Vacuum gauges for the fine and high vacuum

Karl Jousten, PTB, Berlin

1. Measurement of vacuum pressures and the calibration chain
2. Overview of measurement principles and gauge types
3. Direct gauges, indirectly measuring gauges
4. Accuracy of vacuum gauges
Measurement of vacuum pressure

The definition of pressure $p$:

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

Mass \hspace{1cm} Time

Length

It follows one of the measurement principles.

Fine and high vacuum gauges
Measurement of vacuum pressure

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

Gas pressure \( p \approx 0 \)

Balance as force meter

This is a traceable instrument usable as primary standard

Fine and high vacuum gauges
**Errors and uncertainties**

**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.

**Fine and high vacuum gauges**
Measurement of vacuum pressure

\[ p = \frac{F}{A} \]
Errors and uncertainties

The calibration chain

primary standard
secondary standard
working standard
ordinary vacuum gauge

Reliability increases
Uncertainty increases

Fine and high vacuum gauges
Traceability and primary standards

- Fully developed primary standards
- Partly developed standards

Fine and high vacuum gauges
Relative uncertainties of pressures in primary standards

Traceability and primary standards
Measurement principles and gauges

Fine and high vacuum gauges
Measurement principles and gauges

Fine and high vacuum gauges
Measurement principles and gauges

Indirectly measuring vacuum gauges

- Ionisation rate
  - Emitting cathodes
    - Triode
    - Bayard-Alpert Extractor
      - Extractor with energy analysis
  - Crossed electromagnetic fields
    - Lafferty
    - Penning
- Heat conductivity
  - Magnetron, inverted magnetron
  - Pirani
- Momentum transfer
  - Thermocouple
  - Spinning rotor gauge

Fine and high vacuum gauges
The mercury U-tube exists since Torricelli (1644). It is still the most accurate vacuum gauge > 100 Pa (1 mbar)!
The rotating piston gauge

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

Gap: 0.2µm

**Fine and high vacuum gauges**
Measurement principles and gauges

Mechanical gauges

3 Groups:
1. Ref.side $p_{atm}$ and contains meas.dev.
2. Ref.side $p=0$, meas.dev. on test side (1)
3. Ref.side $p=0$ and contain meas.dev.

Fine and high vacuum gauges
Measurement principles and gauges

Mechanical gauges: Bourdon gauges

Fine and high vacuum gauges
Measurement principles and gauges

Mechanical gauges: Bourdon gauges

Fine and high vacuum gauges
Measurement principles and gauges

Mechanical gauges: Bourdon gauges

Fine and high vacuum gauges
Piezoeffect used by membrane
Measurement principles and gauges

Piezoresistive effect

5 μm \[ p_{\text{mess}} \]

\[ p = 0 \]

1 mm

Material: Silicon (MEMS)

Fine and high vacuum gauges
Measurement principles and gauges

Capacitance diaphragm gauge

Sensitivity of deflection: 0.4 nm!
Membrane (INVAR, Ceramic): as low as 25 µm.
Two improve zero stability:
2 capacitors plus thermostated housing
Measurement principles and gauges

Electrical block diagram of capacitance diaphragm gauge

Fine and high vacuum gauges
Measurement principles and gauges

Thermal transpiration effect

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

\[ \frac{p_2}{p_1} = \sqrt{\frac{T_2}{T_1}} \]
Measurement principles and gauges

Thermal transpiration effect

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

Fine and high vacuum gauges
Measurement principles and gauges

Resonance Silicon Gauges
Designed by MEMS

Fine and high vacuum gauges
Happy Birthday
1906-2006
THE PIRANI GAUGE

Fine and high vacuum gauges
Heat conductivity through a gas
Measurement principles and gauges

Uncertainties due to the physical principle of measurement

Example: Pirani gauge

Fine and high vacuum gauges


**Measurement principles and gauges**

**Electrical circuit for Pirani gauge**

Constant temperature
Constant heating
voltage, current, or
power

**Fine and high vacuum gauges**
**Measurement principles and gauges**

**Mikro Pirani (MEMS manufactured) by MKS**

- Heated sheet 60°C
- MEMS: higher Knudsen number, no convection

**Fine and high vacuum gauges**
Correction factor for helium for 4 different Pirani gauges

Fine and high vacuum 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</td>
</tr>
<tr>
<td>2</td>
<td>Thyracont VSP52</td>
<td>0,06</td>
</tr>
<tr>
<td>3</td>
<td>MKS 925C</td>
<td>0,10</td>
</tr>
<tr>
<td>4</td>
<td>Leybold TTR91</td>
<td>0,03</td>
</tr>
</tbody>
</table>
Measurement principles and gauges

Thermocouple gauge

Fine and high vacuum gauges
Measurement principles

Viscosity

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

Sprinning rotor gauge

Fine and high vacuum gauges
Measurement principles and gauges

Sprinning rotor gauge

Residual drag vs. frequency of rotor

Fine and high vacuum 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

Ionisation

Fine and high vacuum gauges
Measurement principles

Ionization gauges for different vacuum ranges

Fine and high vacuum gauges
Measurement principles

Ionisation gauges for fine vacuum

Fine and high vacuum gauges
Previous investigations showed that TDLAS is applicable for vacuum measurement:

CO, mid-infrared (5 µm), resolution down to $10^{-5}$ Pa, high accuracy.

**Measurement principles**

\[
I(\lambda^{-1}) = I_0(\lambda^{-1}) e^{-S\Phi nL}
\]

\[
p = \frac{kT}{S(T)\Phi(\lambda^{-1} - \lambda_0^{-1})L} \ln \left( \frac{I_0(\lambda^{-1})}{I(\lambda^{-1})} \right)
\]

**Fine and high 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>

**Fine and high vacuum gauges**
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...10^3</td>
<td></td>
<td>10^2...10^5</td>
<td>10^-4...10^-3</td>
</tr>
<tr>
<td>Quartz-Bourdon-manometer</td>
<td>10^0...10^3</td>
<td></td>
<td>10^4...10^5</td>
<td>3x10^-4...2x10^-4</td>
</tr>
<tr>
<td>Resonance silicon gauges</td>
<td>10...10^3</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^-3...10^-2</td>
<td>0.1...0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Membrane vacuum gauge</td>
<td>10^-4...10^-3</td>
<td>0.1...0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piezo</td>
<td>10^-4...10^-3</td>
<td>1...0.01</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermocouple gauge</td>
<td>10^-4...10^-3</td>
<td>1...0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Piran gauges</td>
<td>10^-4...10^-1</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^-2</td>
<td>0.1...0.003</td>
<td>10^-4...10^-3</td>
<td>0.006...0.001</td>
</tr>
<tr>
<td>Spinning rotor gauges</td>
<td>10^-5...10^-5</td>
<td>0.1...0.007</td>
<td>10^-6...10^-4</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^-8...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^-9...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>

Fine and high vacuum gauges
How accurate are vacuum gauges?

Fine and high vacuum gauges

Lowest relative uncertainties for vacuum gauges and primary standards

Errors $> 100\%$ (error factor $> 1$) are possible.
Todays commercial gauges

Old classical gauges:
Gauge head + controller
Today: Active gauges or transmitter (all in one)
or
Digital gauges (digital output via interface)

Fine and high vacuum gauges
Today's commercial gauges

Transmitter gauge plus

Profibus Converter

Fine and high vacuum gauges
Today's commercial gauges

Commercial „active“ Line vacuum gauges

Fine and high vacuum gauges
Fine and high vacuum gauges

We have discussed:

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

Thanks for listening!