Pressure influence in capacitive humidity measurement

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Abstract

We investigated the behaviour of a capacitive humidity transducer (Vaisala HMP 234) upon pressure exposure of nitrogen and helium up to 100 bar, using a humidity generator based on saturation of the gases at temperatures below ambient. The increased saturated vapour pressure of water in the presence of nitrogen and helium (enhancement effect) was quantitatively taken into account. The sensor output was found to decrease with nitrogen pressure at fixed relative humidity (RH). Still, by taking the total pressure as an independent calibration parameter, the device can be used in nitrogen gas within error bounds of ±1% RH. For helium no deviation of the sensor output with pressure was observed, showing that the deviation strongly depends on gas properties. For similar pressure calibrations in other gases, accurate data of enhancement factors have to be available. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Capacitive humidity sensing; High pressure; Enhancement

1. Introduction

Capacitive humidity transducers have been widely used in humidity measurement and control, ever since the development of the first stable sensor of this type by Nelson and Amdur in 1965 [1]. An important class of humidity measurement in industrial engineering pertains to pressurised systems. Unfortunately, no published information seems to be available on the behaviour of capacitive humidity sensors at moderate pressures.

Subject of the present investigation is the Vaisala transducer HMP 234, incorporating the patented Humicap sensor. It consists of a polymer film, the capacitance of which changes as it absorbs water molecules, and a Pt100 temperature sensor. At atmospheric conditions, the humidity output is—after electronic signal processing—linear with the RH. The HMP 234 was designed for use at pressurised conditions; however, no quantitative information was available concerning the effect of pressure on the indicated RH value. Since earlier experiments had proven the existence of such intrinsic pressure effects, this work was initiated as a co-operation between EUT and Vaisala.

2. Experimental

Both before and after pressure exposure we checked the factory calibration in pure water vapour. This calibration proved to be reproducible within 0.4% RH (factory specification: ±1% RH), without any hysteresis effects.

The pressure runs were carried out using a specially built humidity generator, the construction of which is based on a detailed description by Wylie and Fisher [3]. A schematic drawing is shown in Fig. 1. Central part of the set-up are two saturators, placed in a thermostatic bath operated in a temperature range from 0°C up to ambient. After cooling down in a heat exchanger tube, nitrogen or helium bubbles through the first saturator, halfway filled with water and containing three layers of different size glass beads. The humidified gas is led to...
Experimental data for a typical pressure run in nitrogen

Table 1

<table>
<thead>
<tr>
<th>$T_s$ (°C)</th>
<th>$T_0$ (°C)</th>
<th>$p$ (bar)</th>
<th>$f_{w,x}$</th>
<th>$f_{w,0}$</th>
<th>$RH_0$ (%)</th>
<th>$RH_i$ (%)</th>
<th>$\Delta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.07</td>
<td>21.89</td>
<td>02.04</td>
<td>1.007</td>
<td>1.006</td>
<td>50.24</td>
<td>50.5</td>
<td>0.26</td>
</tr>
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<td>11.08</td>
<td>21.84</td>
<td>07.30</td>
<td>1.025</td>
<td>1.023</td>
<td>50.49</td>
<td>49.4</td>
<td>1.09</td>
</tr>
<tr>
<td>11.07</td>
<td>21.69</td>
<td>27.60</td>
<td>1.098</td>
<td>1.089</td>
<td>51.28</td>
<td>46.4</td>
<td>4.88</td>
</tr>
<tr>
<td>11.08</td>
<td>21.67</td>
<td>49.38</td>
<td>1.183</td>
<td>1.164</td>
<td>51.73</td>
<td>45.0</td>
<td>6.73</td>
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<tr>
<td>11.07</td>
<td>21.64</td>
<td>69.37</td>
<td>1.266</td>
<td>1.238</td>
<td>52.11</td>
<td>43.4</td>
<td>8.71</td>
</tr>
<tr>
<td>11.08</td>
<td>21.67</td>
<td>93.35</td>
<td>1.374</td>
<td>1.333</td>
<td>52.48</td>
<td>42.4</td>
<td>10.08</td>
</tr>
</tbody>
</table>

The value of $f_w$ is slightly larger at the saturator (lowest temperature), resulting in an overall increase of $RH_0$ with pressure. The effect is small (at most 2% RH at 100 bar nitrogen pressure), but for accurate calibration of the pressure deviation it must be taken into account.

For helium $f_w$ is fully determined by the Poynting correction. For nitrogen there is an additional contribution due to molecular interactions in the gas phase; the values of $f_w$ for this system were correlated—see Ref. [2]—from gravimetric measurements [3,4]. The results are summarised in the Appendix.
These functions can be cast in the form

$$RH_i = RH_0 - \Delta(p_i, RH_0) = RH_0 - \Delta_\infty \times \frac{b(RH_0)p}{1 + b(RH_0)p}$$

(3)

with an asymptotic deviation $\Delta_\infty = 20\%$. Experimental values of the parameter $b$ are shown in Table 2, where each $b$ value is assigned to the average $RH_0$ of the corresponding pressure run. The value at $RH_0 = 0$ is estimated from data measured at Vaisala.

The $b$ values can be correlated with a quadratic function, yielding

$$b(RH_0) = 1.47 \times 10^{-3} + 2.09 \times 10^{-4}RH_0 - 3.74 \times 10^{-7}RH_0^2$$

(4)

where $b$ is in units of (bar$^{-1}$) and $RH_0$ is in %RH. In view of the quality of the correlations, the width of the error seems to be somewhat overestimated.

The form of the above fit function is not arbitrarily chosen; it corresponds to an approximate expression for the Langmuir-like mode of gas sorption in glassy polymers, extensively discussed in a recent paper by Jordan and Koros [5]. For an ideal gas and a polymer with sorption sites larger than the gas molecules, their expression for the Langmuir sorption reads

$$c(p) = \frac{\exp\left(-\frac{G_r}{RT}\right)p}{1 + \exp\left(-\frac{G_r}{RT}\right)p}$$

(5)

where $c(p) = C(p)/N_0$ is the fraction of occupied sorption sites and $R$ is the universal gas constant. Our parameter $b$ corresponds to the exponential factor in Eq. (5). By comparison, an estimate can be obtained for the experimental value of the gas sorption energy $G_r$. Its order of magnitude (about 11 kJ mol$^{-1}$) corresponds to typical values for nitrogen mentioned in Ref. [5].

For practical computations, it is advantageous to correlate $D$ in terms of the observables $RH_i$ and $p$. Using Eqs. (3) and (4) an iterative scheme would be needed to solve for $RH_0$. At least for small deviations, the correlation can be inverted to give

$$RH_0 = RH_i + \Delta'_\infty \times \frac{b'(RH_i)p}{1 + b'(RH_i)p}$$

(6)

with $\Delta'_\infty = 24.3\%$ RH and

$$b'(RH_i) = 1.5 \times 10^{-3} + 1.84 \times 10^{-4}RH_i - 7.29 \times 10^{-7}RH_i^2.$$  

(7)

The residual error in $RH_0$ after correction is smaller than 1% RH for all data points.

### 4. Conclusions

Using a humidity generator based on a principle put forward in Ref. [3], we calibrated the Vaisala HMP 234 capacitive humidity transducer under nitrogen and helium exposure up to 100 bar.

Our results in nitrogen gas show a deviation of the sensor output with pressure, the magnitude of which depends on the RH of the system. This intrinsic deviation can be correlated in terms of pressure and (either real or indicated) RH. This correlation enables the user to compensate for the pressure effect, and measurements can still be carried out with an accuracy better than $\pm 1\%$ RH, including possible hysteresis effects. Helium does not significantly alter the output of the sensor.

The present data clearly establishes the need for calibrating capacitive humidity sensors with the pressure as an independent parameter. Moreover, the kind of gas is shown to be important. If pressure calibrations are to be carried out for other gases, it is essential that accurate enhancement factors are available, which is not always the case.

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1 Formally, this expression should contain $p/p_0$ instead of $p$, with $p_0 = 1$ atm. We merely follow here the original notation of Ref. [5].
Appendix

- Saturated vapour pressure of water:

\[ p_{w}^{sat}(T) = 610.8 \times \exp \left[ -5.1421 \ln \left( \frac{T}{273.15} \right) \right. \]
\[ \left. - 6828.77 \left( \frac{1}{T} - \frac{1}{273.15} \right) \right] \text{ (Pa)} \quad (8) \]

- Enhancement factor in helium (Poynting effect):

\[ \ln(f_{w,He}) = \frac{M_{w} \times [p - p_{w}^{sat}(T)]}{\rho_{l} R_{0} T} \quad (9) \]

with molar mass \( M_{w} = 0.018016 \text{ kg mol}^{-1} \), \( R_{0} = 8.3144 \text{ J mol}^{-1}\text{K}^{-1} \) and liquid density \( \rho_{l} = 999.84 + 0.086 (T - 273.15) - 0.0108 (T - 273.15)^{2} \) (kg m\(^{-3}\)). (10)

- Enhancement factor in nitrogen:

\[ \ln(f_{w,N_{2}}) = \beta(T) \times [p - p_{w}^{sat}(T)] \quad (11) \]

with

\[ \beta(T) = 4.420 \times 10^{-2} - 3.03 \times 10^{-4} T + 7.31 \times 10^{-7} T^{2} \]
\[ - 5.98 \times 10^{-10} T^{3} \quad \text{ (bar}^{-1}\text{)} \quad (12) \]

References


Biographies

Carlo C.M. Luijten graduated 1994 from Eindhoven University of Technology (Applied Physics). Since then he has been working as a Ph.D. student, investigating high pressure condensation phenomena.


Marinus E.H. van Dongen received his Ph.D. degree in 1978 on thermal diffusion effects in compressible boundary layers. He is head of the group Gasdynamics and Aero-acoustics of the Department of Applied Physics at Eindhoven University of Technology.