A Pirani gauge for pressures up to 1000 torr and higher

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In vacuum technique there is a need for a pressure gauge covering a range of 7 to 8 decades, with the upper limit in the neighbourhood of atmospheric pressure. The authors of this article have designed a new and very simple instrument, based on the Pirani gauge, that fulfils these requirements.

The Pirani gauge makes use of the pressure-dependence of the thermal conductivity of a gas. The gas whose pressure is to be measured is admitted to an enclosure containing an electrically heated wire which forms one arm of a Wheatstone bridge. The cooling of the wire due to the thermal conduction of the gas changes the electrical resistance of the wire, and the change is a measure of the gas pressure. This method of measurement, described by Pirani in 1906, can be used at pressures from about $10^{-4}$ torr (about $10^{-6}$ torr when special measures are taken) up to 100 torr at the most; at higher values the thermal conductivity of gases is virtually independent of the pressure. The Pirani gauge has the advantages that the measurement is electrical, no gas is removed from or supplied to the system in which the pressure is being measured, and the instrument can be used for practically all kinds of gas. Moreover, the lower limit of the measuring range conveniently overlaps the upper limit of the widely used ionization gauges. A feature which the Pirani and ionization gauges have in common is that the calibration curve depends on the kind of gas.

Unfortunately the upper limit of the measuring range is still well below atmospheric pressure, and this means that a third type of instrument, such as a mercury gauge, has to be used when pressures above 100 torr in vacuum equipment have to be measured. This would not be necessary if the range of the Pirani gauge could be extended up to about 1000 torr. Various investigators have tried to do this by making use of the pressure dependence of additional cooling due to convection of the gas near the hot wire, this convection being initiated by a second heating element, by using a very hot wire, or by a blower. We have succeeded in obtaining a reproducible pressure-dependent additional cooling of the wire due to convection without introducing extra components and with the wire no hotter than about 300 °C: this has been achieved through a careful choice of the temperature of the wire and the dimensions of the envelope and the wire. By combining this manometer tube with a special control circuit we have produced a very simple pressure gauge that will operate in a range of about 0.0001-1000 torr.

Fig. 1 shows the complete pressure gauge set up for measurement, and fig. 2 shows the design of the manometer tube. The wire is coiled and mounted horizontally some way away from the convex upper wall of the envelope. Mounting the wire horizontally usually gives the strongest natural convection.

Fig. 1. The new Pirani gauge set up for measurement. The control unit with the meter can be seen on the left.
coiling the wire makes tension springs unnecessary and also assists the convection. The wire material is an alloy of platinum with 10% rhodium; this material was chosen because a) it does not react with reactive gases such as oxygen (whereas tungsten, which is often used, does), b) it has a low coefficient of emission for heat radiation (which limits the power taken by the wire in vacuo), and c) it possesses sufficient mechanical stability at the working temperature to be used in the form of a horizontally tensioned coil (pure platinum is too soft for this).

![Diagram of manometer tube](image)

Fig. 2. Design of the new manometer tube, with convex upper wall, for pressures of about 0.0001-1000 torr. The operation below about 10 torr depends on the thermal conduction of the gas, as in the original Pirani gauges; above 10 torr it depends on convection. 1 coiled wire of platinum with 10% rhodium, diameter 25 μm, wound on a 1 mm mandrel. Part 2 of the tube is at room temperature; it is made of copper, has a black matt surface and is fitted with cooling fins. The tube must be used in the position shown, with wire 1 horizontal and wall 2 at the top.

Sensitivity, stability of the convection pattern, and measuring range all imposed different requirements on the design of the new manometer tube, and a compromise had to be found between them. In general the sensitivity increases with the distance between the wire and the upper wall and with the temperature of the wire; this temperature therefore sets a lower limit to this distance. On the other hand the stability of the convection sets an upper limit to this distance, particularly for heavy gases (e.g. CO₂) and high pressures. We have found experimentally that an adequate sensitivity—in other words, a measurable heat loss due to convection—is obtained if the distance between the wire and the upper wall is at least 15 mm at pressures of up to 200 torr, and the wire temperature is higher than about 200 °C. Above 200 torr a distance of about 10 mm would be sufficient, and in that case a lower wire temperature would also be permissible. We also found that adequate stability is assured if the following conditions are satisfied:

1) The distance between wire and upper wall should be 40 mm at the most for pressures up to about 1 bar (760 torr).
2) The inner surface of the envelope above the wire should be smoothly contoured, with no sharp corners, edges or protrusions.

The dimensions of envelope and wire used in our manometer tube ensure the necessary stability and also a smooth transition between the two mechanisms of heat transport, so that a wide range of pressures can now be measured with a single gauge.

The convection principle can also be applied for pressures above 1 bar, but to ensure stable convection at the greater density of the gas the distance between the wire and the upper wall must be smaller, which raises the lower limit of the measuring range. For the range from about 1 to about 11 bars we have made an experimental tube with a cylindrical envelope and a wall distance of 7 mm; some information about this tube is given in the caption to fig. 3.

![Diagram of manometer tube](image)

Fig. 3. Schematic cross-section of a manometer tube with cylindrical envelope, for measuring pressures from 1 to 11 bars. The wire 1 is roughly parallel to the axis of the cylinder, but need not coincide with it. Distance between wire and upper wall is about 7 mm. Wire supports and contact pins are of gas-tight material. Draught effects due to pressure changes, which are troublesome at these high pressures, are largely eliminated by a screen 2 in front of the gas inlet. The stability is very good up to pressures of 11 bars; the maximum measurable pressure is probably much higher.

The following well-known and essentially different methods can be used for the measurement.

1) At a constant bridge voltage $V_b$, the meter reading can be taken as a measure of the pressure [6].
2) The temperature of the wire, and hence its resistance $R_p$, can be adjusted by varying the supply voltage $V_b$ until the voltmeter reads zero, the voltage required being a measure of the pressure.

In method (1) the temperature of the wire decreases with increasing gas pressure; if it were to approach the temperature of the envelope, the calibration curve would become too flat, because of the insufficient temperature difference between wire and envelope (not because the pressure dependence of the thermal conductivity is too small). Method (2) does not show this type of saturation [5]; this is therefore the obvious method for our pressure gauge, which works with a fairly low wire temperature and is intended to measure both high and low pressures.

It is perhaps useful to look for a moment at method (1), which is widely used with the classical Pirani gauge [7]. We shall consider three limiting cases, in which we choose:

1a) $R_0 < R_p$ (and hence $R_1 < R_2$); at constant bridge voltage $V_b$, the voltage across the wire then remains virtually constant.

1b) $R_0 > R_p$ (and hence also $R_1 > R_2$); at constant $V_b$, the current through the wire now remains virtually constant.

1c) $R_0 \approx R_p$; at constant $V_b$ the power dissipated in the wire remains virtually constant (decreasing $R_p$ by 20% reduces the power by 1.2%, and a 40% reduction in $R_p$ decreases the power by 6.25%).

If a material with a positive temperature coefficient (e.g., a metal) is used for $R_p$, the saturation in the calibration curve caused by an insufficient temperature difference between wire and envelope occurs soonest with method (1b) ($I_p$ constant) since the power dissipated in the wire ($I_p^2 R_p$) then decreases with increasing gas pressure. In methods (1a) ($V_p$ constant) and (1c) (power constant) the saturation in this case is slower.

With the method we have chosen (2) it is desirable to keep the wire temperature constant automatically [5]. Not only does this provide the advantage of a direct-reading instrument, but it also avoids the risk of the wire burning out if the operator reduces the voltage $V_b$ too late when the pressure drops suddenly to a low value. For this purpose we use an electronic control unit. The circuit diagram is shown in fig. 5. The bridge difference voltage $\Delta V$ is amplified by a differential amplifier and then used as the supply voltage for the bridge. If the gas pressure increases, the wire temperature falls slightly, causing an increase in $\Delta V$ and hence in $V_b$ that almost completely offsets the cooling.

In addition to the resistors $R_0$, $R_1$ and $R_2$ of the bridge circuit and the differential amplifier, the control unit (on the left in fig. 1) contains a voltmeter for various voltage ranges, which is connected to the voltage $V_b$. The zero reading of the meter is made to correspond to vacuum by subtraction of a constant, but adjustable, voltage $V_o$: in a vacuum the wire still loses heat by radiation and by conduction via the vacuum.

The calibration curve of the combined control unit and manometer tube of fig. 2 is given in fig. 6 for nitrogen. As already noted, the calibration curve depends on the kind of gas being measured; light gases like helium and hydrogen have a higher thermal conductivity. The calibration curve shown for nitrogen is also valid for air and oxygen to a very good approximation. The dashed curve presents for comparison the calibration curve of a "classical" Pirani gauge, with identical wire, in the region where it differs from that of the new type.

[4] Instead of reading the voltmeter, one can also adjust the resistance $R_1$ or $R_2$ (or both of them) until the voltage across $M$ is zero again, and use this resistance value as a measure of the pressure.

[5] See for example M. Pirani and J. Yarwood, Principles of vacuum engineering, Chapman & Hall, London 1961, p. 102. Following Pirani, only methods (1a) and (1b) are generally used besides method (2). Method (1c) is not regarded as important in the literature.
Fig. 6. Nitrogen calibration curve for the gauge unit using the manometer tube of fig. 2. The range below 10^{-1} torr is given with a logarithmic ordinate in the inset. The gas pressure is plotted horizontally, the bridge voltage less the value for a vacuum is plotted vertically \((V_b - V_c, \text{ see fig. 5; } V_c \approx 1 \text{ volt})\). The dashed curve relates to a corresponding "classical" Pirani gauge in the range where it differs from the curve for the new type.

Fig. 7. Nitrogen calibration curve for the gauge unit using the tube of fig. 3; the horizontal scale gives the excess pressure in bars. The voltage \(V_c\) corresponds here to the bridge voltage \(V_b\) at 1 bar (about 12 volts).

Finally fig. 7 shows the calibration curve of the tube in fig. 3 for pressures above 1 bar.

In designing the combined manometer tube and control unit our first concern was to make the equipment simple, reliable and easy to use over the whole pressure range. No attempt was made to achieve the highest possible accuracy and sensitivity in specific pressure ranges, and therefore no attempt was made to stabilize the wall temperature. Nevertheless, the accuracy obtained is sufficient for most applications. With careful use the voltage established at a certain pressure is found to be reproducible to within about 1\% of the full scale deflection of the measuring range in use; the corresponding accuracy of the pressure measured depends on the pressure range and can be determined with the aid of the calibration curve.

Summary. The operation of the Pirani gauge relies on the pressure dependence of the thermal conductivity of a gas. When a gas is admitted into the gauge near a hot wire the change in the electrical resistance of the wire, due to the cooling caused by the thermal conduction of the gas, is used as a measure of the gas pressure. The measuring range (previously from about 0.0001 to 100 torr at the most) can be extended upwards by making use of the convection of the gas around the wire. The article describes a Pirani gauge for a pressure range from about 0.0001 to about 1000 torr in which this principle is applied. The design is extremely simple because of the appropriate choice of wire temperature and of the dimensions of tube and wire. The temperature and hence the electrical resistance of the wire are kept automatically constant in a Wheatstone bridge by means of an electronic control unit; the voltage required is a measure of the gas pressure. The design parameters are briefly discussed in connection with stability and sensitivity. A variant of the tube is suitable for measuring pressures from 1 to 11 bars and perhaps higher.