Flue gas sensor testing and evaluation

Gas sensors for automated stove control systems

Project ERA-NET Bioenergy “Wood Stoves 2020”

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Introduction
Background & selection criteria

- **Automated control systems**
  - **Provide a possibility to improve stove combustion by handling challenge of constantly changing boundary conditions due to short batch cycle and unknown user behavior**
  - **Require correct determination of current combustion conditions**
- **Correct determination of combustion conditions requires sensors for temperature, pressure and/or gas components**
- **Selection criteria for gas sensors**
  - **Costs**
  - **Life span**
  - **Development status & availability**
  - **Temperature resistance, Selectivity & Stability**
  - **Processing and peripherals**

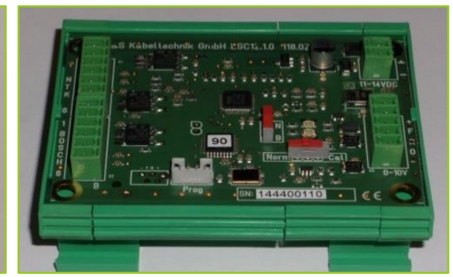
Market research & Literature review Summary

- Limited (but growing) number of available sensors
  - O_2 sensors usually based on solid electrolyte principle (e.g. from NGK Spark Plug, Bosch, LogiDataTech, Scantronic, Heraeus)
  - CO & combination sensors (O_2 & CO) based on solid electrolyte or semiconductor principle (e.g. LAMTEC, FIGARO, Scantronic, SenSiC)
- Long development & implementation time span for new sensors
- Oxygen sensors
  - In general god accuracy, little cross sensitivity, good long term stability
- Sensors for CO & unburned gases
  - Combined signal for all unburned components (still rather poor selectivity for single components)
  - Noticeable cross sensitivities (oxygen, moisture, temperature)
  - Improvable accuracy & long term stability, but reliable trends & ranges

Long-term sensor evaluation – RISE
Sensor selection

- **Switching type Lambda probe OZA685-WW1 (NGK)**
  - **3 units, operated with Lambda Transmitter (LT-OZA)**
- **Broadband type Lambda probe ZFAS-U2 (NGK)**
  - **3 units, operated with Lambda system control (LSC)**
- **SenSiC CO/O_2 sensor**
  - **3 units in total, operated with SenSic electronics**

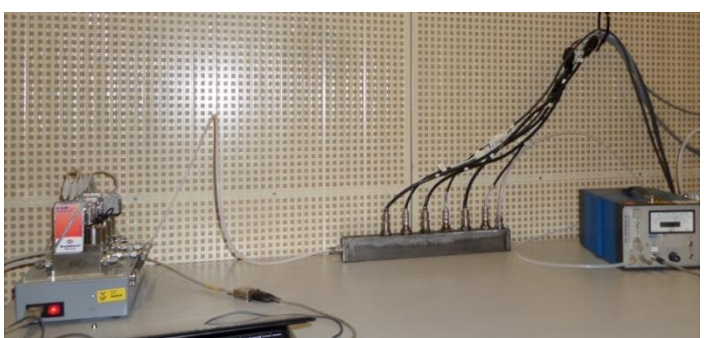


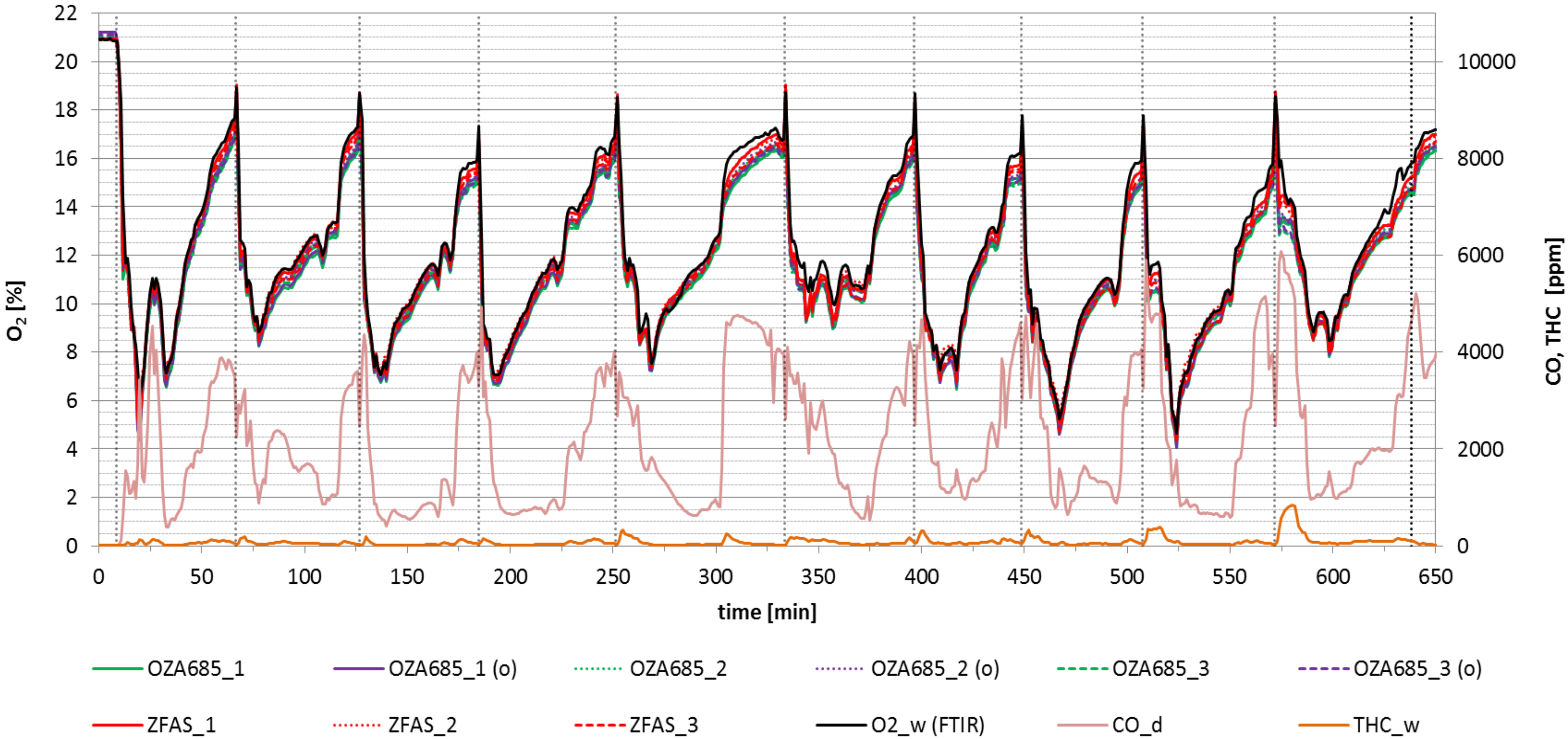
Long-term sensor evaluation – RISE Procedure

- Initial check of lambda probes in test gas rig
- 1st evaluation period
  - Ca. 300h stove operation, 33 test days, 259 batches, bark free birch wood
- Intermediate control in test gas rig
- 2nd evaluation period
  - Ca. 250h stove operation, 26 test days, 211 batches, birch wood with bark
- Final control check in test gas rig






Long-term sensor evaluation – RISE
Lambda probes at stove operation



Notes:

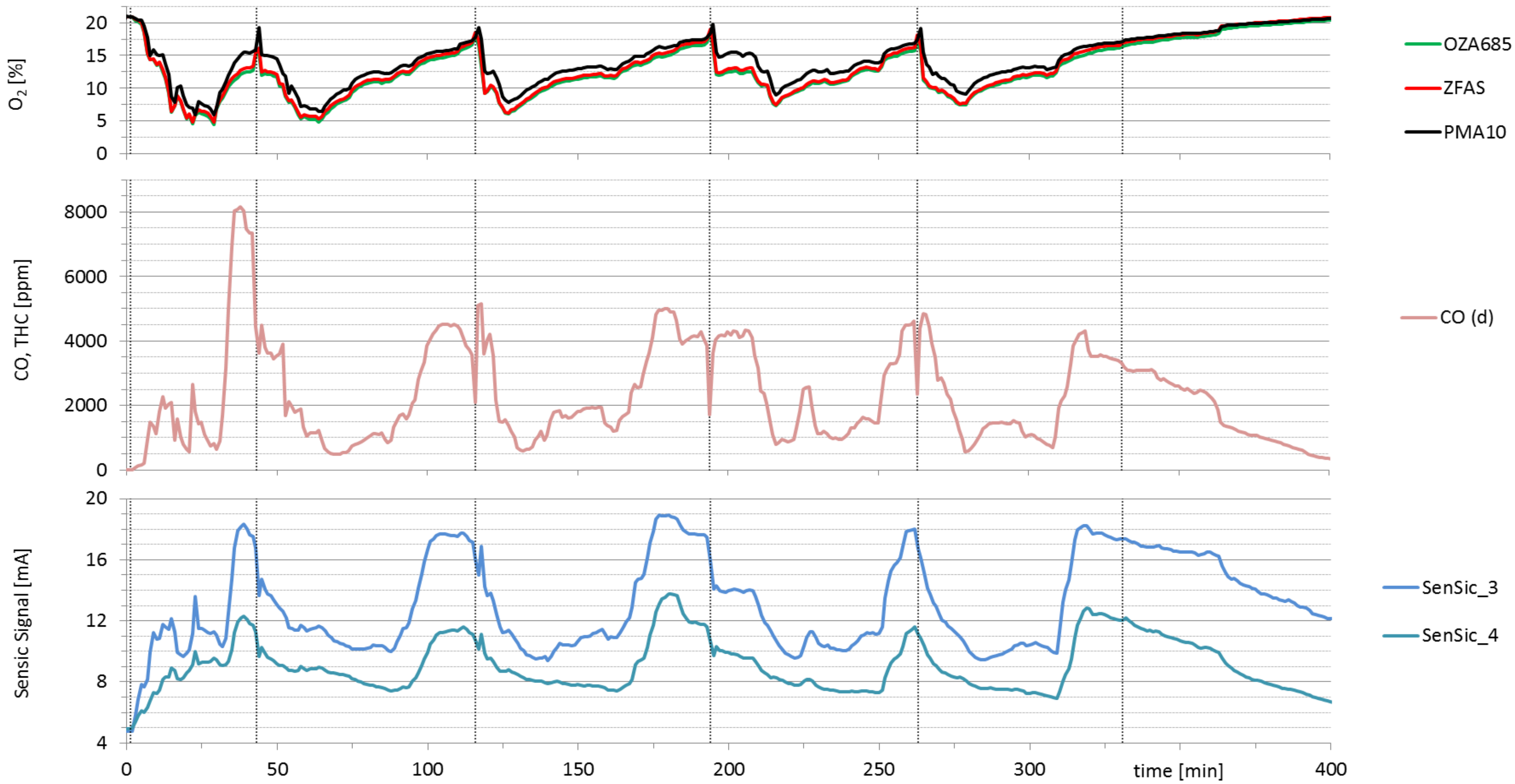
- Chart from day 50 (2nd evaluation period)
- Analyzers used: PMA10, X-Stream XEGC, FTIR
- O2_w (FTIR) calculated by using O_2 (d) from oxygen analyzer and H_2O values from FTIR
- Consider also for comparison: different sampling locations, cross sensitivities for probes & analyzer, different gas condition (dried gas for standard analyzer)

Long-term sensor evaluation – RISE
Lambda probes at stove operation

Batch			Ignition	1	2	3	4	5	6	7	8	9
Gas Analyzers	CO_2	%	7,1	6,7	7,9	7,6	6,4	6,6	7,8	8,8	8,5	6,9
	O_2	%	13,3	13,7	12,4	12,8	13,9	13,7	12,6	11,4	11,8	13,5
	CO at 13% O_2	mg/m^3_N	2673	2698	1800	2144	3594	3095	2706	2202	2501	3150
	OGC at 13% O_2	mg/m^3_N	106	110	64	88	124	144	140	106	143	322
	$O_{2,w}$ (FTIR)	%	12,3	12,6	11,4	11,9	13,1	12,7	11,6	10,4	10,8	12,4
	$O_{2,w}$ (EN13240)	%	12,3	12,7	11,4	11,8	13,0	12,7	11,6	10,5	10,8	12,5
O_2 OZA685	OZA685_1	%	11,6	11,9	10,8	11,2	12,4	11,9	10,9	9,7	10,0	11,6
	OZA685_1 (o)	%	11,7	12,0	10,9	11,3	12,5	12,0	11,0	9,8	10,1	11,7
	OZA685_2	%	11,6	12,2	11,1	11,5	12,6	12,1	11,2	10,0	10,4	11,8
	OZA685_2 (o)	%	11,7	12,3	11,2	11,6	12,7	12,2	11,3	10,1	10,5	11,9
	OZA685_3	%	11,6	12,0	10,9	11,3	12,5	11,9	11,0	9,9	10,2	11,6
	OZA685_3 (o)	%	11,7	12,2	11,0	11,4	12,6	12,0	11,1	9,9	10,3	11,7
O_2 ZFAS	ZFAS_1	%	12,1	12,5	11,3	11,7	12,9	12,3	11,4	10,2	10,5	12,0
	ZFAS_2	%	11,9	12,5	11,3	11,8	12,9	12,3	11,5	10,3	10,6	12,0
	ZFAS_3	%	11,9	12,3	11,0	11,4	12,6	12,1	11,1	9,9	10,2	11,7

Notes:
- Table with results from test on day 50 (2^{nd} evaluation period)
- Time average values for single batches
- $O_{2,w}$ (EN13240) calculated according to EN13240 using wood moisture & hydrogen content
- $O_{2,w}$ (FTIR) calculated by using O_2(d) from oxygen analyzer H_2O values from FTIR

Long-term sensor evaluation – RISE
SenSic sensor at stove operation



Notes:
- Chart from day 59 (last day of evaluation)
- Analyzers used: PMA10, X-Stream XEGC
- Sensor SenSic_3 operated at 250°C; SenSic_4 at 200°C
- Consider also for comparison: different sampling locations, cross sensitivities for probes & analyzer, different gas condition (dried gas for standard analyzer)

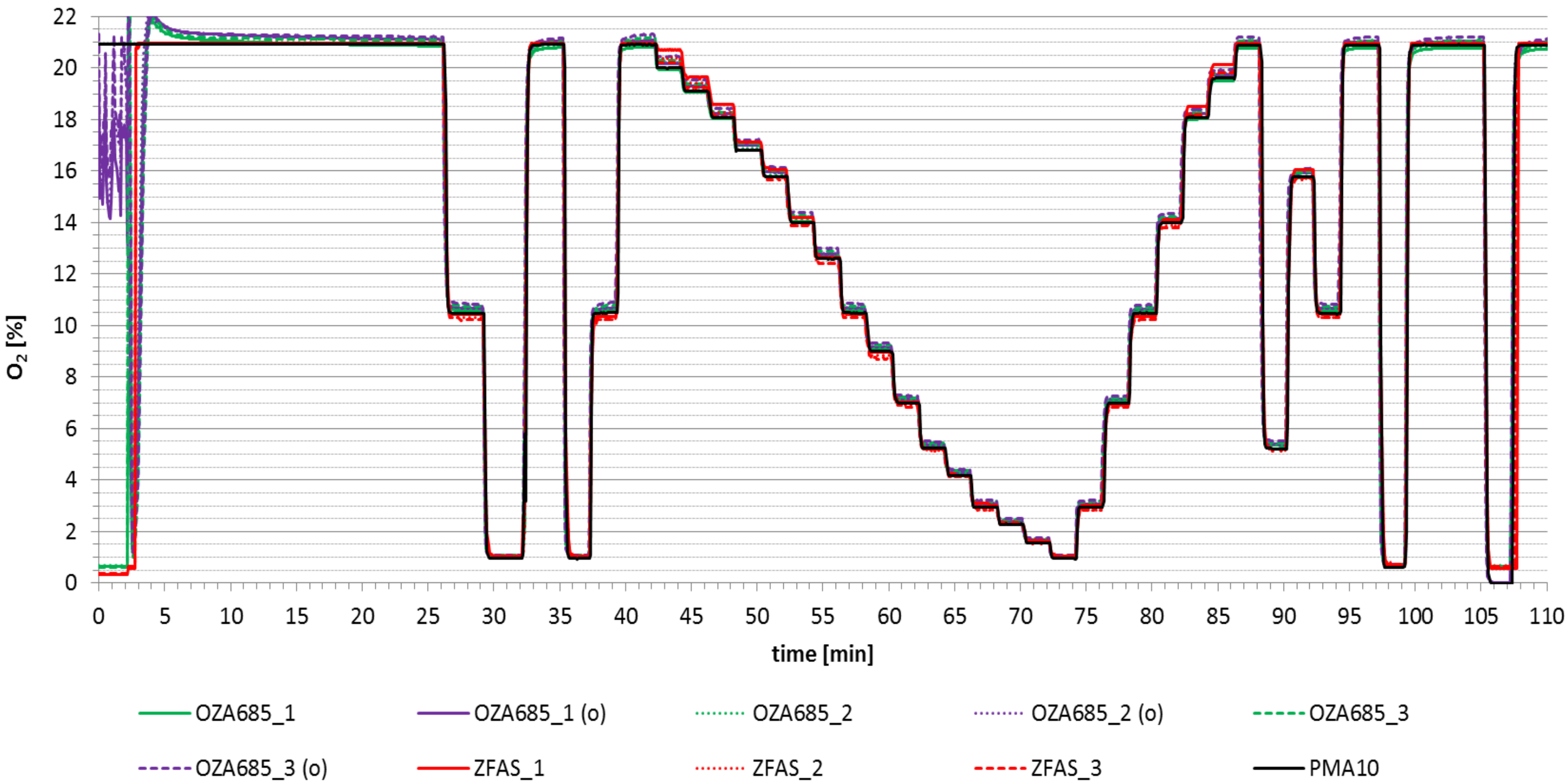
Long-term sensor evaluation – RISE
Probe condition at end of 2nd evaluation period





Notes: All probes in operation for whole 2nd evaluation period
Loose, non-sticking deposit on lambda probes, easy to remove
Visible tar deposit on outer shell of SenSic probe, did not get to sensor electronics

Long-term sensor evaluation – RISE
Lambda probes in test gas rig



Notes: Lambda probes final control check in test gas rig
Probes uncleaned; Feeding voltage 12V
Start of control check ca. 25 min after power on
Lambda transmitter signals (switching type probe) not adjusted
Paramagnetic oxygen analyzer values as comparison (equal set point values)

Long-term sensor evaluation – RISE Results & Conclusions (I)

Overall

- **Reliable determination of current combustion condition at all times during whole evaluation period**

O_2 & CO determination

- **Lambda probes with highly accurate determination of O_2 concentration within the whole oxygen range when controlled in test gas rig**
- **Only minor deviation in O_2 determination during stove operation (compared to standard analyzer), mainly due to cross sensitivities to HC & CO with ZFAS-U2 slightly more accurate than OZA685-WW1**
- **SenSic sensor with reliable detection of CO gradients & overall CO range (identification of batch ignition & start of char coal burn-out)**
- **Significant impact of O_2 on sensor signal complicate determination of exact CO concentration (Impact can be reduced by adjusting sensor temperature; will also affect CO resolution capacity)**

Long-term sensor evaluation – RISE Results & Conclusions (II)

Long term durability

- No aging effect observed for lambda probes during long term evaluation (same probe signals, unaffected by particle deposit)
- Signal drift for Sensic sensors during first operation hours & improvable electronics (sensor-probe interaction & miniaturization)

Conclusions

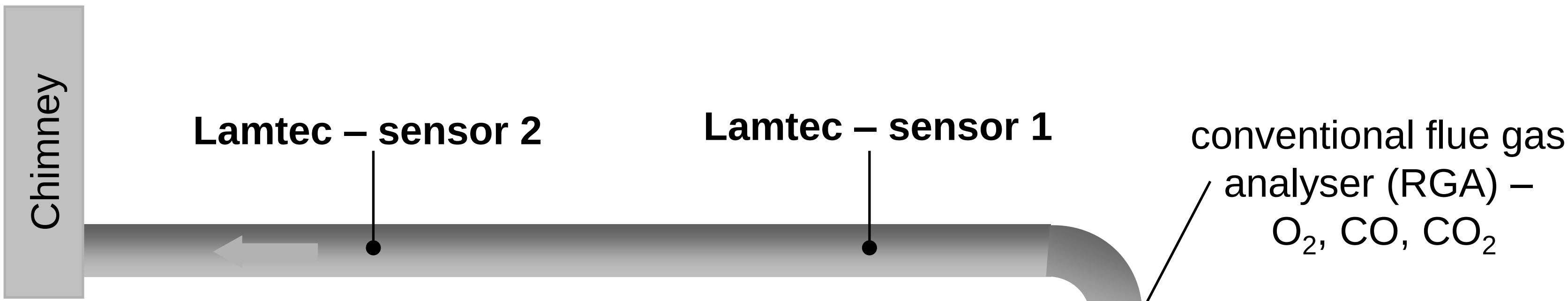
- Both lambda probe types suitable for automated control systems
- Broadband type with slight advantage in O_2 determination accuracy, Switching type with advantage in cost and simplicity of implementation
- SenSic sensor usable for stove operation, but cost for sensor and electronics are currently still too expensive for a wider use in the stove sector (especially when considering extra O_2 determination)

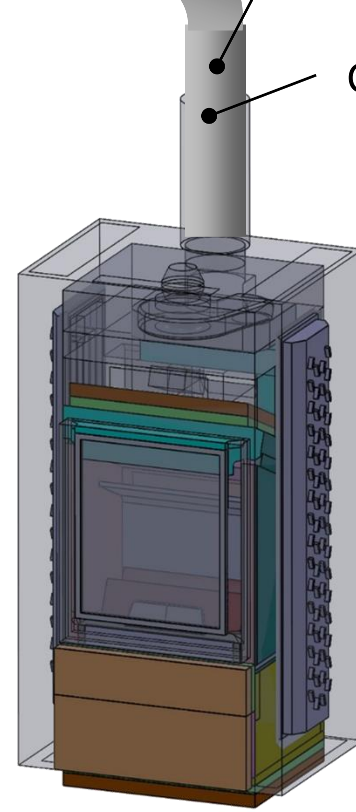
Long-term sensor evaluation – BIOS
Sensor selection

Combination probe KS1D (Lamtec)

- **Measured components & principle**
  - **Oxygen (0-21 vol% w.b.), COe = equivalent of all combustibles gases (0-10.000 ppm)**
  - **Combined Nernst- and Non Nernst Sensor**
- **Calibration**
  - **O_2: calibrated with dry ambient air prior to the test runs**
  - **COe: zero point calibration with dry ambient air; span calibration performed at stable operating conditions during test run with CO value (~ 1,000 ppmv) measured by the conventional flue gas analyser**

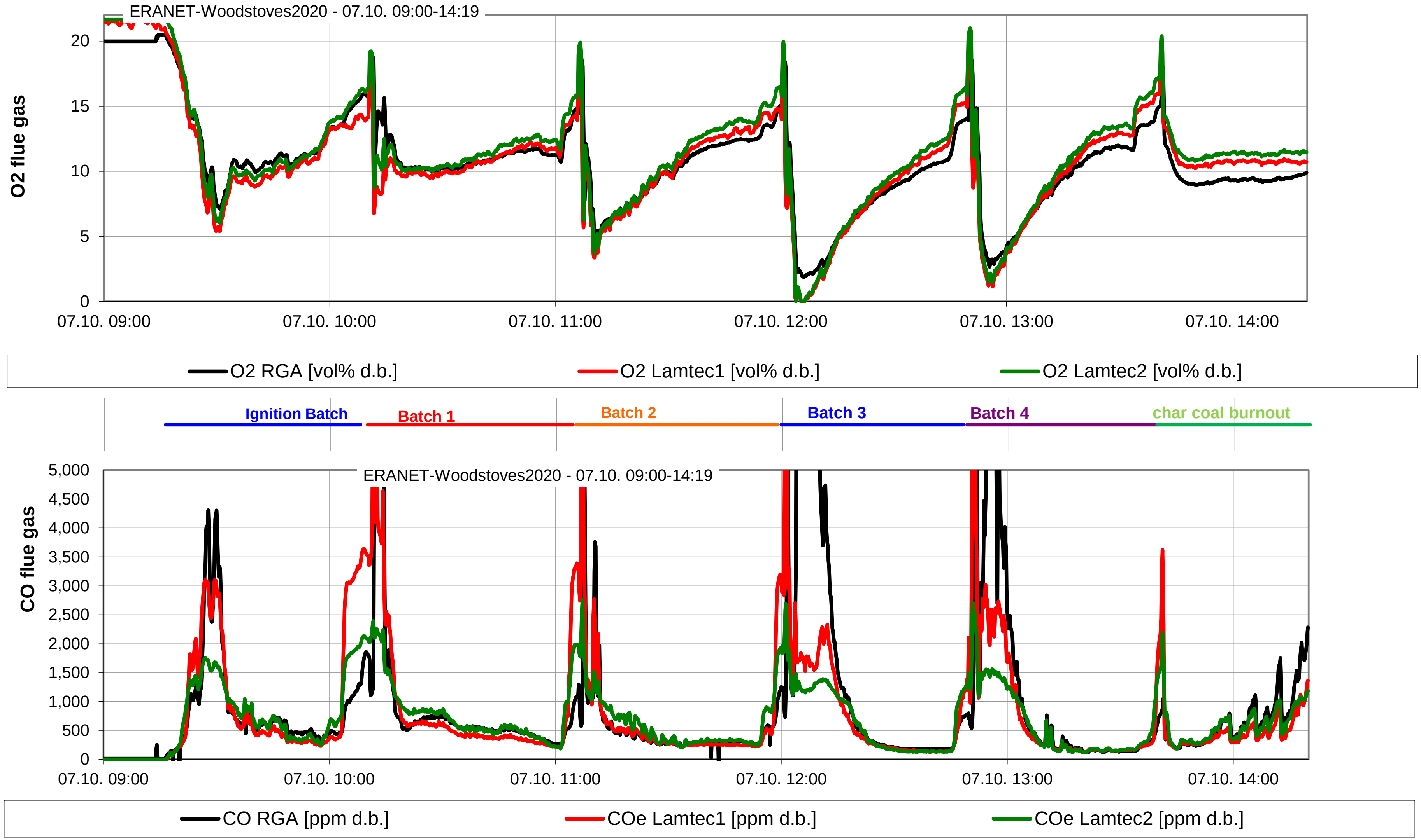
Long-term sensor evaluation – BIOS Procedure





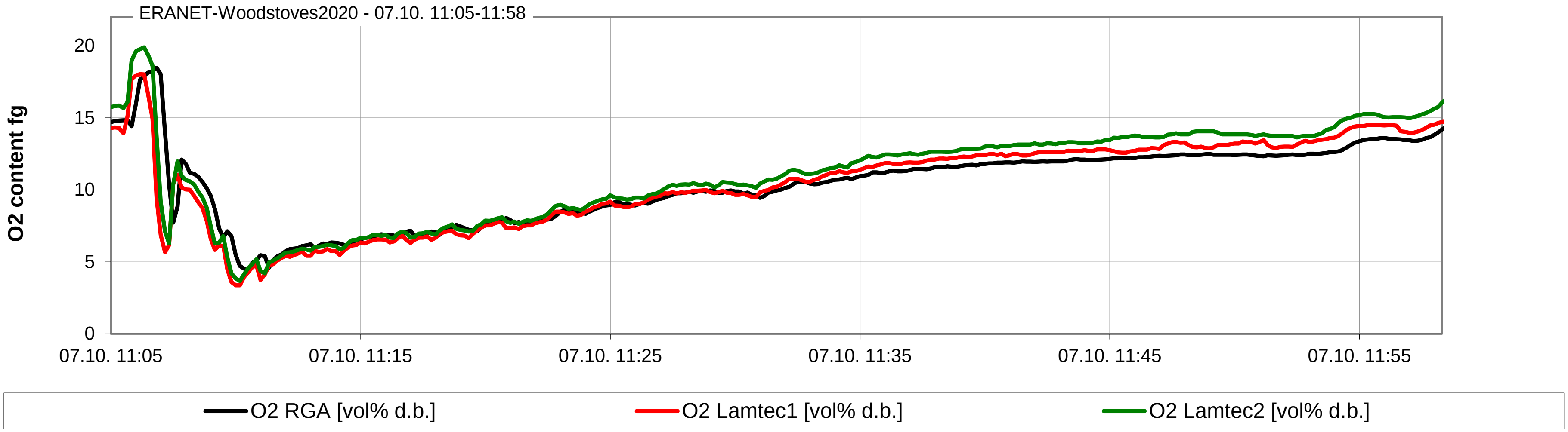
- **2 identical sensors have been tested at a 8 kW logwood chimney stove**
- **Logwood chimney stove operation over approx. 255 h (273 batches) – sensor 1 tested for 150 h**
- **Test fuel:**
  - **hardwood (beech) without bark, triangle shape**
- **Flue gas composition (O_2, CO, CO_2) – measured with conventional flue gas analyzer (Emerson NGA 2000)**

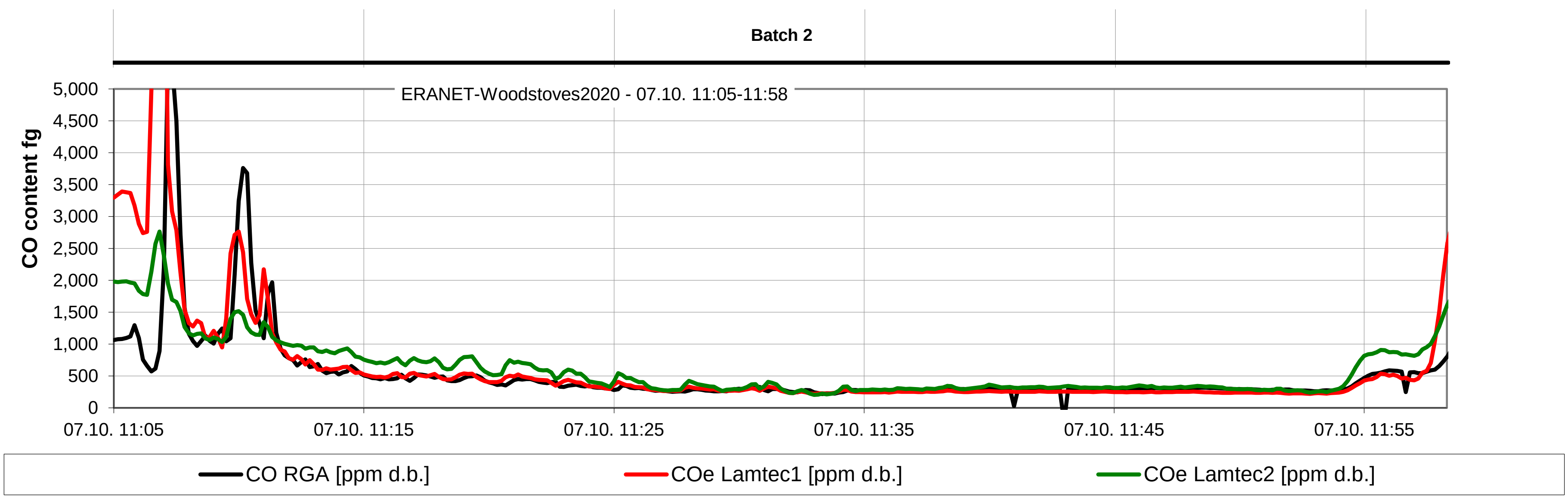
Long-term sensor evaluation – BIOS
O_2 and CO trends – day 26



Notes: • O_2 and CO emissions related to dry flue gas

Long-term sensor evaluation – BIOS
O_2 and CO trends – batch 2 of day 26

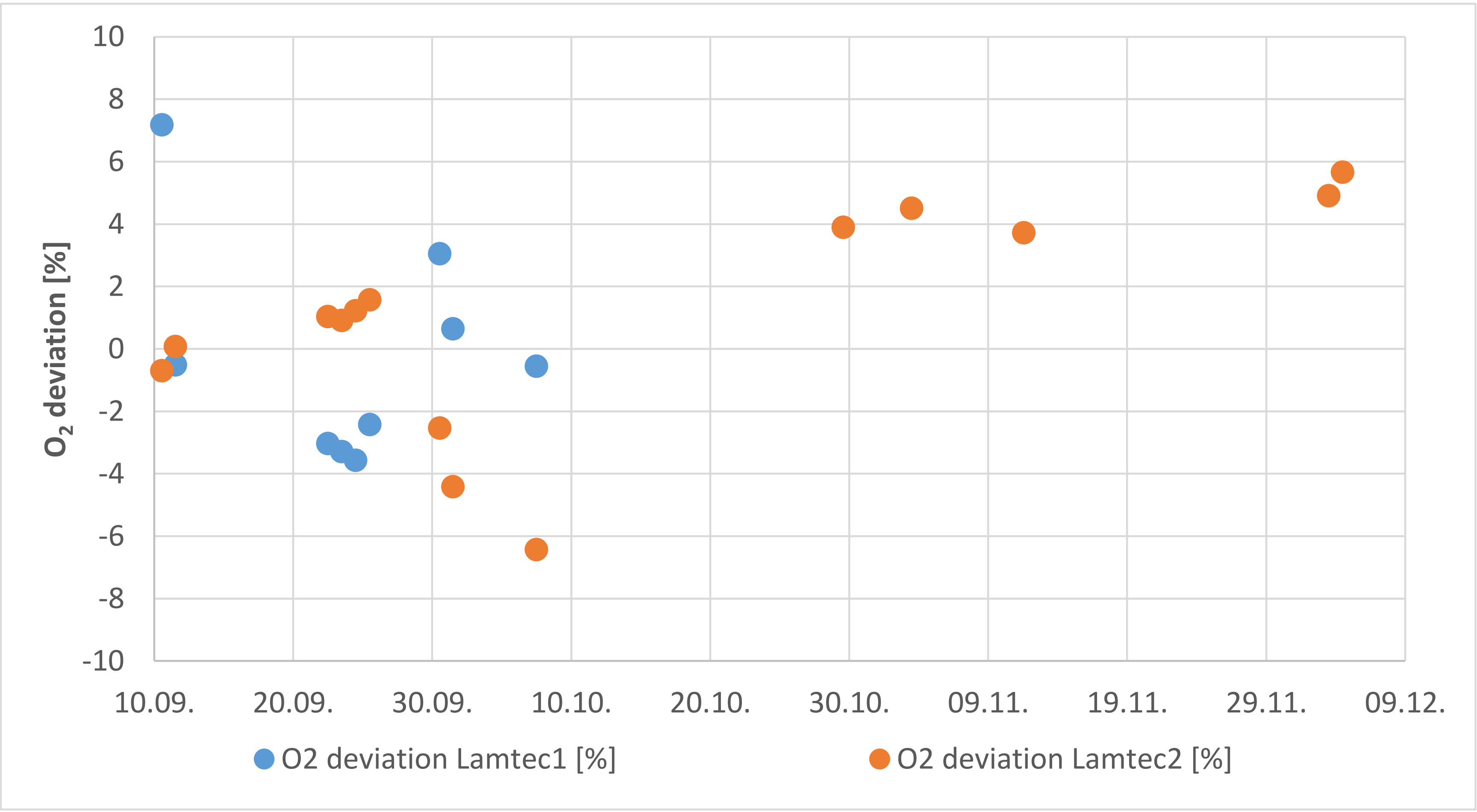




Notes: • O_2 and CO emissions related to dry flue gas

Long-term sensor evaluation – BIOS Evaluation (I)

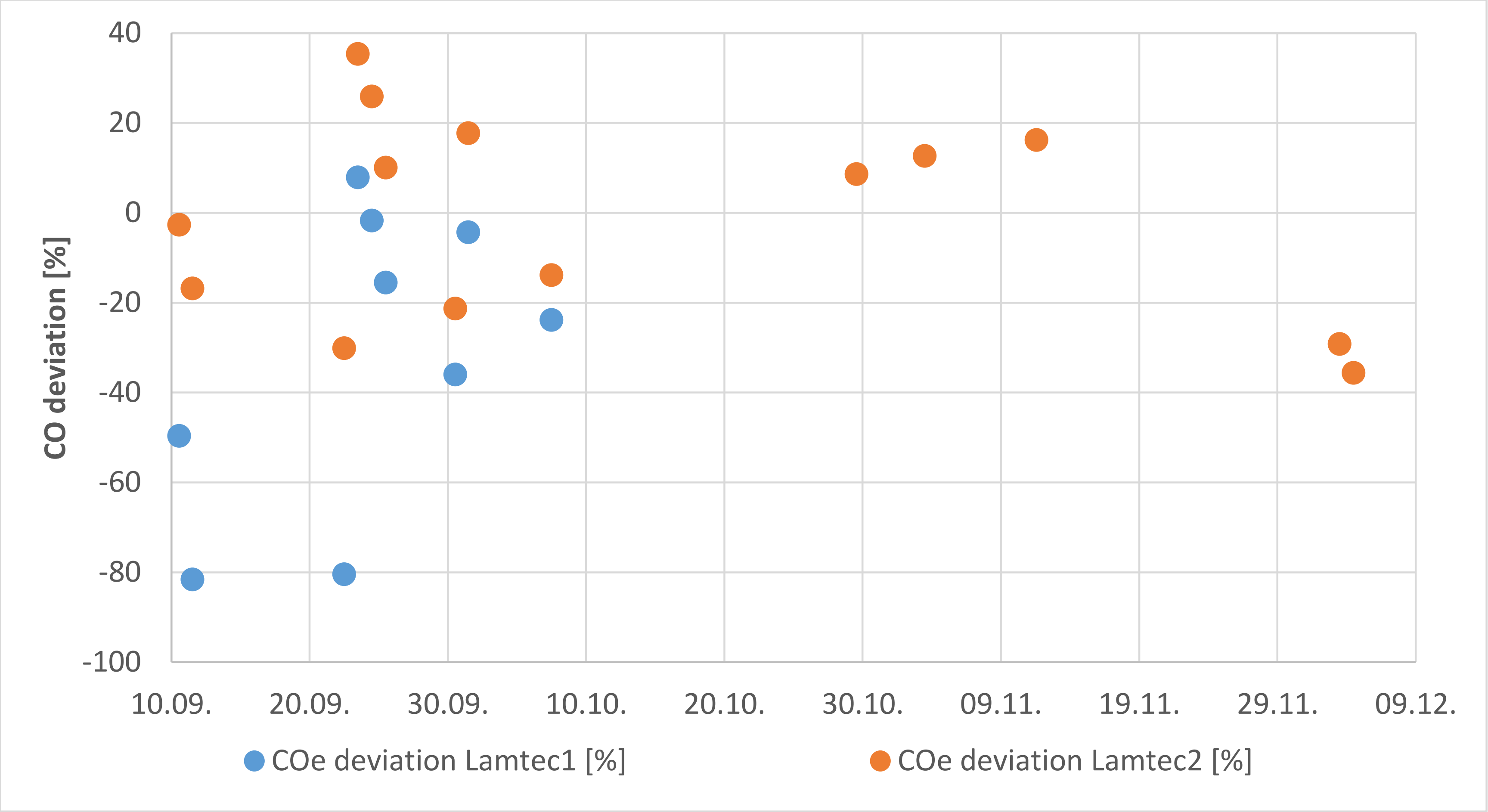
Trends of deviations of O_2 during long-term operation



Notes: • O_2 deviation calculated as [1-(O_2 Lamtec)/ (O_2 flue gas)]*100 in %; Sensor Lamtec1 has only been tested till 07/11

Long-term sensor evaluation – BIOS Evaluation (II)

Trends of deviations of CO during long-term operation



Notes: • CO deviation calculated as [1-(COe Lamtec)/ (CO flue gas)]*100 in %; Sensor Lamtec1 has only been tested till 07/11

Long-term sensor evaluation – BIOS Evaluation (III)

- **Probe condition at the end of the evaluation period**

Sensor before the test runs

Sensor after approx. 255 h of operation

Notes: • no cleaning of sensors has been performed

Long-term sensor evaluation – BIOS Results & Conclusions (I)

Overall

- **Reliable determination of current combustion condition at all times during whole evaluation period**

O_2 & CO determination

- **The sensor can well reproduce the O_2 trend over the entire range of operation of a wood stove (relative deviation: -6 to +7 %)**
- **Slightly higher deviation could be observed for O_2 values lower than 5 vol% d.b. and higher than 14 vol% d.b.**
- **The sensor supplies stable CO signals and can reproduce the CO trend over the entire measurement range.**
- **For CO values higher than 1,500 ppmv the relative deviation increases up to 80%**

Long-term sensor evaluation – BIOS Results & Conclusions (II)

Long term durability

- No aging effect observed for both sensors during long term evaluation
- However, the deviation of Sensor 2 regarding O_2 slightly increases with the operation time

Conclusions

- The O_2 and CO trends are sufficiently well predicted
- Generally, the combination probe KS1D seems to be suitable for the implementation into an automated stove control concept based on the results achieved so far
- By now the costs of purchase (single unit: 600 – 1,000 € including converter) are too high for an integration into a wood stove. In future the converter may be integrated in the controlling plate of the automated control system of the stove and thereby the costs can be significantly reduced.

Concluding summary

- Evaluation confirmed conclusion from other studies regarding gas sensor accuracy at biomass combustion
  - Accurate oxygen determination
  - CO determination with correct identification of gradients & ranges
- Evaluated sensors have proven their suitability to be used in the stove sector
  - Withstand exposure to temperature, dust load, gas concentration range
- Automated control systems can rely on sensor signals
- Economic considerations
  - Oxygen sensors, as e.g. well proven lambda probes, provide an affordable choice for utilization of gas sensor based control systems
  - CO sensors & combination sensors (O_2+CO) are at the moment still too expensive for a wider use in the stove sector

Flue gas sensor testing and evaluation

Further information can be found at
http://www.tfz.bayern.de/en/162907/index.php

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