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Humidity calibration equipment for food processing applications

S. Tabandeh, V. Fernicola

INRIM Istituto Nazionale di Ricerca Metrologica, *Turin, Italy*

s.tabandeh@inrim.it
v.fernicola@inrim.it

Synopsis

- Background and motivations
- Industrial demand
- Design criteria and working principle
- Experimental set-up
- Microwave hygrometry
- System optimization
- Uncertainty estimation
- Comparison and validation
- Conclusions

Background and motivations

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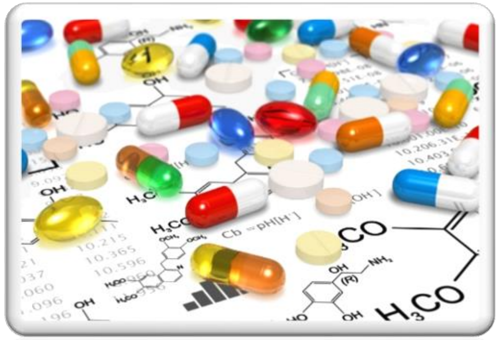
Food processing



Pharmaceutical

Paper production

- **Drying** is estimated to cost EU industry some 30 billion € per year in energy costs. Every 0.1 % improvement in drying efficiency due to better process control could save around 30 M€/year.
- **Monitoring humidity at temperatures above 100 °C is a key factor in controlling drying processes.**
- The **food industry** is the second largest manufacturing sector in the EU with a total manufacturing turnover of over 900 billion Euto.
- Drying and baking are key processes in the food industry and humidity control **is a key parameter in controlling product quality.**

Environment motivations

- The European Directive 2012/27/EU on **Energy Efficiency** and the identification of improving energy efficiency as one of the most effective way to reduce **greenhouse emissions** and other pollutants and thus to **mitigate climate change.**

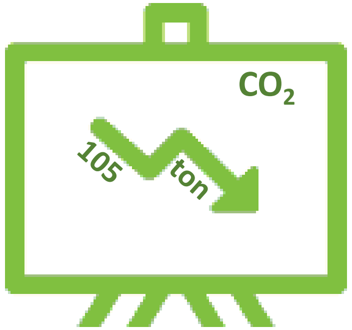
- The reliability of humidity measurements directly affects the drying efficiency, and significant savings are expected by the outcomes of this project.

- The targeted improvements in energy efficiency through better humidity monitoring in drying processes would result in

Significant reduction in the **emissions**

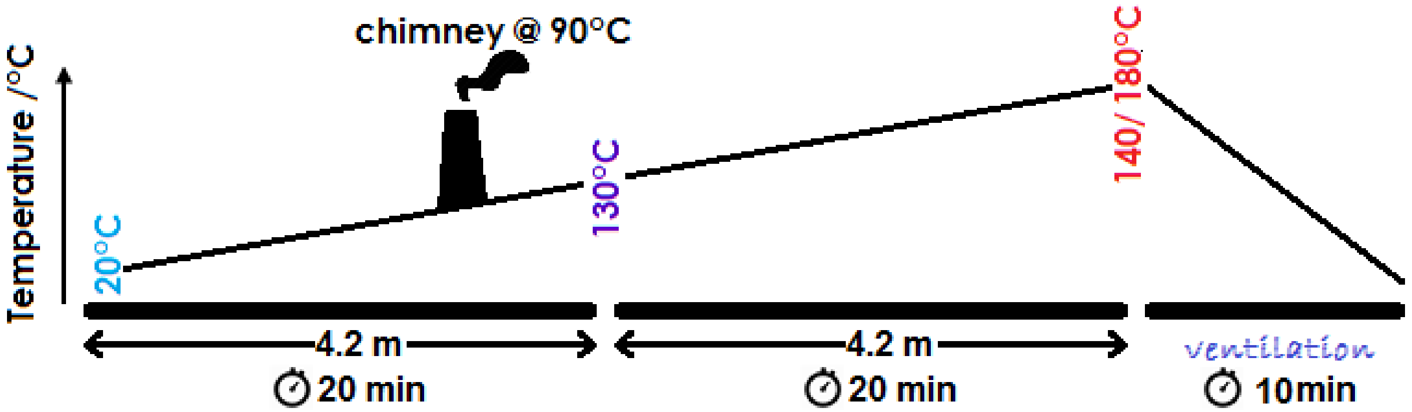
Improvements in **process control**

Reduce **waste** material



Industrial demand

Although humidity measurements are carried out in many processes **significantly above 100 °C** and humidity sensors are specified for such conditions, humidity **calibrations are usually not performed at temperatures above 100 °C** and the calibration equipments available in the industry cannot be operated in this range.



Example of tunnel oven-drying and roasting: 45-50 minutes at **140 °C** for a mild processing to ensure a good final quality in terms of residual water content (<1%), lipid oxidation and color. Alternatively, nuts are heated up to **180 °C** for 20 minutes in fast drying process.

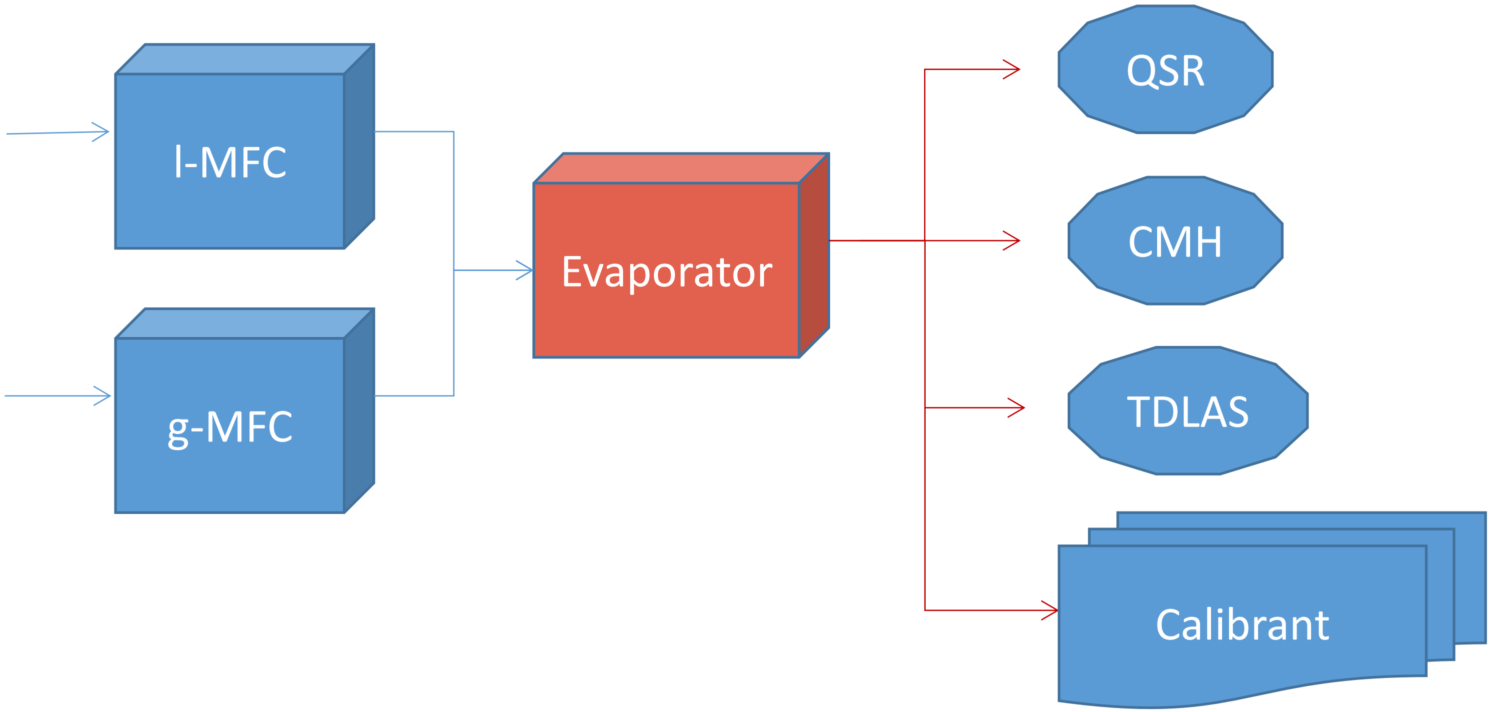
Design criteria

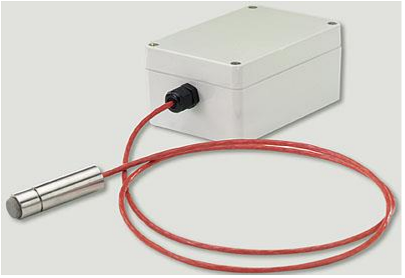
To support the **operating range of industrial dryers**, the generator :

- is based on controlled, SI-traceable, mixing of a water mass flow evaporated into a dry air mass flow
- air temperature up to 180 °C
- dew-point temperature up to 140 °C

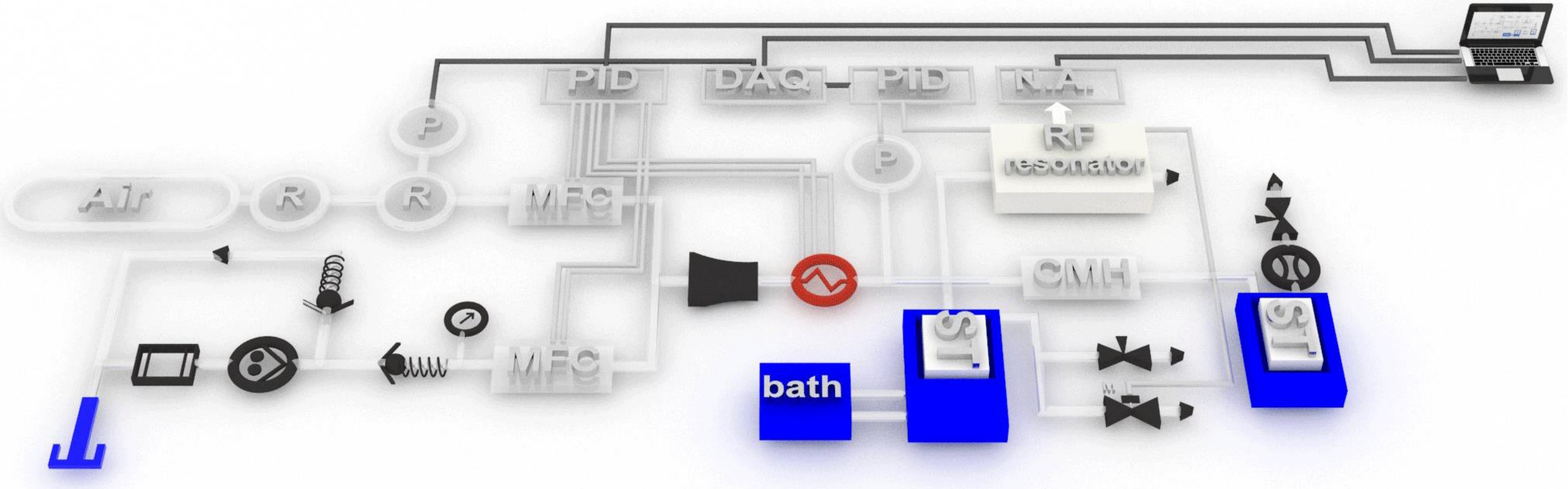
- pressure up to 6 bar(abs)
- The vapor/steam generator should operate over a wide range of absolute humidity, from 25 g/m^3 at atmospheric pressure to 1000 g/m^3 at 6 bar(abs).

Working principle

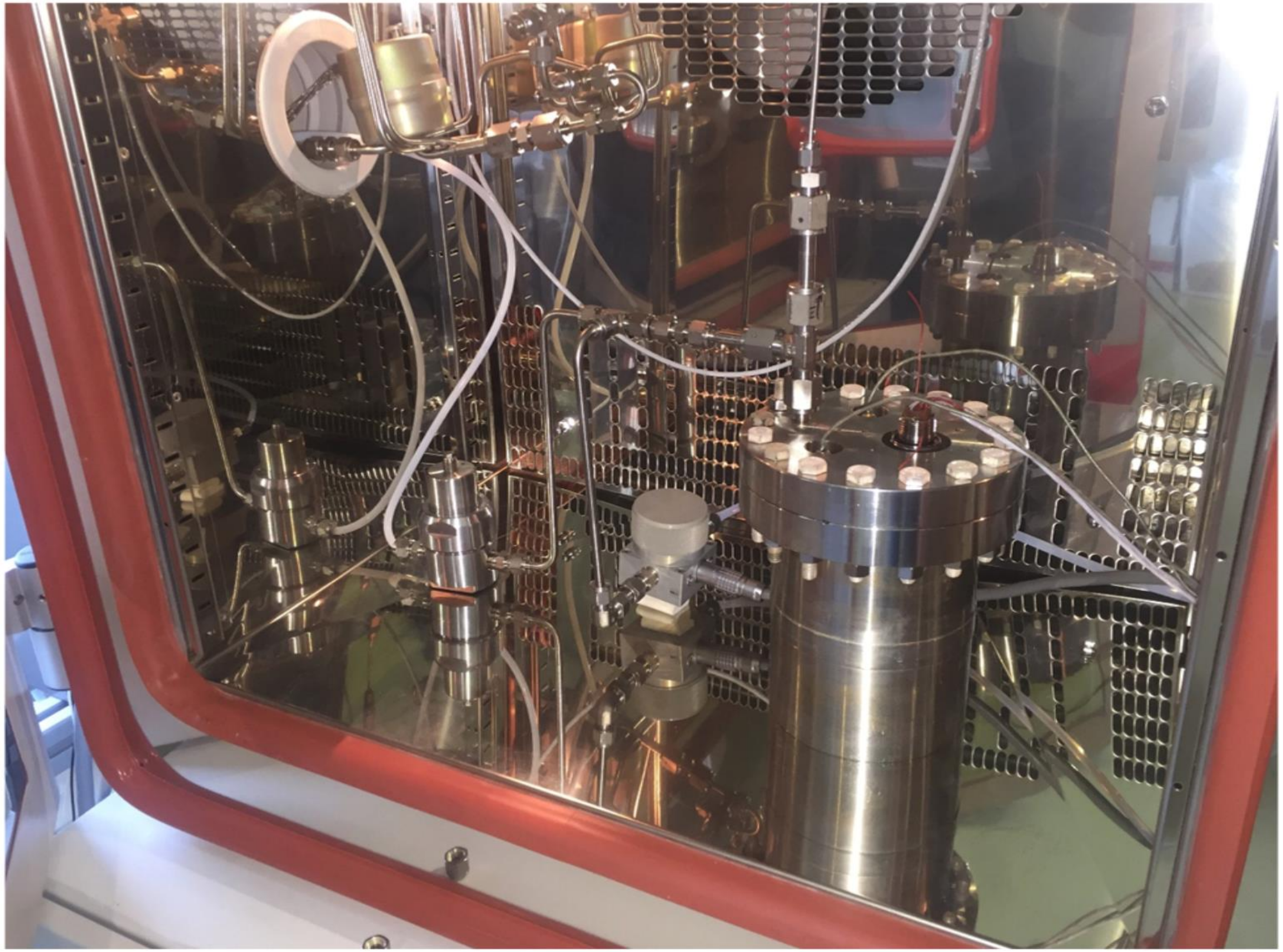




Experimental set up I

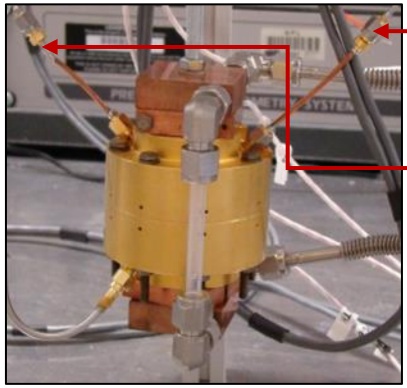


Experimental set up II



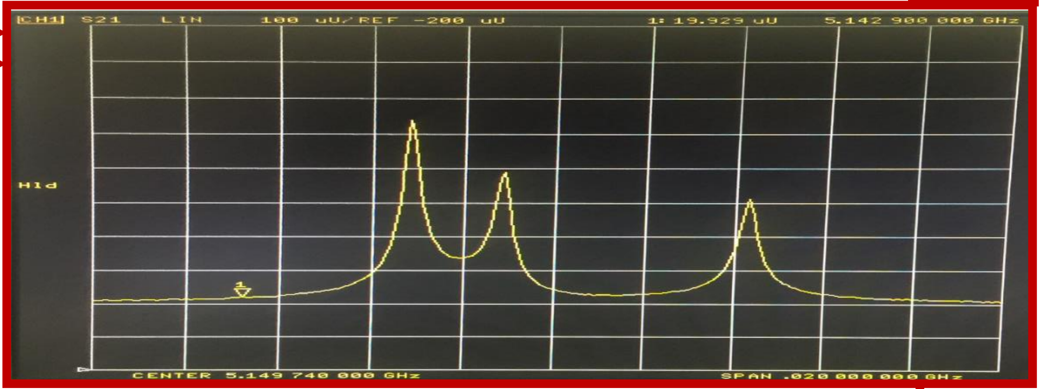
QSR hygrometry I

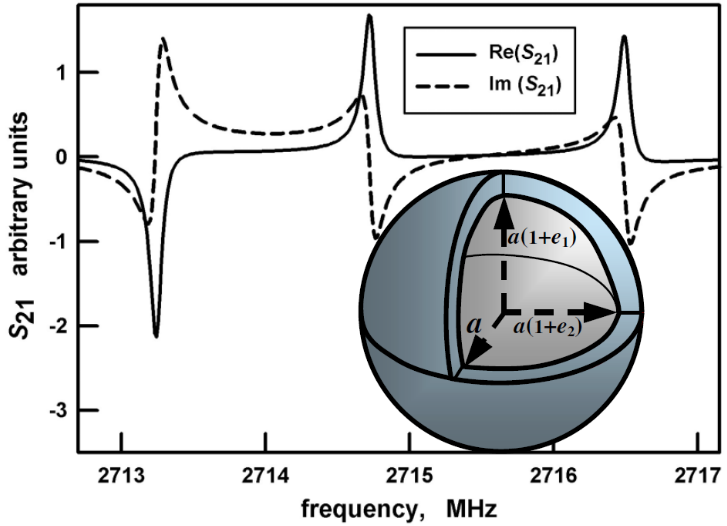
triaxial ellipsoidal cavity
axes: a, $a\,(1+\varepsilon_1)$, $a\,(1+\varepsilon_2)$
with a = 25.4 mm;
$\varepsilon_1 = 0.001$, $\varepsilon_2 = 0.003$



maraging steel, plated with a 10 μm thick layer of gold.

N.A.





$$\left[\frac{c_0}{\langle f+g\rangle_{l,n}^{\mathrm{TM,TE}}}\,\frac{z_{l,n}^{\mathrm{TM,TE}}}{2\pi a(p,T)}\right]^2 \rightarrow \text{Dielectric constant} \rightarrow \frac{2\rho\wp+1}{1-\rho\wp} \rightarrow p,\ T,\ X$$

QSR hygrometry II

$$\varepsilon_{\text{mix}} = \frac{2\rho_{\text{mix}}\wp_{\text{mix}} + 1}{1 - \rho_{\text{mix}}\wp_{\text{mix}}}$$

Thermodynamics

$$\rho_0 = p/(RT) \qquad \rho_{\text{mix}} = \rho_0 / (1 + B_{\text{mix}}\rho_0)$$

$$B_{\text{mix}} = x_1^2 B_1 + 2x_1x_2B_{12} + x_2^2 B_2$$

Polarizability

$$\wp_{\text{mix}} = \sum_i x_i \wp_i$$

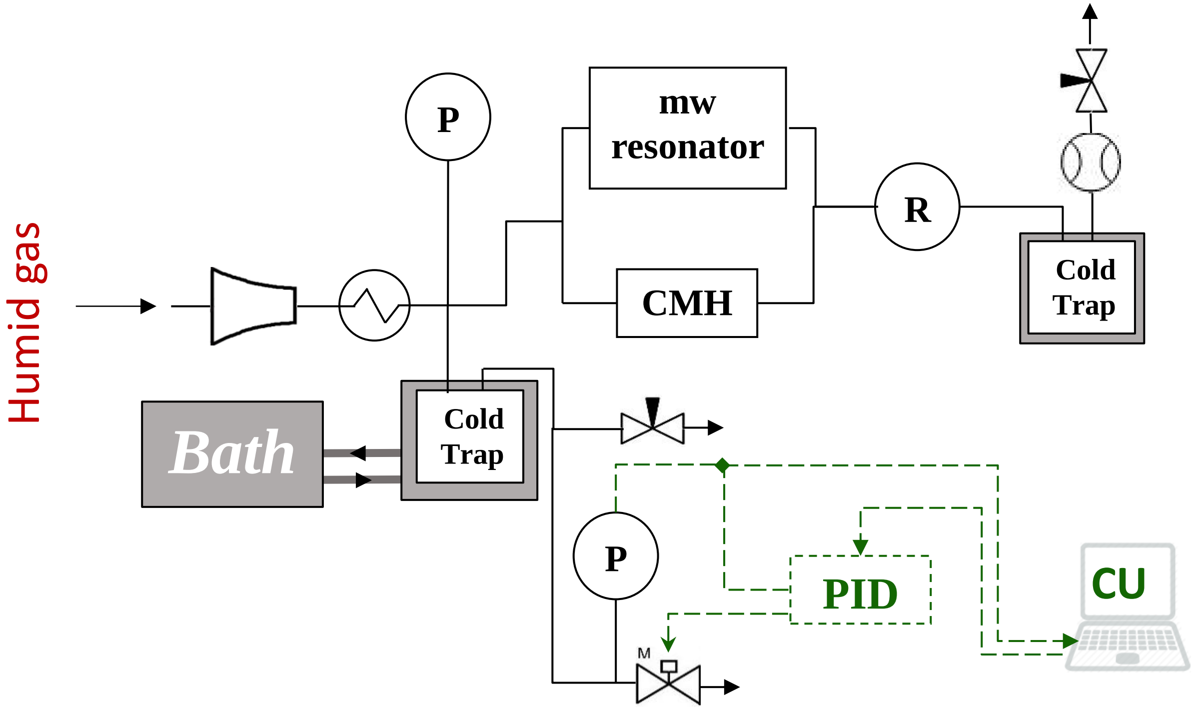
$$\wp_{\text{w}} = A_{\text{w}} + B_{\text{w}}/T$$

experimentally, to determine ε_{Mix} using a mw resonator resonance frequencies f (and half-widths g) are, for instance, measured at the same temperature T in vacuum and at pressure p

$$\boxed{\varepsilon_{\text{mix}} = \left(\frac{\langle f+g\rangle_0}{\langle f+g\rangle_p}\right)^2 = \left(\frac{\langle f+g\rangle_0}{\langle f+g\rangle_p (1 - k_T p/3)}\right)^2}$$

and the isothermal compressibility of the cavity k_T can be determined from measurements in He as a function of pressure

Pressure control



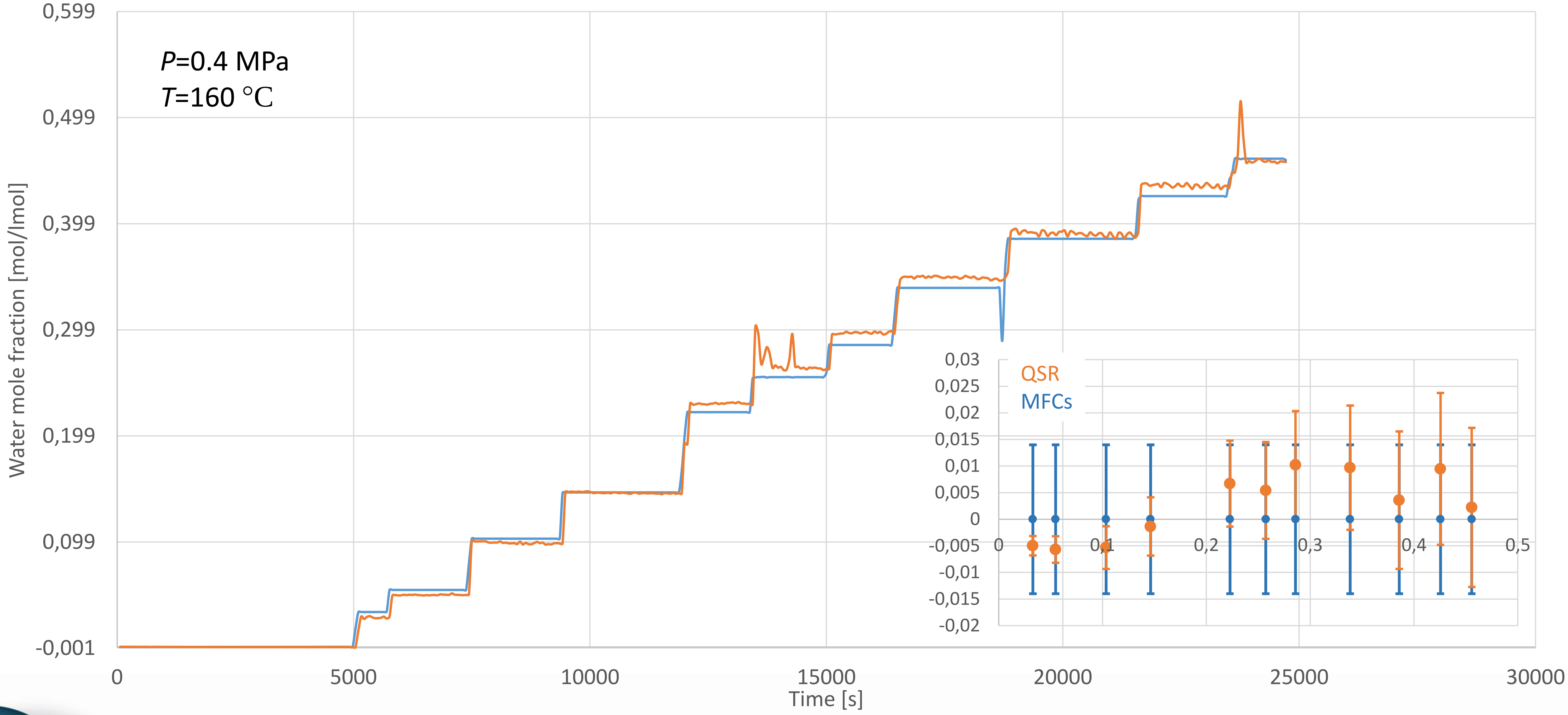
Initial design

Sensor and actuator were far from each other
Stability of pressure is about **4 per thousand**
P is source of 70% of the uncertainty
Forming of droplets inside the cold trap is a source of instability

revised design

Sensor and actuator are side by side -> no delay
Stability of pressure is about **1 per thousand**
Cascade control of pressure by using two different control units.
Significant reduction of the uncertainty

Results I – response time



Uncertainty evaluation

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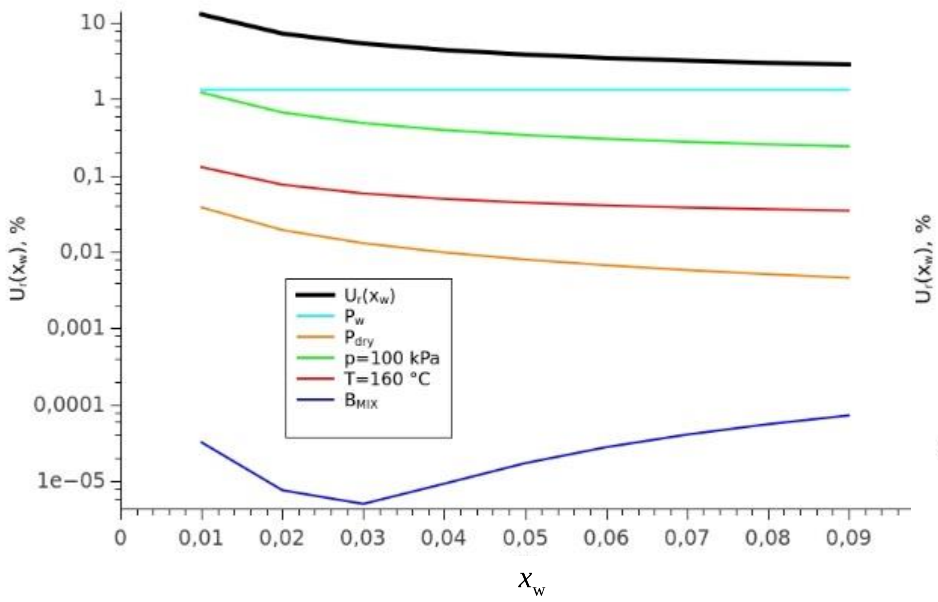
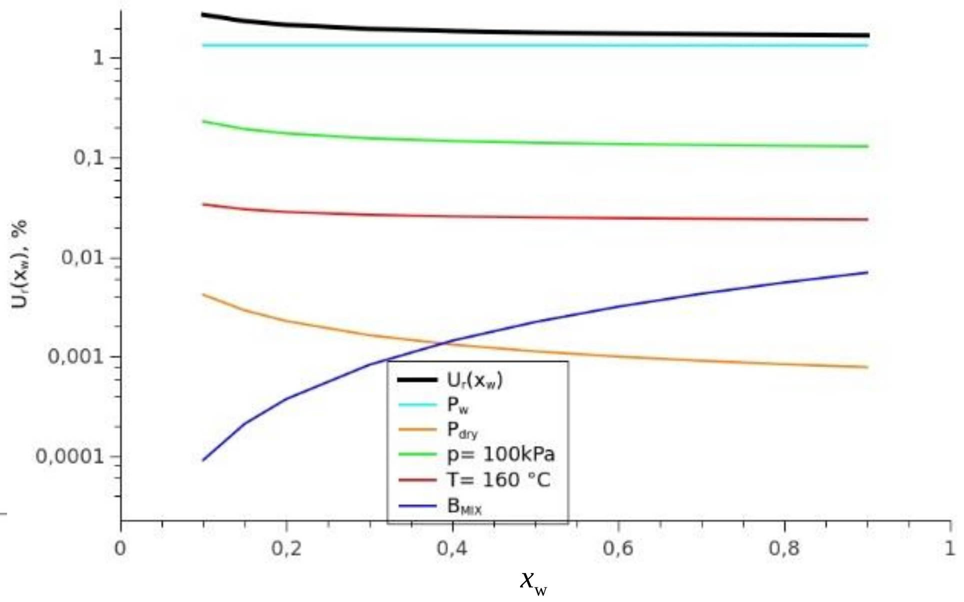


$0.01 < x_w < 0.1$

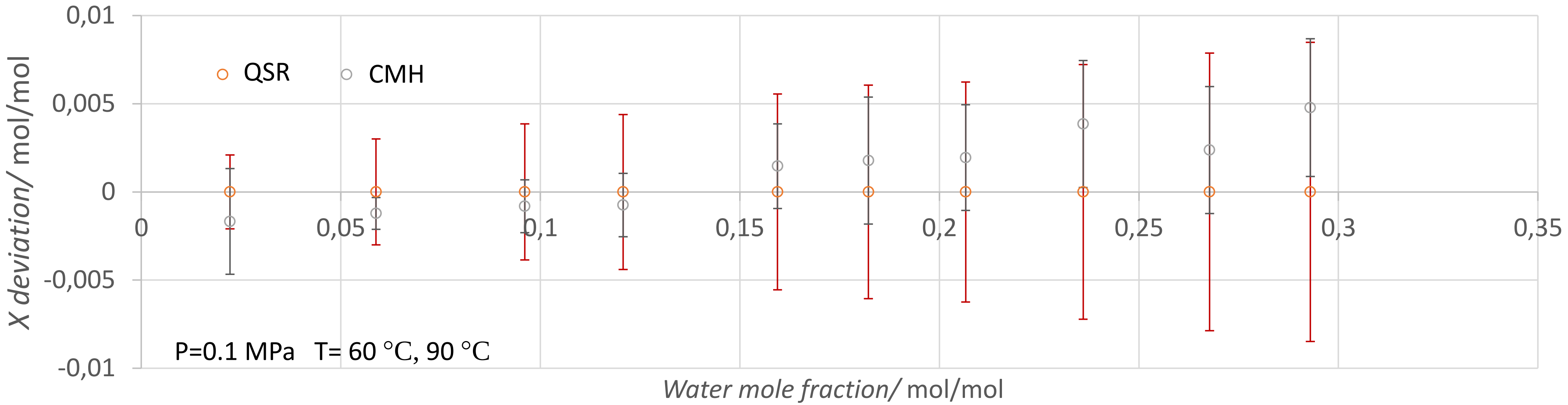


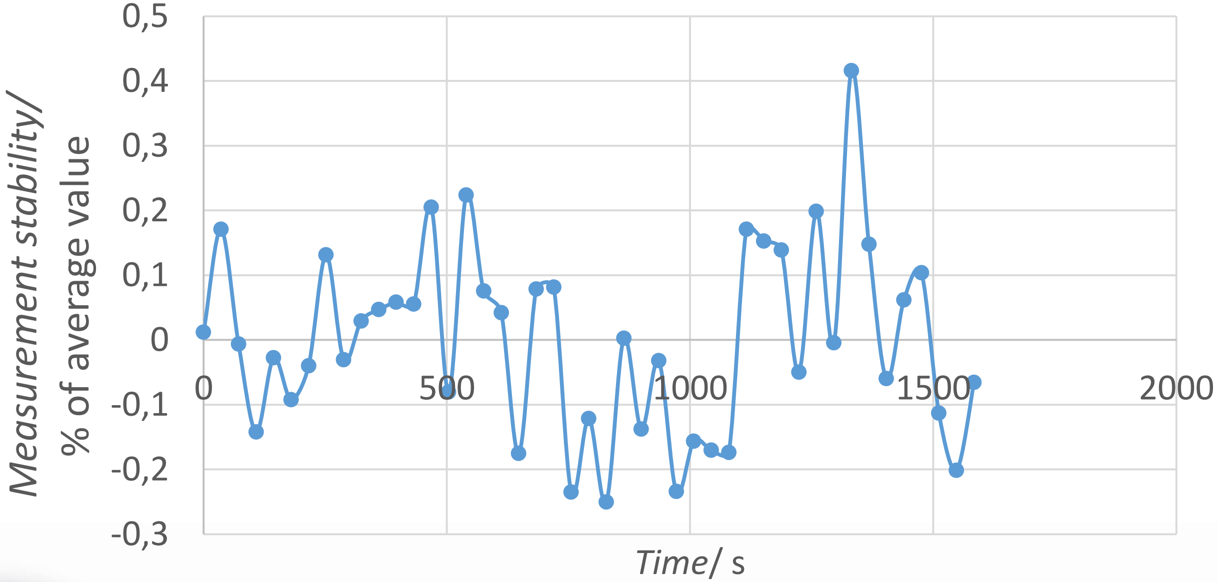
$0.1 < x_w < 1$

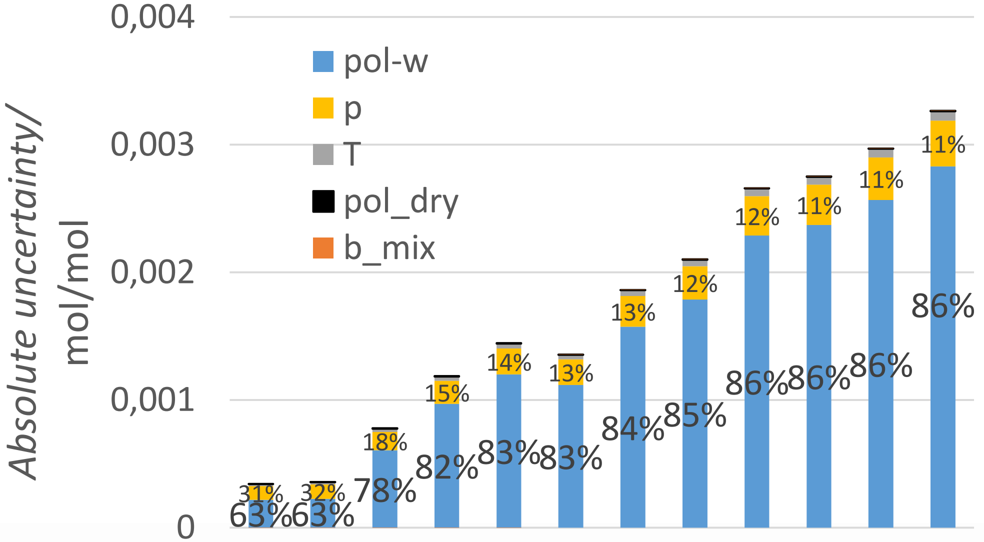
the uncertainty in the independent knowledge of the polarizability of water **(Debye constants)** dominates

	Reference date	*A*	*B*
Groves and Sugden	1935	4.3 ±1.2	(2.074±0.054)×10⁴
Stranathan	1935	4.03 ±0.39	(2.071±0.014)×10⁴
Hurdes and Smyth	1942	3.4 ±1.2	(2.087±0.053)×10⁴
Essen and Froome	1951	3.585±0.011	(2.061±0.002)×10⁴
Birnbaum and Chatterjee	1952	3.84 ±0.72	(2.092±0.024)×10⁴
Essen	1953	4.157±0.012	(2.041±0.002)×10⁴
Boudouris	1958	3.99 ±0.60	(2.081±0.020)×10⁴

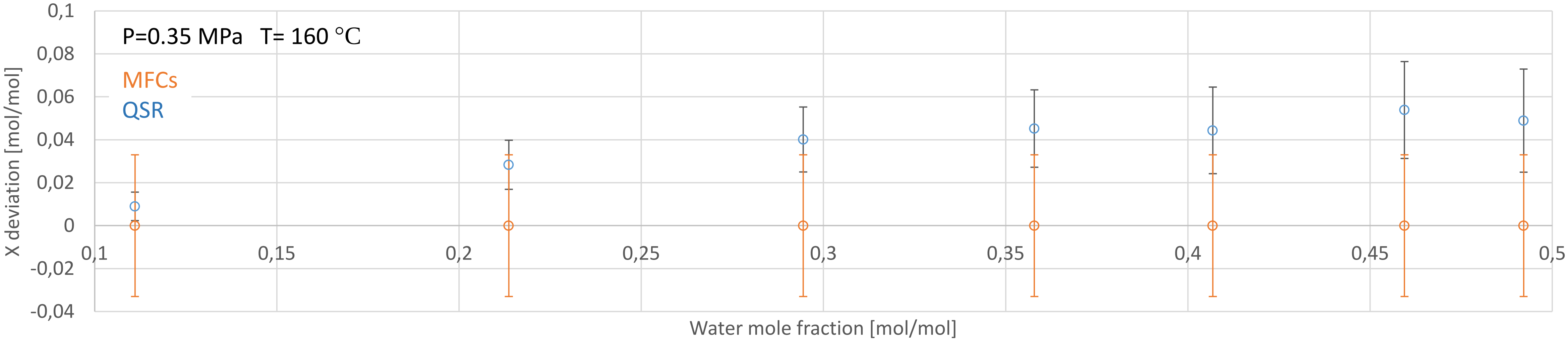
QSR vs. CMH calculation

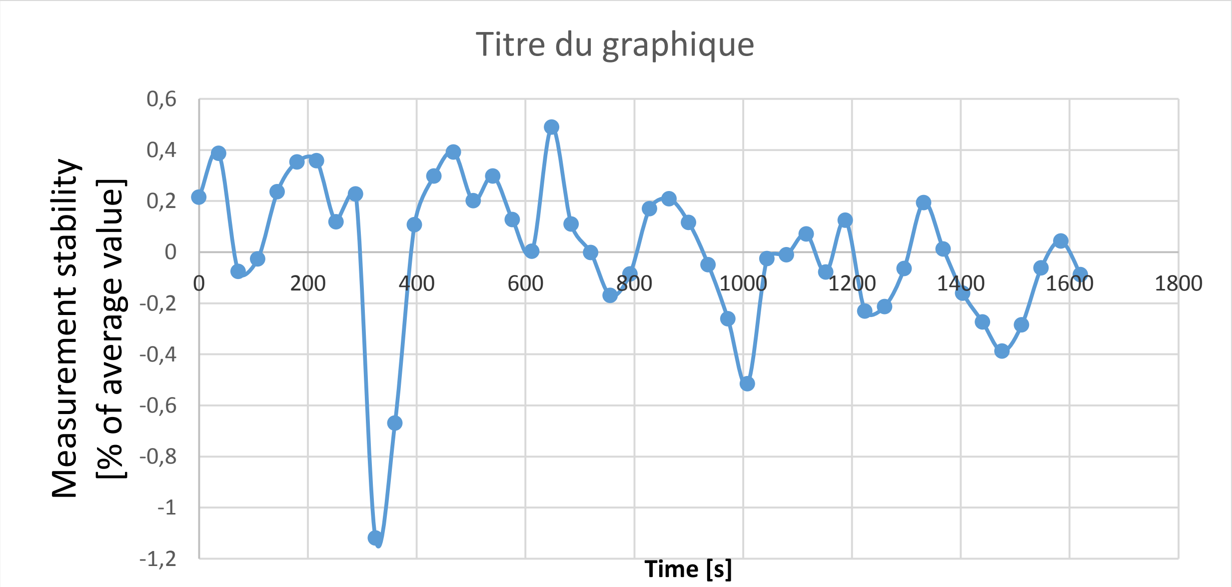


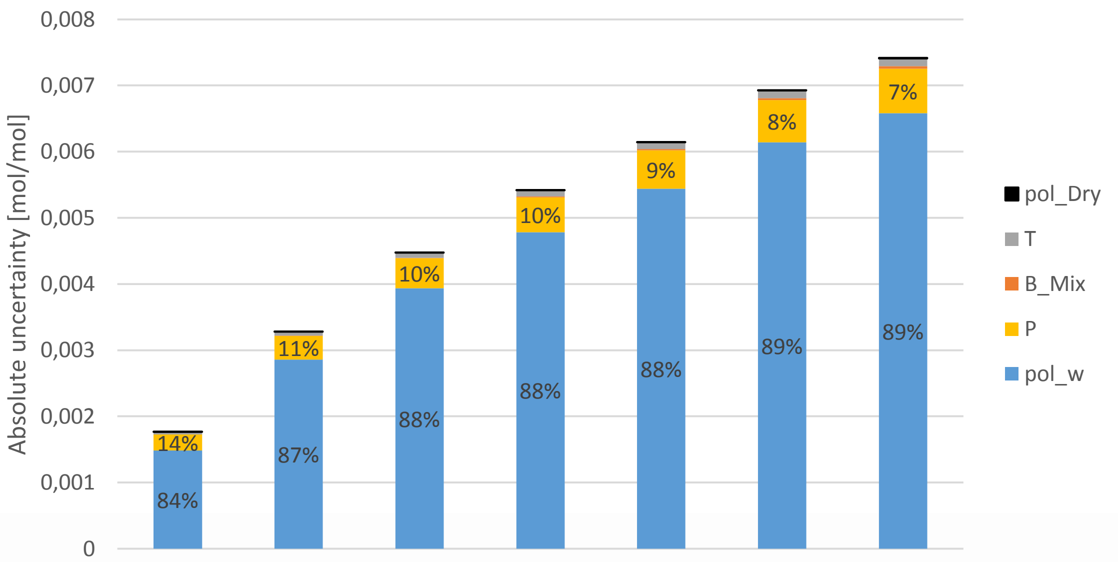




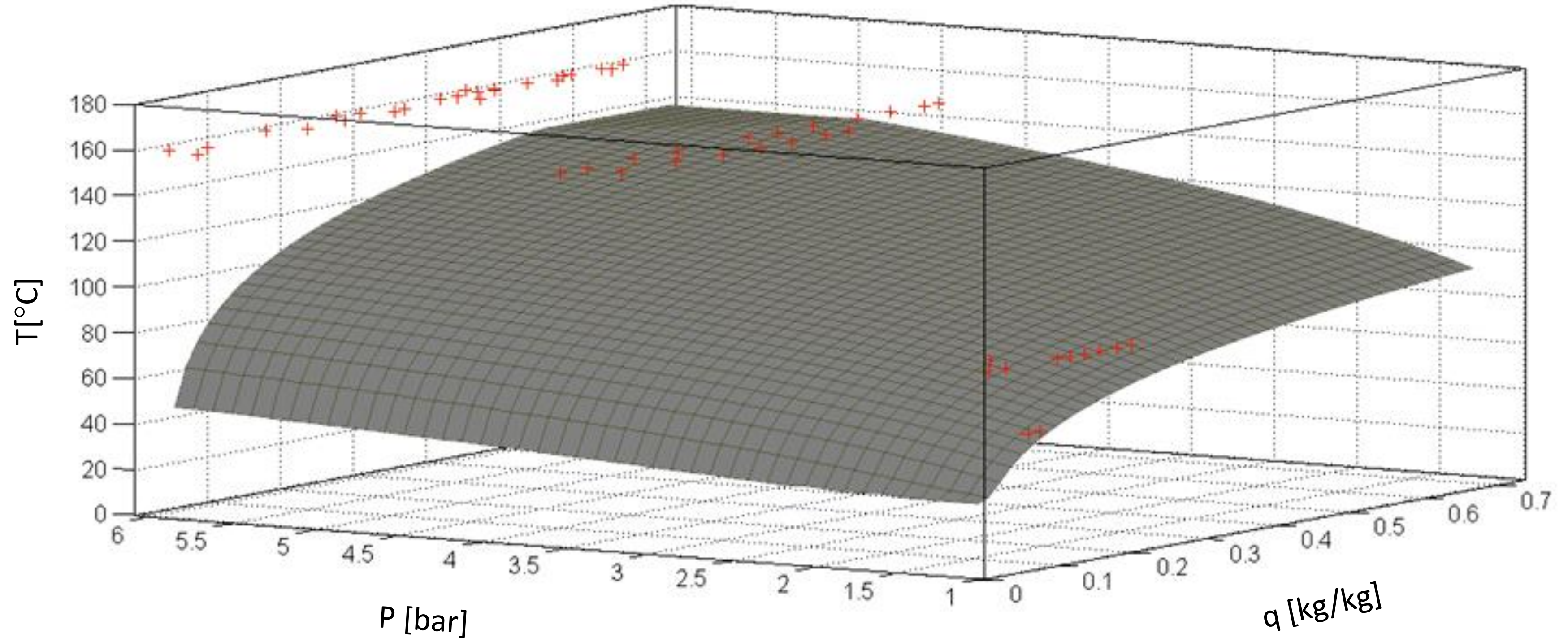
QSR vs. Mass flow calculation







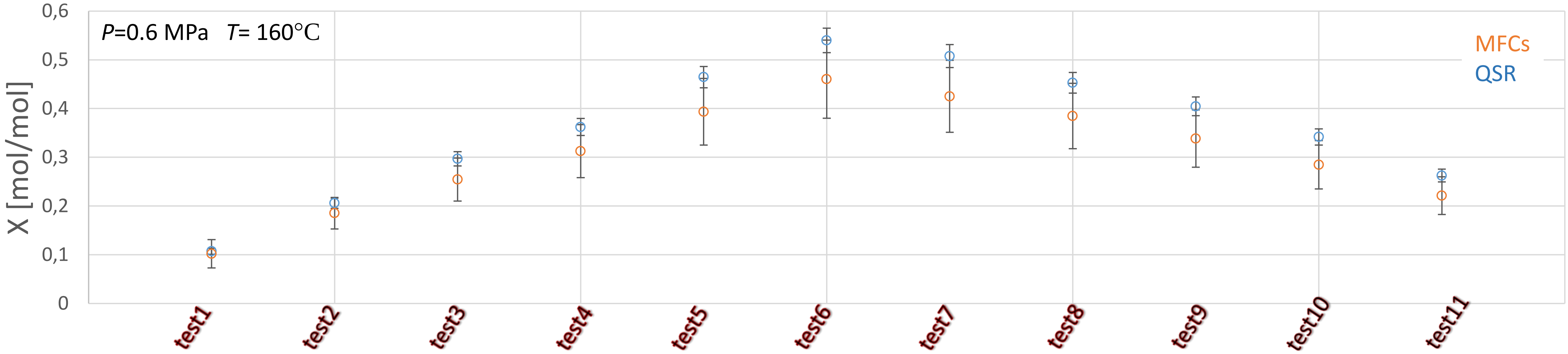
Operating range

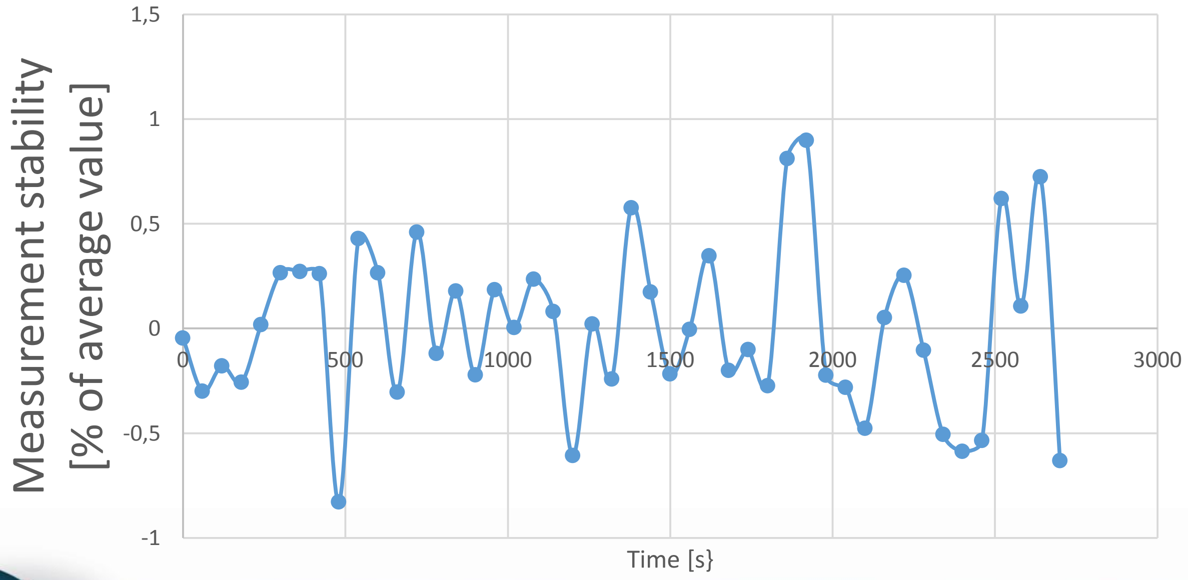


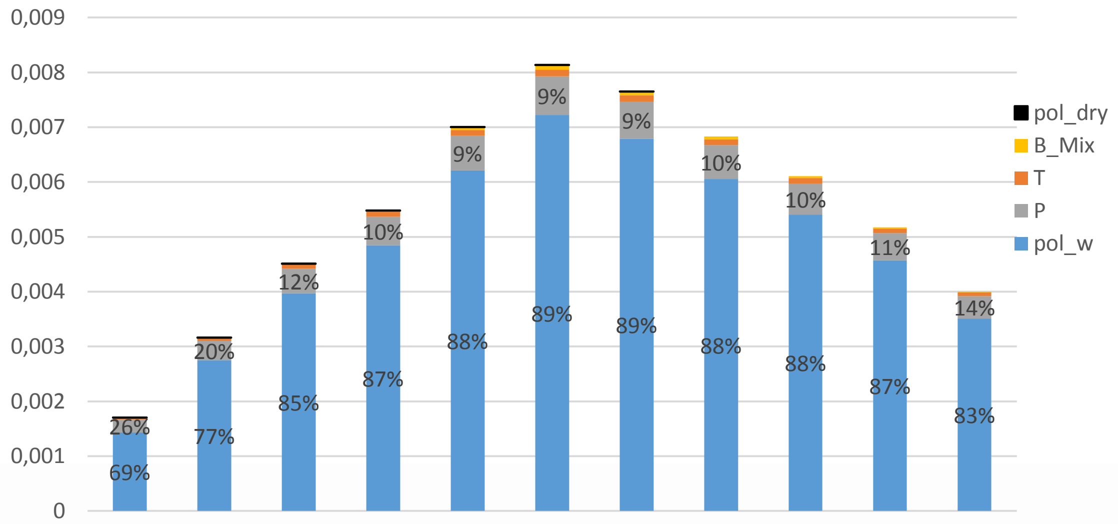
- The operating range is defined <u>above</u> the plot surface.
- Generator has been validated against traceable CMH and QSR hygrometers at 55 different points.
- Tests has been carried out with nitrogen and air.

	Min	Max
Temperature [°C]	60	161
Pressure [bar]	1.02	6.08
Specific Humidity [kg/kg]	0.07	0.646
Dew Point Temperature [°C]	38	142.44
Flow [l/m]	1	40

Validation over the operating orange







Conclusions

- A mass fraction humidity generator has been developed at INRIM to provide traceable calibrations of humidity sensors at temperatures above 100 °C.
- The principle of operation is based on mixing and evaporating a known mass of water into a known mass of dry air.
- The generator operates up to 180 °C, with dew point temperatures up to 140 °C and pressures up to 6 bar(abs).
- A gold-plated quasi-spherical microwave resonator (QRS) has been integrated with a mass fraction humidity generator developed at INRIM.
- The humidity generator has been thoroughly validated at 55 different operation conditions against CMH and QSR.

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