, whereas the outer regions containing most of the gas have only slightly elevated temperature. Finally, from Eq. (6) one gets of the energy stored in the gas:

$$E_{gas} = 5.5 \times 10^{-2}\,\text{J}. \tag{7}$$

Comparing the steady-state energies stored in the gas (Eq. (7)) and in the wire (Eq. (3)) one notes, that the gas at atmospheric pressure contains some 100 times more energy than the wire.

3. Time constant of the Pirani sensor

The dynamical behaviour of the Pirani sensors during heating and cooling is determined by the propagation velocity of temperature changes within the gas. The velocity increases with increasing thermal conductivity and decreases with increasing heat capacity (thermal diffusivity). The first quantity is (almost) independent or pressure, and the second one is proportional to pressure. Thus, the propagation velocity is inversely proportional to pressure.

For a rough estimation of the time required for the thermal coupling between wire and gas one may use the time constant τ_D for diffusion processes. For cylindrical geometry this is given small pressures, as follows from the time constant calculated in Section 3. At a particular time during the heating process, the wire has the temperature ϑ. The supplied power P_{heat} is used for heating the wire and for compensating the heat losses:

$$P_{heat} = c_{wire} m_{wire} \frac{d\vartheta}{dt} + P_{stat} \frac{\vartheta - \vartheta_a}{\vartheta_i - \vartheta_a}. \tag{9}$$

The solution of the differential Eq. (9) is a wire temperature ϑ which increases exponentially with time t:

$$\vartheta(t) = \vartheta_a + \frac{P_{heat}}{P_{stat}} (\vartheta_i - \vartheta_a) \times \left[1 - \exp\left(-\frac{t}{\tau}\right)\right]. \tag{10}$$

The time constant τ of the temperature rise is just the ratio of thermal energy E_{wire} of the wire (see Eq. (3)) and heat losses P_{stat} (both taken at pre-set temperature ϑ_i):

$$\tau = \frac{E_{wire}}{P_{stat}} = \frac{c_{wire} m_{wire} (\vartheta_i - \vartheta_a)}{P_{stat}}. \tag{11}$$

The time constant depends on gas pressure via the heat losses P_{stat}. Integration of the power terms in Eq. (9) over the duration of the pulse gives the corresponding energies. In our case with constant temperatures ϑ_a and ϑ_i, the heating energy E_{wire} of the wire is constant. This gives the following relation between supplied heating power P_{heat} and pulse duration t_{pulse}:

$$\frac{t_{pulse}}{\tau} = \ln\left(\frac{P_{heat}}{P_{heat} - P_{stat}}\right). \tag{12}$$

In order to test the validity of Eq. (12), the pulse duration t_{pulse} was measured as function of supplied heating power P_{heat}. When the measured values for pulse length t_{pulse} are plotted against the corresponding logarithm of the term in parenthesis in Eq. (11), the data should lie on a straight line. With logarithmic abscissa and ordinate, the line should have a slope of one. The ordinate value at abscissa value 1 is just the time constant τ.

The measured data are shown in Fig. 3. As can be seen, the data meet the expected behaviour when the pressure is sufficiently small (0–10 mbar). This result demonstrates that the dynamical behaviour of the Pirani sensor at small pressure can be described by two quantities, i.e. heat energy of the wire E_{wire} (independent of pressure) and

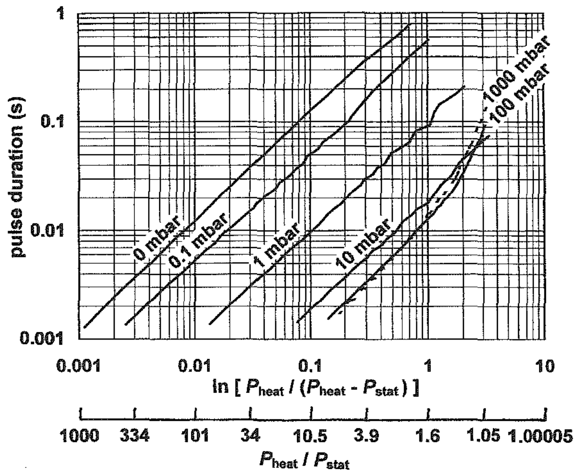

Fig. 3. Measured relationship between electrical heating power supplied to the wire (related to the heat losses according to Eq. (5)) and time required for heating the wire to a pre-set temperature (pulse duration). Gas used was ambient air with ~1 vol% water vapour.

power consumed by stationary heat losses P_{stat} (proportional to pressure).

The experimental data (Fig. 3) at pressures of 100 mbar and 1000 mbar also lie on a straight line as long as the pulse duration is short (below 0.01 s). This is understandable since during the short time interval practically only the wire is heated, but not the gas which couples to the wire by a time constant (see Section 3). At longer pulse duration, also the surrounding gas is heated. Since this heating of the gas requires a considerable amount of energy, more energy has to be delivered and the actual pulse duration becomes considerably longer than the duration extrapolated from Eq. (12).

The shape of the curve in Fig. 3 measured at 1000 mbar clearly shows a strong effect of gas pressure on pulse duration for long pulses. In principle, this effect may be used to provide a signal for pressure measurement. A practical realisation suffers from the fact that the increase of pulse length with pressure occurs at rather long pulse duration at which the supplied power is only slightly above the stationary power losses at a preset temperature. The power losses, unfortunately, are influenced by the ambient temperature and by the sensor orientation owing to convection, and thus are not constant. The problem of unstable losses can be overcome by measuring the losses in situ. This task can be performed by an intelligent controller which measures the relationship between pulse length and heating power.

5. Cooling process of the Pirani sensor

As calculated in Section 2, under stationary conditions and ambient pressure there is more thermal energy in the gas than in the wire. Thus, it seems to be promising to investigate the cooling process which depends on both, the thermal energy stored in the gas (proportional to pressure) and the thermal conductivity of the gas (which is almost constant at pressures in the range 100–1000 mbar).

In order to measure the cooling process, the following procedure was used. Initially, the wire is operated stationary at a pre-set temperature ϑ_i and the temperature profile of the gas assumes that of the stationary case (Eq. (4)). Then the heating power of the wire is switched off. Due to the heat losses, the temperatures of gas and wire now gradually decrease. This cooling can be monitored with the wire by measuring its resistance versus time. The measuring current has to be sufficiently small to avoid a noticeable heating. This condition could be well fulfilled in our measurements except for the non-interesting pressures below 0.1 mbar.

Fig. 4 shows the measured cooling curves. The cooling is fastest at a pressure of 30 mbar and becomes slower at smaller and at higher pressures. Since some curves for high and low pressures cross each other, for the sake of clarity the data have been plotted in two separate diagrams, both containing the curve for 30 mbar.

The upper part of Fig. 4 shows curves obtained at pressures 0.1–30 mbar. At negligibly low gas pressures, there is only minor cooling by disturbances (thermal radiation, losses at the wire ends) and the cooling is very slow. With increasing gas pressure, the cooling becomes faster which is due to the increasing thermal conductivity of the gas. A rough examination of the curves gives an exponential shape with time constants close to the

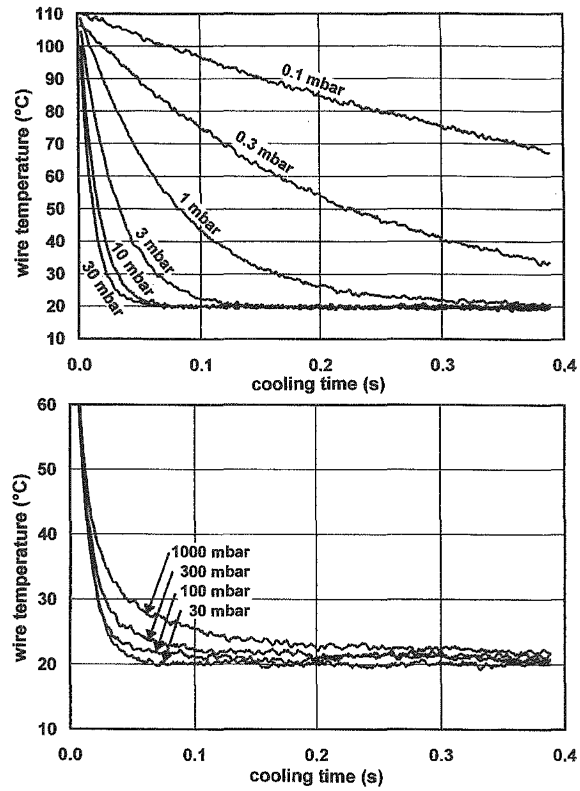

Fig. 4. Measured cooling down of the wire vs. time. Top: at pressures from 0.1 to 30 mbar. Bottom: at pressures from 30 to 1000 mbar. Gas used was ambient air with ~1 vol% water vapour at 50% humidity.

ones obtained for the heating process (Fig. 3). The data can be easily described by the energy stored in the wire and the thermal conductivity of the gas. The energy stored in the gas is negligible.

The lower part of Fig. 4 shows curves obtained at pressures 30–1000 mbar. Here, the first phase of the cooling process (cooling time below 0.01 s) is practically independent of pressure. The following phase shows a gradually decreasing tail. With increasing pressure, the cooling process becomes slower.

This result may be surprising at first glance. The estimates in Section 3 revealed that at pressure above 30 mbar the dominant part of the stored total thermal energy is contained in the gas. Since at 1000 mbar there is 33 times more energy in the gas than at 30 mbar, and since the thermal conductivity at both pressures is almost the same, the cooling at 1000 mbar should occur much slower than at 30 mbar. The observed behaviour can be explained by a more detailed consideration: Important parameters for the cooling process are the radial temperature profile and the time constant for thermal equilibrium (Section 3). Due to the logarithmic profile, only gas in close proximity to the wire has a substantially elevated temperature. This amount of gas is so small that its thermal energy is negligible compared to that of the wire. Accordingly, the first phase of the cooling (<0.01 s) is not affected by the gas, even at atmospheric pressure.

In the following cooling phase the wire approaches rather small temperatures of 30°C and below. Then the gas within the housing which has a mean temperature of 26°C starts to retard the cooling of the wire. The bulk of the contains a considerable amount of thermal energy which gradually flows to the sensor housing at ambient temperature. As a consequence, the cooling of the wire at high pressures becomes much slower.

The data (Fig. 4) clearly demonstrate that the cooling of the wire at temperatures a few Centigrade above ambient are indeed sensitive to gas pressure in the range 100–1000 mbar. Here the influence of the heat capacity of the gas is directly visible. It seems promising to use this feature in order to improve the pressure measurement by the Pirani sensor in this range.

6. Quasi-stationary operation of the Pirani sensor

In the commercially available pulsed Pirani-Sensor [6], the manufacturer does not aim mainly for improved specifications, but for more simple electronics. Operation with pulsed heating makes the control circuit for constant wire temperature as well as the DAC (Digital-to-analogue-converter) for a digital display superfluous, and a simple timer circuit which can be provided by the already existing micro-controller is only required.

We suggest to achieve these advantages by a quasi-stationary operation of the Pirani sensor. In this operation mode, the wire is operated intermittently in the following way: In the time between the pulses, the sensor cools to ambient. During a pulse, the heating voltage is gradually increased from zero. When the slope is sufficiently small, the temperatures of wire and gas in the Pirani sensor practically follow as for the static case. A comparator circuit monitors the wire temperature via its resistance. When the temperature reaches the pre-set value, the pulse is terminated. The duration of the pulse is recorded by the microprocessor and converted to a pressure reading. This is a viable operating concept and would give the same characteristics as the stationary mode. A disadvantage, however, is the slow reaction of such an instrument to pressure changes.

For a more practical device we made exploratory measurements of such a non-stationary operation of our Pirani sensor employing a linearly ramped fast-rising voltage. The voltage increase per unit time was chosen to be quite high to keep the pulse duration below 0.1 s. Clearly, at pressures below a few mbar, the heating process is far from a quasi-stationary behaviour (compare the response times in Fig. 4) but this pressure range is not interesting in our study. At higher pressures, the heating is fairly well quasi-stationary.

The measured characteristics of heating time versus pressure are shown in Fig. 5. For comparison, also the stationary measured voltage versus

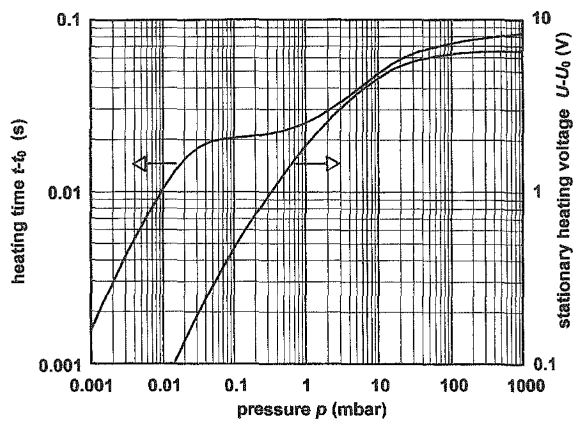

Fig 5. Characteristics of the wire versus pressure. Left ordinate scale: time required for heating the wire to a pre-set temperature by a pulsed-ramp voltage. Right hand scale: voltage applied to wire at stationary operation at same pre-set temperature. Gas used was ambient air with ~1 vol% water vapour.

pressure characteristic is shown. For both curves, the plotted signals are corrected for the signal at vanishing pressure. Comparison of both curves gives similar shape in the range 3–30 mbar, as expected. Furthermore, the comparison gives a substantially increased slope of the heating time curve as compared to the stationary voltage curve in the range 30–1000 mbar. Clearly, at atmospheric pressures the sensitivity of the measuring signal to pressure is substantially improved in the pulsed-ramp operation compared to that in stationary operation.

7. Conclusions

Our investigations of the heating and cooling of the wire have provided quantitative information on the dynamical behaviour of the Pirani sensor at different gas pressures. A small, but significant effect on the behaviour caused by the heat capacity of the gas was established. This effect can be used for a substantially improved pressure measurement in the range 100–1000 mbar. The required generation of a non-stationary heating power, dynamical monitoring of the wire temperature, and optimisation of the working point can nowadays be realised by a smart electronic controller. A corresponding advanced version of the Pirani gauge may work in the common stationary mode at small pressures and in an intermittent mode at higher pressures (above some 10 mbar). Practical advantages of such an operation are the better performance at higher pressures and the smaller average power consumption.

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