

Gas Correction Factors for Vacuum Pressure Gauges

Factors Affecting the Sensitivity of Ionisation and Thermal Type Vacuum Gauges with Different Gases

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1 Introduction

Knowing the pressure within a system is crucial for almost all vacuum applications for many reasons, including interlocks, switches, control of production processes and even safety. The subject of vacuum is almost unique in that it has a dynamic range extending over 15 orders of magnitude with no single pressure gauge covering the whole range. Pressure gauges fall into one of two categories; those that measure pressure directly (through the force exerted when gas molecules impinge on a surface) and those that measure it indirectly. Indirect gauges usually measure a physical property such as thermal conduction, viscosity or number density, these values being different for different gas species. This means that indirect gauges are gas type dependent.

2 Correction Factors

Vacuum gauges usually come from manufacturers calibrated for measurement of nitrogen so this is attributed a correction factor of 1. If the gas being measured is predominantly a different species then a correction factor must be applied to the measured pressure to give the true pressure for that gas and this will depend on the sensitivity of the gauge to the gas relative to nitrogen. The true pressure, P_i for gas species i is given by:

$$P_i = \frac{S_{N_2}}{S_i} \cdot P_{N_2}$$

where S_i and S_{N_2} are the relative sensitivities of the gauge to gas i and nitrogen ($S_{N_2} = 1$ by definition). It should be noted that some sources (manufacturers and in literature) will quote a sensitivity factor equivalent to S_i which the measured pressure should be *divided* by to gain the true pressure and some



will give a gas correction factor equivalent to S_{N_2} / S_i by which the measured pressure should be *multiplied* to gain the true pressure. In most cases it will be stated which form is being used, but not always.

If the gas being measured contains a mixture of species, then Dalton's law for total and partial pressure can be used to extend this correction:

$$P_{\text{true}} = \frac{\sum_{i=1}^N r_i}{\sum_{i=1}^N S_i \cdot r_i} \cdot P_{\text{measured}}$$

where r_i is the relative proportion (partial pressure) of gas species i compared with nitrogen so $r_i = P_i / P_{N_2}$. For example, if a Pirani gauge measures a pressure of 0.1 mbar for a 50:30:20 mixture of nitrogen, helium and krypton (correction

factors 1, 1.05 and 2.32 respectively) then the true pressure is:

$$P_{\text{true}} = \frac{\left(\frac{1}{1}\right) + \left(\frac{3}{5}\right) + \left(\frac{2}{5}\right)}{\left(1 \cdot \left(\frac{1}{1}\right)\right) + \left(1.05 \cdot \left(\frac{3}{5}\right)\right) + \left(2.32 \cdot \left(\frac{2}{5}\right)\right)} \cdot 0.1 = 7.95 \cdot 10^{-2} \text{ mbar}$$

2.1 Constant Correction Factors

Generally correction factors employed are constant for the range of pressures over which the gauge operates. Due to the large number of factors which influence a gauge's response (there is even difference between seemingly identical gauges) there can be significant variation in quoted values for correction factors between different literature sources and manufacturers.

SUMMARY

Vacuum pressure gauges will typically arrive from a manufacturer calibrated for nitrogen; for other gases, to avoid potentially significant measurement errors, a correction factor must be used to convert 'measured' or 'indicated' pressure to 'true' pressure. The correction factors used are influenced by a

large number of factors and these vary with gauge type. In this article the factors leading to varying gauge sensitivity with different gases are examined and values for correction factors provided by manufacturers and in literature are presented.

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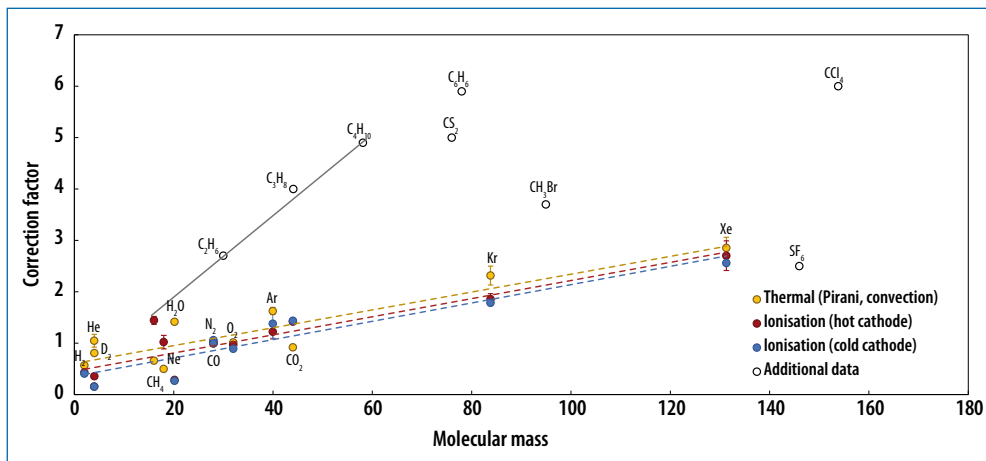


FIGURE 1: Summary of correction factor data for a range of common gases from various literature sources and manufacturers for thermal and ionisation type gauges and additional data for less common gases from a single source.

Fig. 1 shows the variation in correction factors of a range of gases for thermal and ionisation gauges plus additional data on less common gases. The points show the mean value with the error bars giving the standard deviation of the data from multiple sources (the additional data is from a single source). These are relative to nitrogen which has, as discussed, a nominal correction factor of 1. It can be seen that for all gauge types there is a roughly linear increase in correction factor with molecular mass. It can also be seen that there is a significant variation (as much as 41%, 38% and 60% for Pirani, hot cathode and cold cathode respectively) in correction factors from manufacturers and other

sources. This can be due to the specific gauge used for measurement as well as calibration and ambient conditions. Additional data for other gases shows the larger correction factor for more complicated, multi-atomic molecules although there is still a dependence on mass as shown by the C_nH_{2n+2} series. Fig. 2 shows the correction factors quoted by some of the leading gauge manufacturers for hot cathode ionisation gauges only.

2.2 Calibration Curves

Although using a constant correction factor gives a generally reasonable approximation for the middle of the gauge's range it can lead to significant errors at the upper extreme of the range. This is demonstrated in Fig. 3 where curves of displayed pressure against true pressure for a Pirani gauge are shown. The inset shows the approximately linear region where correction factors are measured. For pressures above around 1 mbar there is signifi-

cant departure from linearity (to be discussed below) and therefore readings in this range should only be used for indication. Most manufacturers will give both a range of higher accuracy and an extended range over which the gauge can still be used but accuracy is reduced. It can be seen that below around 10^{-3} mbar there is little difference between measured and true pressure and between different gases. This is due to radiation, which is not dependant on gas species, taking over as the largest contribution to heat loss (discussed below).

2.3 Gauge Accuracy

The accuracy of a gauge will depend on many factors but, in general, a gauge which arrives from a manufacturer with only a 'rough' calibration (with no correction factors applied) can have 20–50% uncertainty within the stated range. Using a constant gas correction factor can improve this to 10–20%. Where high accuracy is required, gauges should be calibrated over their whole pressure range to give curves such as those in Fig. 3. Long term accuracy of gauges is determined by their sensitivity. For a high quality gauge, individually calibrated for each gas species over the full range against a primary standard, accuracy can be improved to 2–5%.

3 Gauge Mechanisms

To appreciate the reasons certain factors affect gauge correction factors, it is important to understand the operating principles by which the different gauges work. From the perspective of

ZUSAMMENFASSUNG

Gaskorrekturfaktoren für Vakuumdruckmessgeräte

Vakuummessgeräte werden üblicherweise von den Herstellern für Stickstoff kalibriert. Um die bei Druckmessungen in anderen Gasen auftretenden Messfehler zu vermeiden, muss mit Hilfe eines Korrekturfaktors der angezeigte Druck in den tatsächlichen Druck umgerechnet werden. Die verwendeten Korrekturfaktoren hängen von vielen, ihrerseits wiederum messgerätabhängigen Faktoren ab. Im Beitrag werden verschiedene, die gasartabhängige Sensitivität der Messgeräte beeinflussende Faktoren untersucht und Werte für Korrekturfaktoren präsentiert.

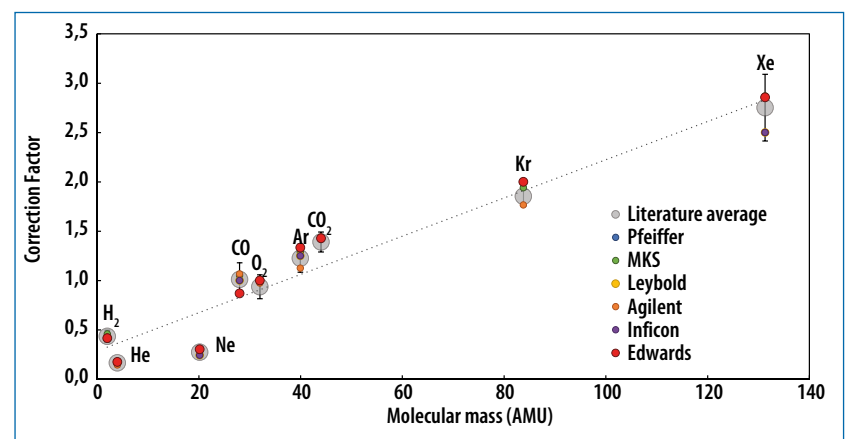


FIGURE 2: Summary of correction factor data from gauge manufacturers against literature averages.

sensitivity to different gases, there are two key types of pressure gauge; ionisation and thermal. They are both indirect but vary in the way in which they measure pressure associated with residual gas molecules.

3.1 Ionisation Gauges

Ionisation (or ion) gauges are most commonly used for low pressure measurements where the highest accuracy is not critical. They work by ionising gas molecules and causing ions to be accelerated to a detector which measures a current from molecular impacts. They split into two categories depending on the mode of creation of ionising electrons; hot cathode gauges (HCG) use a heated filament to produce electrons whereas cold cathode gauges (CCG) use a crossed electric and magnetic field [1]. Historically there are many kinds of hot cathode gauge however the most common version is the Bayard-Alpert (BA).

BA gauges from different manufacturers generally follow the same design and this allows gauges to be used interchangeably with a single controller. Electrons are produced from a heated filament at around 30V (as this produces the electron energy giving the highest ionisation probability) generating an electron current of 0.1 to 10 mA. They are accelerated toward the anode, which is usually in the form of a spiral and held at a positive potential as shown in Fig. 4. This design means that any electrons which do not collide with gas molecules and pass out the far side of the spiral will be drawn back in, reducing losses. As electrons travel through the gas they will collide with molecules and ionise them. Since these ionised molecules have a positive charge they will be repelled from the grid and collide with the collector. The collector is usually a thin wire down the centre of the grid held at ground. Each time an ionised molecule collides with the collector it causes a current to pass through the wire and thus the pressure of the gas can be measured from the number of collisions and hence density of molecules.

The pressure of the gas is directly proportional to the number density of molecules:

$$P = nkT$$

The positive ions colliding with the collector take an electron from it to become neutral, thereby generating a current I_c . The pressure is directly proportional to the current generated:

$$P \propto \frac{I_c}{I_e}$$

where I_e is the electron current from the filament which has a fixed value. The gauge can be inserted directly into the chamber 'nude' (the most common option), or enclosed in a glass envelope which is attached to the vacuum chamber.

In cold cathode gauges, the electrons are generated not by thermionic emission, but by discharge in a crossed electric and magnetic field and hence they are also known as 'crossed-field' gauges. The magnetic field also has a secondary affect in that it causes the electrons to travel in a helical path within the gauge and leads to secondary electron generation, maintaining the discharge. The larger mass ionised molecules are less affected by this and can travel directly to the collector. This means that as electrons make several passes around the gauge they are more likely to ionise gas molecules and less likely to collide with the collector. The discharge created by a cold cathode gauge is almost linearly proportional to pressure however, unlike hot cathode gauges, the ion current at the collector does not vary linearly with pressure but has a more complicated relationship. This leads to decreased accuracy, particularly at very low pressures.

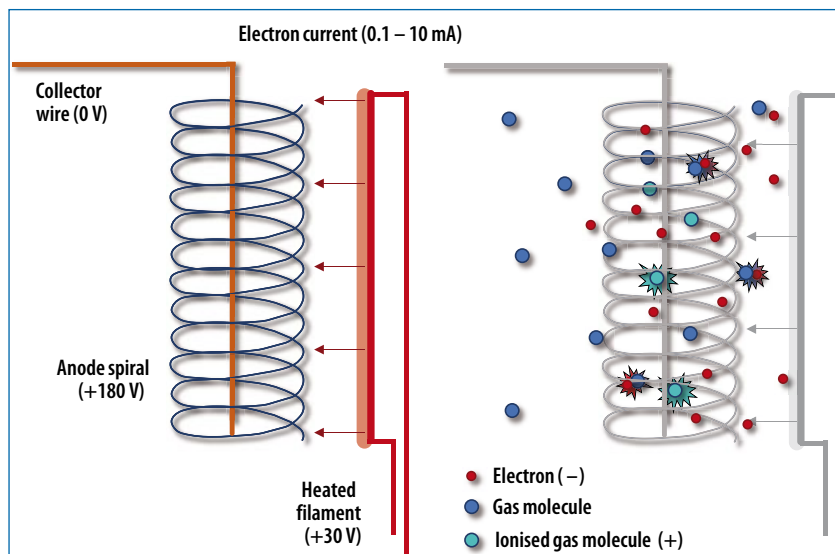


FIGURE 4: Diagrams showing the three electrode construction of the Bayard-Alpert gauge and the process of ionisation and collection.

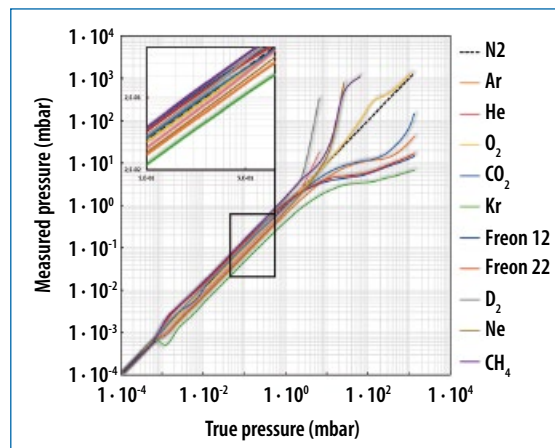


FIGURE 3: Typical calibration curves showing displayed pressure against true pressure for a convection enhanced Pirani gauge with various gases (courtesy of InstruTech).

There are many different designs of cold cathode gauge with the most common being the Penning, magnetron and inverted magnetron. The Penning gauge is the most simple and based on the original design, as shown in Fig. 5.

This basic design was improved on in the magnetron gauge. In this, the anode is an open 'cylinder' with the cathode through the centre and as endplates. This is reversed in the inverted magnetron, where the anode forms the central rod and the cathode is the almost closed cylinder surrounding it. For both of these the magnetic field which is parallel to the axis can be significant; around 0.2 T for magnetron gauges and slightly lower for inverted magnetron gauges. Both these designs are shown in Fig. 6.

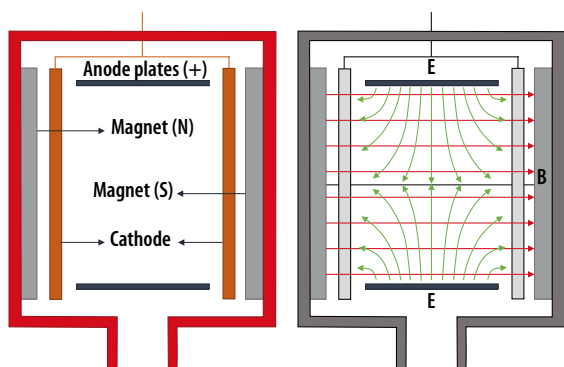


FIGURE 5: Diagrams showing the design of a Penning CCG with crossed electric and magnetic fields.

3.2 Thermal Gauges

There are several types of pressure gauge based on thermal transport but the most common is the Pirani gauge. The basic principle behind all thermal gauges is that when gas molecules come into contact with a hot surface there will be a transfer of energy from the surface to the gas. The rate of energy loss will depend on the number of collisions with gas molecules and therefore the pressure of the gas. Heat can also be lost via radiation or conduction through the supporting structure however these do not depend on the pressure and are constant or negligible over the operational pressure range.

The Pirani gauge uses a simple Wheatstone bridge design as shown in Fig. 7. One arm of the bridge is comprised of a thin wire filament, usually platinum or tungsten, which is heated electrically and exposed to vacuum. As heat is lost to gas molecules the resistance of the wire changes and this is measured by the bridge circuit. Generally a constant resistance, R , is used and since the power, W , supplied is given by:

$$W = I^2 R$$

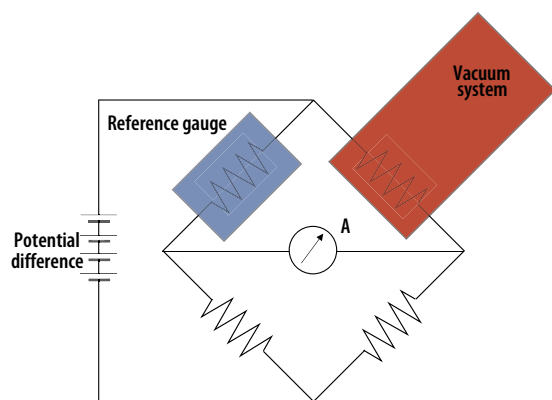


FIGURE 7: Diagram showing the setup of the circuit used in a Pirani gauge.

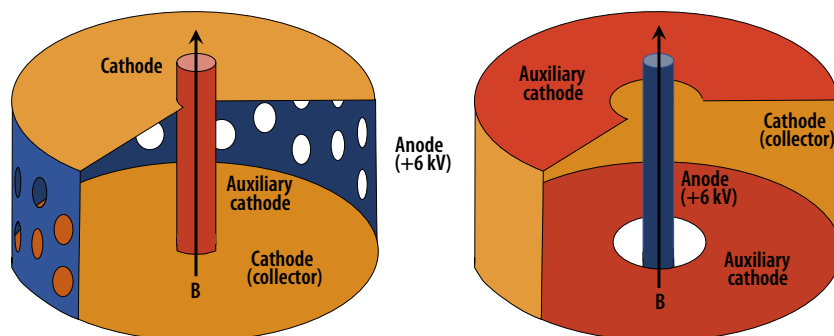


FIGURE 6: Diagrams showing the design of magnetron (left) and inverted magnetron (right) gauges.

the current, I , required to keep this balance is a measure of the pressure. A reference (control) gauge, comprised of an identical sensing element in a sealed volume at known pressure, can be used to account for changes in the local conditions (ambient temperature and pressure) replacing one arm of the bridge.

4 Factors Affecting Sensitivity

There are a large number of factors which affect the response of gauges to different gases, some of which are specific to certain gauge types. For example; with ionisation gauges variation in sensitivity can be due to grid voltage, current, envelope geometry, ionisation cross section or molecular polarisability whereas with thermal gauges variation can be due to thermal accommodation coefficient, molecular mass or ratio of specific heats.

For all gauge types, the correction factor depends on pressure as has been shown in Fig. 1. Although the correction factor remains relatively constant with pressure at low pressures, this can lead to significant errors when measuring at high pressure. The effect is particularly apparent in ionisation type gauges where a higher pressure leads to an increase in the ionisation efficiency of the electrons and therefore repeat ionisation of the gas molecules. This means a higher proportion of the gas molecules will become ionised and those that are ionised can become multiply charged. Both these effects lead to a higher current being detected and therefore the pressure measured becomes inaccurate.

For both ion and thermal gauges, the correction factor is temperature dependent. This can be due to changes in the external ambient and envelope

temperature or, for Pirani and hot cathode, positioning of the heated filament within the housing. Generally, if the gauge is allowed to reach an equilibrium before readings are taken then this is not a significant issue. For conditions with extreme temperatures, an additional correction can be applied:

$$S_{T_0} = S_T \cdot \frac{T_1}{T_0}$$

where T_0 is ambient temperature and S_T is the sensitivity at temperature T .

4.1 Factors Affecting Ionisation Gauges

There are some factors which affect the gas dependence of gauges which are specific to ionisation gauges due to their design.

The most simple of these is due to the voltage supplied to the grid. Fig. 8 shows the variation in correction factor with grid voltage (relative to the filament) for nitrogen, argon and xenon. It can be seen that the chosen correction factor of 1 for nitrogen occurs at a grid potential of 150 V. Therefore it is this value which is used in almost all cases. The reason for the variation is that the voltage has an effect on both the electron trajectories and the ionisation efficiencies of the electrons. Furthermore, the relationship between voltage and sensitivity is different with different gas species as demonstrated by the curves for gases shown in Fig. 8. The sensitivity of the gauge can vary by as much as 0.1 %/V for filament-to-grid potential and up to 1 %/V for filament-to-ground. It is therefore important that the correct voltages are used and kept as constant as possible.

Whilst the electron current generated in an ion gauge does have an effect on the correction factor, this is usually only minimal. It does however

decrease the useful range of the gauge if an inappropriate value is chosen. If the electron current is too high it will cause a non-linearity in the pressure response and therefore a lower current is preferred; generally less than 0.1 mA is recommended. If the current is allowed to increase to 10 mA this can cause a decrease in the correction factor by as much as 20 % and significant non-linearity above 10^{-5} mbar.

The geometry of the gauge can also have an effect on sensitivity, examples of this are the filament to grid spacing, collector location and size and grid end-closure and diameter. Whilst these are usually only small contributions, they are difficult to predict and can vary from gauge to gauge even with the same design. The largest contribution comes from the envelope (when present). This is due to accumulation of charge on the inner surface. This charge causes alterations in electron paths and can lead to shifts in the measured pressure. The most common solution to this is to add shielding to the gauge to prevent charge accumulation or simply use a nude gauge.

The largest effect on the correction factor comes from two closely linked factors; the ionisation cross section and molecular polarisability. Molecular polarisability arises from the shape and structure of the gas molecules themselves. The quantised movement of electrons around the atoms can lead to an uneven distribution of charge which makes the molecule temporarily polar. This can also be induced by an external electric or magnetic field. The more strongly polarised a molecule is the greater the charge and the more likely it will be to attract an electron. This therefore will influence the ionisation cross-section.

The ionisation cross section of a molecule is a measure of the likelihood of that molecule becoming ionised. The more likely a particular gas is to become ionised the more molecules will acquire a charge and collide with the detector. This means that a gas with a higher ionisation cross-section will generate a larger current at the collector and therefore register a higher pressure than a gas of lower ionisation cross-section at the same true pressure.

The relationship between the correc-

tion factor and molecular polarisability and (relative) ionisation cross-section are shown in Figs 9 and 10 respectively. It can be seen that in both cases there is a strong linear relationship with the correction factor.

4.2 Factors Affecting Thermal Gauges

It has been shown (Fig. 1) that higher mass molecules tend to have larger correction factors. In the case of thermal transfer gauges this can be attributed to larger molecules generally having higher (heat) conductivity. There are a number of factors which contribute to the conductivity of a particular gas species including interaction effects, specific heats and accommodation coefficients.

Interaction effects cover a range of characteristics such as the number of degrees of freedom a molecule has (which is influenced by its shape, bonding of constituent atoms and vibrations/rotations) and whether the molecule is polar. These will all affect how the molecules behave with each other and how likely they are to collide with the filament for heat transfer. This is usually only a relatively minor effect. Another minor effect is the accommodation coefficient. This is a measure of how likely a molecule is to arrive at the filament, stay a period of time, and leave with an energy distribution corresponding to the filament temperature. It is dependent on the gas species and the filament temperature and surface material.

One of the largest contributions to the sensitivity and therefore correction factor is the specific heat ratio. Specific heat C is defined as the amount of heat (energy) required to raise the temperature by $1\text{ }^{\circ}\text{C}$. For gases this is given under two conditions; constant pressure, C_p and constant volume, C_v . Of these, C_p will be higher since it represents the case where heat is also lost in doing work; expanding the volume to keep pressure constant. The ratio of these, γ (or alternatively k or κ), is therefore always greater than unity. Both specific heats are also temperature dependent with the ratio tending to one with increasing temperature.

From fundamental principles, it has been shown [3] that the gas energy transfer, W_G in a thermal gauge is given

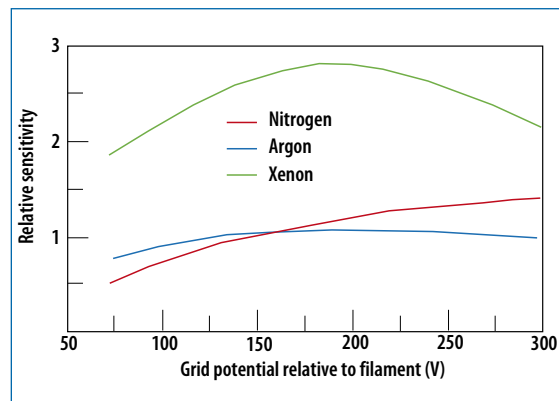


FIGURE 8: Plot showing the dependence of gauge sensitivity on grid potential for N_2 , Ar and Xe.

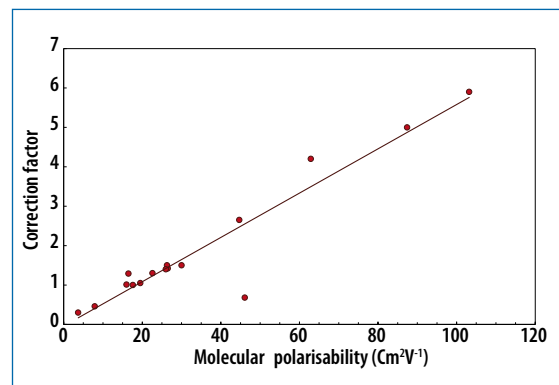


FIGURE 9: Plot showing the dependence of gauge sensitivity on molecular polarisability [2].

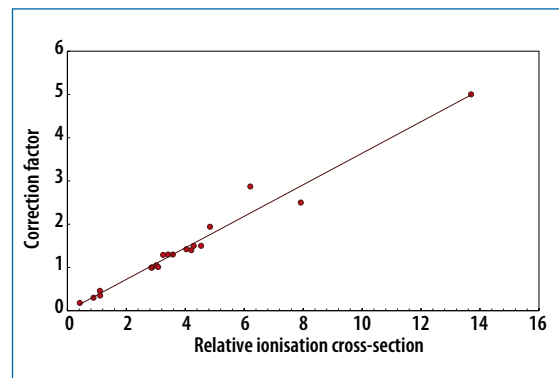


FIGURE 10: Plot showing the dependence of gauge sensitivity on relative ionisation cross section [3].

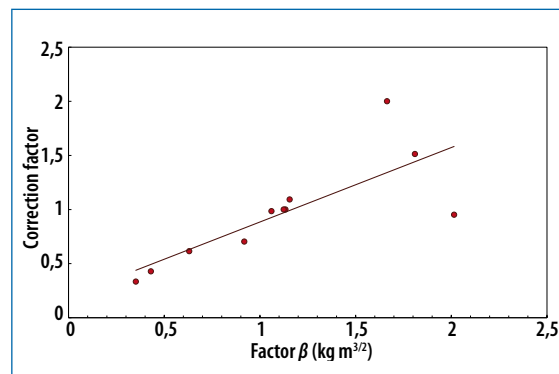


FIGURE 11: Plot showing the dependence of gauge sensitivity on specific heat and molecular mass.

by:

$$W_G \propto \left(\frac{\gamma+1}{\gamma-1} \right) \cdot \sqrt{\frac{1}{M}} \quad P = \beta P$$

which shows the dependence on specific heat and mass M . Since Pirani gauges measure heat lost to the gas, W_G is proportional to the correction factor for a certain gas. This is demonstrated in Fig. 11 where literature values for correction factors are compared with factor β .

Whilst other heat transfer mechanisms do not significantly influence the functioning of thermal gauges in their typical operating region, they can limit the range. At low pressures, where there are fewer gas molecules present, radiation and conduction through the filament support become dominant and therefore pressures measured will be higher than the true pressure, setting a lower limit on measurable pressure as shown in Fig. 12. These effects can be minimised by using a filament with high length/diameter ratio made from a low emissivity material.

At high pressure, where the mean free path of the molecules is of the order of the size of the filament, the mean free path limits measurement. In general operation, it is assumed that the mean free path is long; gas molecules are more likely to collide with the container and filament than each other. However at higher pressures, this is not the case. Gas molecules leaving the wire lose their heat within a short distance due to collisions with other gas molecules and a hot sheath is formed around the wire. This prevents further heat transport away from the wire and sets the upper limit on measurable pressure. The upper range can be extended by creating convection within the gas to disperse the sheath.

5 Conclusions

It has been demonstrated that response of both ionisation and thermal gauges (their *sensitivity*) is dependent on the species of gas present. It is therefore critical for accurate measurement that correction factors are used. These correction factors are dependent on a number of factors and these vary with gauge type. For ionisation gauges the grid voltage, ionisation cross section and molecular polarisability are key whereas for thermal gauges the molec-

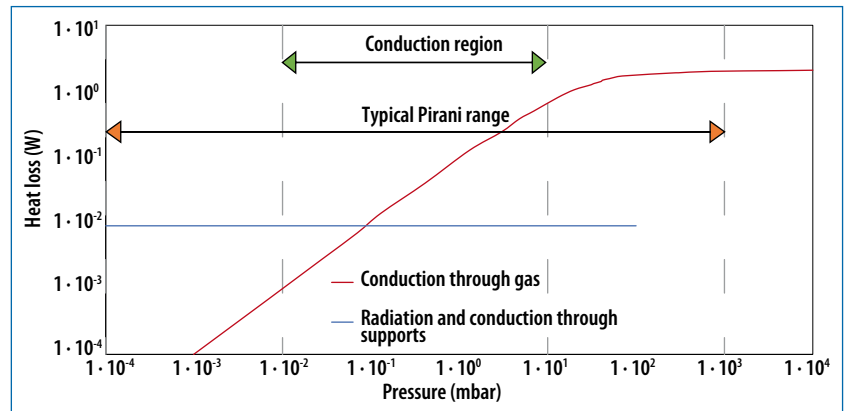


FIGURE 12: Plot showing the dominant heat loss mechanisms for a typical Pirani gauge at different pressures [4].

ular mass and heat capacity have the most significant effect.

Whilst generally a constant correction factor is used, it has been shown that this only holds for certain pressure ranges. Generally, at the higher pressure end of their respective ranges there are significant departures from this. Using a constant correction factor will typically improve the uncertainty in measurement (compared with not applying a correction factor) from 20–50 % to 10–20 %. However, if better accuracy is needed gauges can be calibrated for each gas over the whole pressure range against a commercially available secondary/transfer standard, or in extreme cases, a primary standard.

The factors affecting the gauge sensitivity to a particular gas can be calculated or measured but there will also be significant variation from gauge to gauge. Manufacturers will normally provide correction factors for a certain gauge type however there can still be variation between seemingly identi-

cal gauges. It is therefore important to always employ appropriate correction factors but bear in mind that there will still be uncertainty in measured pressures, particularly at the extremes of the operational range.

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