Vacuum Gauges I

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1. Measurement of vacuum pressures and the calibration chain
2. Overview of measurement principles and gauge types
3. Crossed field gauges („cold cathode“ gauges)
4. Accuracy of vacuum gauges

PTB, Siemens-Building, Berlin-Charlottenburg
References

CERN Accelerator School 2006
“Vacuum in Accelerators”
CERN-2007-003
Chapters “Gauges for fine and high vacuum“ pp. 65 and „UHV gauges“ pp.145
The measurement process

Any physical quantity is a product of a **number and a unit**

\[ Q = \{Q\} \times [Q] \quad \text{e.g.: } D = 39.8 \text{ mm} \text{ or } p = 4.7 \times 10^{-5} \text{ Pa} \]

Each measurement process is a comparison between the physical quantity and the unit.

The unit is provided by a calibration.

SI Unit for pressure: 1 [Pa] = [N] [m]^{-2} = [kg] [m]^{-1} [s]^{-2}

1 [Pa] = 10^{-2} [mbar]

“Torr” and “micron” were related to the height of the mercury column and are obsolete.
The calibration chain

Reliability increases

Uncertainty increases

primary standard for Pa

secondary standard

working standard

ordinary vacuum gauge
Traceability and primary standards

- Fully developed primary standards
- Partly developed standards
**Error**: A wrong reading of a gauge. A deviation from a true value defined by the SI units.

**Uncertainty**: The possible range by which a reading *may* not reflect the true value defined by the SI units.
**Error and uncertainty**

**Measurement uncertainty of a type of gauge:** Must include error of reading and uncertainty!

**Measurement uncertainty of a specific gauge:** Error of reading is known from calibration certificate and can be corrected!

\[
\text{Corrected value} = \text{true value} - \text{Uncertainty of specific vacuum gauge}
\]

\[
\text{Uncertainty of type of vacuum gauge} = \text{Indicated value} - \text{True value}
\]
Accuracy and uncertainty

International Vocabulary of Metology (VIM)

Uncertainty: The possible range by which a reading may not reflect the true value defined by the SI units.

Accuracy: closeness of agreement between a measured quantity value and a true quantity value of a measurand

NOTE 1 The concept ‘measurement accuracy’ is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error or uncertainty.
Equations for realization and measurement

Wide spread definition of pressure $p$:

$$p = \frac{F}{A}$$

More suitable for vacuum (at $10^{-7}$ Pa and $A=10\, \text{cm}^2$, it is $F=10^{-9}\, \text{N}$, range of AF microscopes):

$$p = nkT$$

Access to optical methods (absorption, refractive index)

Primary standards under development!
Measurement of vacuum pressure

Piston gauge or pressure balance:

\[ p = \frac{F}{A} \]

This is a traceable instrument usable as primary standard.
Relative uncertainties of pressures in primary standards

- **Mercury Manometer**
  - Continuous expansion
  - Series expansion

- **Piston gauges**

Relative Uncertainties ($k=2$)

- $p_{atm}$

$p$ in Pa

Best accuracy available
Measurement principles and gauges

- Ionisation and Suppression of X-ray and ESD
- Ionisation
- Viscosity
- Heat conductivity
- Piezoelectric
- Piezoresistive
- Membrane
- Mechanical Resonance
- Capacitance
- Piston/Cyl U-tube

Pressure in Pa

Measurement uncertainty

Gas independent
Total pressure

$\frac{F}{A} = p$
Mechanical (direct) vacuum gauges

Pressure as force per area

Solid area

- Membrane vacuum gauge
  - Capacitance diaphragm gauge
  - Resonance Silicon gauge
- Piston gauge

Elastic element gauge types
- Bourdon gauge

Liquid area

- U-tube manometer
- McLeod
Measurement principles and gauges

Indirectly measuring vacuum gauges

- Ionisation rate
  - Emitting cathodes
    - Triode
    - Bayard-Alpert
      - Extractor
        - Extractor with energy analysis
    - Lafferty
    - Penning
  - Crossed electromagnetic fields
    - Magnetron, inverted magnetron
    - Pirani

- Heat conductivity
  - Thermocouple
- Momentum transfer
  - Spinning rotor gauge
Capacitance diaphragm gauge

Membrane (INVAR, Ceramic): as low as 25 µm.

Two improve zero stability:
2 capacitors plus thermostated housing

Sensitivity of deflection: 0.4 nm!

Measurement range with different types of fullscale:
1 mPa … 100 kPa
Measurement principles and gauges

Electrical block diagram of a type of capacitance diaphragm gauge (MKS)

Bridge amplitude: proportional to pressure
Phase: Direction
Thermal transpiration effect

\[ n_1 c_1 = n_2 c_2 \]

\[ \frac{n_2}{n_1} = \sqrt{\frac{T_1}{T_2}} \]

\[ \frac{p_2}{p_1} = \sqrt{\frac{T_2}{T_1}} \]
Thermal transpiration effect

\[ \sqrt{\frac{318}{296}} = 1.036 \]

\[ Kn := \frac{\lambda}{d} \]

Calibration curve by PTB for two gases
Heat conductivity through a gas: Pirani gauge
Pirani gauge

Wire: typically tungsten, $d \approx 10 \, \mu m$, 80 °C … 100 °C

Heat transport by gas

Radiation and conduction

Convection
Measurement principles and gauges

Electrical circuit for Pirani gauge

Constant temperature
Measure the power needed
Measurement principles and gauges

Mikro Pirani (MEMS manufactured)

Heated sheet 60°C

MEMS: higher Knudsen number, no convection
Correction factor for helium for 4 different Pirani gauges

Helium

MEMS Pirani

Correction factor $CF_{He/N2}$

VM1 (Pfeiffer)
VM2 (Thyracont)
VM3 (MKS)
VM4 (Leybold)
Mean

$p$ in mbar

$1E-03$ $1E-02$ $1E-01$ $1E+00$ $1E+01$ $1E+02$
Measurement principles and gauges

Experimental standard deviations of repeat calibrations for 4 different Pirani gauges at various pressures

<table>
<thead>
<tr>
<th>#</th>
<th>Gauge</th>
<th>$s$ in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0,05 mbar</td>
</tr>
<tr>
<td>1</td>
<td>Pfeiffer TPR 280</td>
<td>0,19 0,13</td>
</tr>
<tr>
<td>2</td>
<td>Thyracont VSP52</td>
<td>0,06 0,35</td>
</tr>
<tr>
<td>3</td>
<td>MKS 925C</td>
<td>0,10 0,12</td>
</tr>
<tr>
<td>4</td>
<td>Leybold TTR91</td>
<td>0,03 0,09</td>
</tr>
</tbody>
</table>

This partly excellent repeatability must not fake that this is an accurate instrument (gas dependence, non-linearity, temperature dependence, …)
Measurement principles and gauges

Thermocouple gauge

![Diagram of a thermocouple gauge with symbols for $R_0$, $U_H$, and Indication.]
Measurement principles

Viscosity: The spinning rotor gauge

\[ p = \sqrt{\frac{8kT}{\pi m}} \cdot \frac{\pi d \rho}{20\sigma} \left( \frac{d\omega}{dt} - RD(\omega) \right) \]
Measurement principles and gauges

**Spinning rotor gauge**

1. rotor
2. thimble
3. magnet
4. coils (vertical stabilization)
5. driving coils
6. pick-up coils
8. coils (horizontal stabilization)
Measurement principles and gauges

Spinning rotor gauge

Residual drag vs. frequency of rotor

![Graph showing residual drag vs. frequency of rotor](chart.png)
Measurement principles and gauges

**Sprinning rotor gauge**

No gas consumption (e.g. by ionization)

No dissociation (hot cathode)

Low outgassing rate

Predictable reading

High accuracy

High long-term stability
Measurement principles

![Diagram of ionisation process]
Measurement principles

Ionisation probability of different gas species for electrons between 10 eV and 10 keV
Crossed field gauges

The Penning gauge
2nd generation 1949
Crossed field gauges

Scheme of Penning gauge
Crossed field gauges

Directions of electrical field in Penning gauge
Crossed field gauges

Field strength, potential, electron densities (left) and electron trajectories (right) in typical Penning gauge
Crossed field gauges

\[ I^+ = K \cdot p^m \]

Calibration curve of typical Penning gauge
Crossed field gauges

Commercial
Penning gauge
Crossed field gauges

The Magnetron

![Diagram of the Magnetron with labels: Anode, Cathode, Auxiliary cathode, Ion current amplifier, and 6 kV voltage source.](image)
Crossed field gauges

The inverted Magnetron
Crossed field gauges

Trajectories in inverted magnetrons

\[ I^+ = K \cdot p^m \]
Crossed field gauges

Penning gauge:

\[ I^+ = K \cdot p^m \]

W.J. Lange, J.H. Singleton and D.P. Eriksen, JVST 3 (1966), 338
Crossed field gauges

Reducing the magnetic field strength outside of the inverted magnetron

Lethbridge, Asl, 1993

Drubetsky, Taylor 1996
Crossed field gauges

\[ I = Kp^m \]

<table>
<thead>
<tr>
<th></th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2 )</td>
<td>1.15</td>
</tr>
<tr>
<td>( \text{He} )</td>
<td>1.30</td>
</tr>
<tr>
<td>( \text{N}_2 )</td>
<td>1.17</td>
</tr>
<tr>
<td>( \text{Ar} )</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Up to 8!
Crossed field gauges

Stability of $K$ rather good

![Graph showing stability of $K$ over time. The graph indicates that the constant $K$ is relatively stable with minor fluctuations.](img1)
Crossed field gauges

Ignition of inverted magnetrons

- 7.5E-8 Pa
- 3.2E-7 Pa

He, H2, N2, Ar
## Comparison ionization gauge types

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Crossed fields (&quot;cold cathode&quot;)</th>
<th>Emitting (&quot;hot&quot;) cathode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping speed</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Accuracy, stability</td>
<td>moderate</td>
<td>good</td>
</tr>
<tr>
<td>Size, mechanical stability</td>
<td>good</td>
<td>moderate</td>
</tr>
<tr>
<td>Sensitivity towards outside magnetic field</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Outside magnetic field</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Susceptibility to contamination</td>
<td>high</td>
<td>moderate</td>
</tr>
<tr>
<td>Start-up problems</td>
<td>occur</td>
<td>none</td>
</tr>
<tr>
<td>X-ray limit</td>
<td>none</td>
<td>$10^{-10}$ Pa to $10^{-6}$ Pa</td>
</tr>
<tr>
<td>Electron stimulated desorption</td>
<td>negligible</td>
<td>Dependent on gas species</td>
</tr>
<tr>
<td>Price</td>
<td>low</td>
<td>high</td>
</tr>
</tbody>
</table>
How accurate are vacuum gauges?

Reasons for inaccuracies of vacuum gauges

<table>
<thead>
<tr>
<th>General</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainties due to calibration chain</td>
<td>Has the vacuum gauge been ever calibrated? Against what standard?</td>
</tr>
<tr>
<td>Uncertainties due to installation</td>
<td>Pressure at gauge position may not reflect the pressure where the experiment takes place.</td>
</tr>
<tr>
<td>Uncertainties due to operation</td>
<td>Outgassing of an ion gauge may falsify an outgassing rate measurement.</td>
</tr>
<tr>
<td>Inaccuracies caused by the physical principle of measurement</td>
<td>Thermal conductivity or ion gauge is used, but gas mixture is not (accurately) known.</td>
</tr>
<tr>
<td>Uncertainties caused by the device itself</td>
<td>See Table 2.</td>
</tr>
</tbody>
</table>
How accurate are vacuum gauges?

Reasons for inaccuracies

Gas species dependence:

Real total pressure only for force/area measuring gauges and > 100 Pa (1 mbar)! Below 100 Pa consider the thermal transpiration effect.

Spinning rotor gauges: Use a weighted mean mass, if approximate relative composition is known.

$$m_{\text{eff}} = \left( \sum_{i=1}^{n} a_i \sqrt{m_i} \right)^2 \quad \sum_{i=1}^{n} a_i = 1$$

Thermal conductivity gauges and ionisation gauges: Scaling factors are available, but do have high uncertainties.

$$CF_{\text{eff}} = \sum_{i=1}^{n} a_i CF_i$$
How accurate are vacuum gauges?

**Uncertainties due to the vacuum gauge itself**

<table>
<thead>
<tr>
<th>General</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset measurement</td>
<td>residual drag in SRG, zeroing of Pirani gauge, X-ray- and ESD-effect for ion gauges</td>
</tr>
<tr>
<td>Offset instability (drift)</td>
<td>Offset drifts with environmental temperature (Piroutte effect in SRG), bridge is no more balanced with time</td>
</tr>
<tr>
<td>Resolution</td>
<td>Number of digits shown</td>
</tr>
<tr>
<td>Influences of environment (mainly temperature)</td>
<td>Enclosure temperature of Pirani changes varies, thermal transpiration effect changes in CDG, amplifier changes amplification</td>
</tr>
<tr>
<td>Non-Linearity</td>
<td>Ion gauge (sensitivity changes with pressure)</td>
</tr>
<tr>
<td>Integration time (scatter of data), repeatability</td>
<td>Same signal at repeat measurements? Integration time in SRG, in picoammeter with ion gauge.</td>
</tr>
<tr>
<td>Reproducibility (stability of calibration constant)</td>
<td>Calibration constants change with time.</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>Mechanical gauges (up, down measurement)</td>
</tr>
<tr>
<td>Prior usage, cleanliness</td>
<td>Surfaces change, accommodation coefficients change, secondary yield changes</td>
</tr>
</tbody>
</table>
How accurate are vacuum gauges?

Table: Relative measurement uncertainty of commercially available vacuum gauges.

<table>
<thead>
<tr>
<th>Gauge type</th>
<th>Measurement range in Pa</th>
<th>Normal uncertainty</th>
<th>Optimum range in Pa</th>
<th>Lowest uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston gauges</td>
<td>10...10^5</td>
<td></td>
<td>10^2...10^5</td>
<td>10^-4...10^-5</td>
</tr>
<tr>
<td>Quartz-Bourdon-manometer</td>
<td>10^3...10^5</td>
<td></td>
<td>10^3...10^5</td>
<td>3x10^-4...2x10^-4</td>
</tr>
<tr>
<td>Resonance silicon gauges</td>
<td>10 ... 10^5</td>
<td>0.003...0.0005</td>
<td>100 ... 10^5</td>
<td>2x10^-4...5x10^-5</td>
</tr>
<tr>
<td>Mechanical vacuum gauge</td>
<td>10^2 ... 10^5</td>
<td>0.1 ... 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membrane vacuum gauge</td>
<td>10^2 ... 10^5</td>
<td>0.1 ... 0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezo</td>
<td>10^2 ... 10^5</td>
<td>1 ... 0.003</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple gauge</td>
<td>10^-1 ... 10^-2</td>
<td>1 ... 0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pirani gauges</td>
<td>10^-1 ... 10^-4</td>
<td>1 ... 0.1</td>
<td>1 ... 100</td>
<td>0.02 ... 0.01</td>
</tr>
<tr>
<td>Capacitance diaphragm gauges</td>
<td>10^-4 ... 10^-5</td>
<td>0.1 ... 0.003</td>
<td>10^-1 ... 10^-5</td>
<td>0.006 ... 0.001</td>
</tr>
<tr>
<td>Spinning rotor gauges</td>
<td>10^-5 ... 10^-1</td>
<td>0.1 ... 0.007</td>
<td>10^-3 ... 10^-1</td>
<td>0.006 ... 0.004</td>
</tr>
<tr>
<td>Penning gauges</td>
<td>10^-7 ... 1</td>
<td>0.5 ... 0.2</td>
<td>10^-5 ... 1</td>
<td>0.3 ... 0.1</td>
</tr>
<tr>
<td>Magnetron gauges</td>
<td>10^-8 ... 1</td>
<td>1 ... 0.1</td>
<td>10^-6 ... 1</td>
<td>0.1 ... 0.02</td>
</tr>
<tr>
<td>Ionisation gauges (Emission cathodes)</td>
<td>10^-10 ... 10^-2</td>
<td>1 ... 0.05</td>
<td>10^-8 ... 10^-2</td>
<td>0.2 ... 0.02</td>
</tr>
</tbody>
</table>
How accurate are vacuum gauges?

Lowest relative uncertainties for vacuum gauges and primary standards

Errors > 100 % are possible.
Todays commercial gauges

Either
Gauge head + controller

or

Active gauges or transmitter (all in one)

or

Digital gauges (digital output via interface)

Disclaimer: Just example, no recommendation of these products
We have discussed:

- Metrological system - primary standards-calibration chain
- Measurement principles and gauges
- Crossed field gauges
- Sources of uncertainties with values from 0.001% up to 100% or factor