

Vacuum gauges and partial pressure analysers

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Abstract. This paper briefly reviews the characteristics of several important vacuum instruments; capacitance diaphragm gauges, ionization gauges, spinning rotor gauges, and partial pressure or residual gas analysers.

1. Introduction

Instrument characteristics can affect the accuracy of measurements. This article will briefly describe such characteristics for several common vacuum gauges; capacitance diaphragm gauges (CDGs), ionization gauges, spinning rotor gauges (SRGs), and partial pressure or residual gas analysers (PPAs), all of which are discussed in more detail in [1]. However, the user should also be aware of other factors, in addition to instrument performance, that can have significant effects on vacuum measurement accuracies. Order of magnitude pressure gradients can exist in a vacuum system and either the gauge must be located in the region where knowledge of the pressure is desired, or the system must be designed to minimize pressure gradients. The partial pressures of certain molecular species are often more important than the total pressure, but the gas composition may be unknown and difficult to control, in which cases partial pressures must be measured. Most high-vacuum gauges use a hot filament (cathode) or high-voltage discharge. Depending on circumstances, this can cause the gauge to either generate or pump gases, and quite often will produce significant quantities of gaseous chemical reactants, e.g. reactions between water, hydrogen, and carbon impurities in hot filaments produce carbon monoxide.

2. Capacitance diaphragm gauges

The CDG is a true pressure gauge, that is, it measures a force per unit area. It employs a stretched thin metal diaphragm; applied pressures cause the diaphragm to deflect, the deflection is determined by the change in capacitance between the diaphragm and adjacent plates. The CDG differs from the multitude of other pressure gauges and transducers in that it has exceptional sensitivity (10^{-4} Pa in the lowest-range gauges), permitting its use into the high-vacuum range, and the materials and methods of construction result in a clean, leak-tight gauge that is compatible with ultra-high-vacuum (UHV) systems. Some units can be baked at elevated temperatures; they are compatible with most gases; and the readings are for most purposes, independent of gas species.

The principal limits of the CDG are zero instabilities, calibration shifts, and thermal transpiration effects. The lowest-pressure measurements are limited by unpredictable, pressure-independent changes in the instrument output, generally referred to as zero instabilities. Over a day these will typically be between 10^{-5} and 10^{-4} of the instrument's full range, although individual instruments can be an order of magnitude better or worse

than these limits [2]. The instability of the calibration factor will also vary greatly from one instrument to another, but on the average it is about 0.4% over one or two years [2–4]. In order to minimize zero instabilities, CDGs operate at a controlled elevated temperature. For pressures below about 10 Pa the thermal transpiration effect [5] causes a pressure-dependent increase in the pressure in the heated gauge. For the typical CDG operating around 45 °C this causes the gauge to read higher than the true pressure by as much as 3–4% at the lowest pressures [6, 7].

3. Ionization gauges

The forces generated by pressures in the high- and ultra-high-vacuum ranges are generally too small to measure, and vacuum gauges must employ alternative techniques that are sensitive to the molecular density. The most common of these is the impact ionization of gas molecules by low-energy electrons. Gauges employing this technique are known as ionization gauges, and are generally divided into two types, reviewed in [8–10], by the method of electron generation. Hot-cathode gauges rely on thermionic emission of electrons from a heated filament; the electrons are accelerated towards a positively biased grid, and the generated ions are attracted to a collector, generally maintained at ground potential. To a first approximation, the ion or collector current is proportional to the electron emission current and the gas density. The gauge is usually characterized by a sensitivity with units of inverse pressure, $S = I^+ / I^- P$, where I^+ is the ion current and I^- is the current of ionizing electrons. Typical sensitivity values [11] are of the order of 0.1 Pa^{-1} .

Cold-cathode ion gauges establish an electron discharge that is confined between crossed electrical and magnetic fields. The discharge is sustained by secondary electrons generated by the ionization of gas molecules; this current of electrons is used as a measure of the gas density or pressure. Under typical operating conditions, for a given pressure the electron current in a cold-cathode gauge is several orders of magnitude larger than the ion current in a hot-cathode gauge. However, the electron current is not linearly proportional to the pressure; it generally follows a power law, whose characteristics will vary with gauge design and pressure [12].

Ion gauges are sensitive and operate over a wide range of pressures; the common Bayard–Alpert (BA) gauge operates between 10^{-8} and 0.1 Pa; the low-pressure limit is determined by pressure-independent residual currents due to the photo-ejection of electrons from the collector and electron-stimulated desorption of ions from the grid. Specialized gauge types can extend this limit to 10^{-12} Pa, and perhaps lower. Ion gauges are relatively simple and inexpensive and have a fast response time. However, the user should be aware of a number of limitations, many of them surface related [13]. The probability of electron-impact ionization depends on the molecular species, so ion gauge sensitivities vary by more than an order of magnitude for different gases, and ion gauge readings are correspondingly uncertain where the gas species is not known. Even under optimum laboratory conditions, sensitivity changes of several percent per year should be expected [14, 15]. The heated filaments used in hot-cathode gauges will react with many gases, changing the vacuum environment, and can burn out if exposed to high pressures. Cold-cathode gauges have the advantage of no hot filament to burn out, require less power and do not generate heat. However, the high-voltage discharge (typically through a potential of several kV) can provoke significant chemical reactions with gases such as water; their response is generally less stable and predictable than that of hot-cathode gauges, and the magnetic field (tenths of teslas) can interfere with neighbouring instruments.

4. Molecular drag gauges

The spinning rotor gauge (SRG) measures pressure by determining the molecular drag on a spinning levitated steel ball. The 4–5 mm diameter bearing ball is magnetically suspended by a combination of permanent and electromagnets, spun up to about 400 Hz by an inductive drive, and then allowed to coast. The rotation rate of the ball is determined by timing the signal generated by the rotating component of the magnetic moment induced in the ball. Most, but not all, gas molecules striking the surface of the ball are momentarily absorbed, then desorbed from the ball's rotating frame of reference in random directions. This causes the ball to slow down at a rate determined by the pressure, the absolute temperature, and the square root of the gas molecular weight. Using measuring times of up to 30 s, and statistical data reduction algorithms, it is possible to achieve sensitivities of the order of 10^{-6} Pa of nitrogen [16, 17]. At pressures above 0.1 Pa the rate of slowing with pressure becomes non-linear because of viscosity effects, but with correction the gauge can be used up to 10 Pa. The absence of a hot filament or high-voltage discharge is a significant advantage when working with reactive gases, and the calibration of the gauge is more stable than that of ion gauges; typical changes do not exceed 1–2% over a 1–2 year period [18–20]. Since the change in rotation frequency is a measure of the accumulated momentum transfer, it is quite easy to use the SRG to measure integrated pressures or gas doses.

The primary factor limiting the performance of the SRG is the residual drag, a pressure-independent slowing of the ball caused by eddy currents [21–23]. The magnitude of the residual drag varies from gauge to gauge, typically between 10^{-4} and 10^{-2} Pa. However, once a ball is suspended the residual drag is relatively stable and the commercial SRGs include an offset correction to allow for the residual drag. Since the average momentum exchanged with scattered molecules will depend on the microscopic surface roughness and the small fraction of molecules that are specularly scattered with no exchange of momentum, the SRG must be calibrated for the best accuracy. The calibration constant, known as the effective accommodation coefficient, will typically vary between about 0.95 and 1.1 for 'smooth' (production polish) balls. The SRG is more sensitive to vibration and temperature changes than a ion gauge, requires longer measuring times at low pressures, and is much more expensive. However, the SRG is clearly the best choice for applications requiring the best accuracy or an inert sensor.

5. Partial pressure analysers

The molecular composition of the residual gases in vacuum chamber is a useful diagnostic of the vacuum system condition, and many experiments and industrial processes require the detection and control of specific molecular species. Mass-spectrometer-type instruments, known as partial pressure analysers (PPAs) or residual gas analysers (RGAs) are commonly used for this purpose. These instruments are bakeable and generally smaller than analytical mass spectrometers. They generally consist of an electron-impact ionizer, a mass/charge filter, and a detector. The ionizers are similar to the cathode and grid structure of an ion gauge, but generally much more complex. Most modern instruments use a quadrupole filter, although magnetic-sector and time-of-flight filters are used as well. Ions that pass through the filter are detected with either a Faraday cup or a secondary electron multiplier (SEM).

The design, performance, and interpretation of PPA results are far too complex to adequately cover in this review. Even when used only as a qualitative indicator of vacuum system performance, there is a certain 'art' required in the interpretation of results, as

discussed in [24]. The more stringent requirements for quantitative measures of partial pressures have prompted several recent studies of PPA performance several of which are referenced in [25]. In very brief summary, the performance of the PPAs can be highly dependent on ionizer operating parameters, particularly the ion extraction voltage (ion 'energy' control). Space charge effects can cause significant changes in the sensitivity with pressure, particularly for low ion energy settings. The relative sensitivity for different gases can be strongly dependent on the resolution controls, and relative sensitivities can differ by an order of magnitude from the values published for ion gauges. In some instruments the sensitivity for one gas can be strongly dependent on the pressure of other gases; this may be due to space charge effects and charge exchange phenomena in the ionizers. Operation with reactive gases (e.g. water, oxygen, hydrogen) can cause significant (factor of two) changes in PPA sensitivity that appear to decay with time and/or baking. The gain of SEMs is dependent on time and use, and order of magnitude changes are possible over periods of days or weeks.

These comments are not intended to discourage the use of PPAs; for many applications they are one of the most useful vacuum instruments. However, the user must understand the limits of their particular instrument if they are to establish reasonable limits on the validity of the results. For the most accurate results, use Faraday cup detectors or regularly check the SEM gain, calibrate the PPA over the pressure range of interest with pure gases using a BA ion gauge (corrected for relative gas sensitivities) as the reference standard, adjust the emission current and extraction voltage to optimize the linearity as a function of pressure, calibrate with all gases of interest, and periodically check the stability of the sensitivity, particularly after operation with reactive gases.

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