Sensor screening and evaluation

Gas sensors for automated stove control systems

Project ERA-NET Bioenergy "Wood Stoves 2020"

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Introduction (I)

- **ERA-NET Bioenergy**
  - **ERA-NET Bioenergy is a network of national research and development programmes focusing on bioenergy which includes 14 funding organisations from 10 European countries: Austria, Denmark, Finland, France, Germany, Ireland, The Netherlands, Poland, Sweden and the United Kingdom. Its mission is to enhance the quality and cost-effectiveness of European bioenergy research programmes, through coordination and cooperation between EU Member States.**

- ***Woodstoves 2020***
  - **The project *Woodstoves 2020* (Development of next generation and clean wood stoves) has been supported in the period between October 2009 and September 2012 by ERA-NET Bioenergy under 7th Joint Call for Research and Development of the ERA-NET Bioenergy from 2013.**
  - **The project aimed at the development of innovative measures and technologies in order to further reduce emissions from wood stoves, to increase their thermal efficiency and to expand their field of application from solely single room heating to central heating. The latter could especially be of relevance for future applications in low energy buildings.**

Introduction (II)

The detailed objectives of the project had been structured as follows

- **Objectives related to emission reduction**
  - Automated control systems as a feature of new stoves but also as retrofit units
  - Evaluation and test of catalysts specially adapted to wood stoves
  - Evaluation & test of foam ceramic materials for efficient PM emission reduction.
  - Evaluation of the implementation of modern chimney draught regulators.
- **Objectives related to increasing efficiency and new fields of application**
  - Development & evaluation of efficient and novel PCM (phase change material) heat storage options for stoves
  - Investigations regarding efficient heat recovery from stoves
- **Objectives related to the implementation of the different measures**
  - Test of the most promising concepts by performing test runs with prototypes.
  - Development of design guidelines for stove manufacturers
  - Development of guidelines for retrofit of selected measures for old stoves

Introduction (III)

- Within the project a consortium of 4 research organisations and 4 industrial partners from 4 European countries collaborated
  - Technology and Support Centre in the Centre of Excellence for Renewable Resources (TFZ), Germany
  - BIOS BIOENERGIESYSTEME GmbH, Austria
  - RISE Research Institutes of Sweden
  - Technical University of Denmark, Department of Chemical and Biochemical Engineering
  - RIKA Innovative Ofentechnik GmbH, Austria
  - Kutzner + Weber GmbH, Germany
  - Nibe AB, Sweden
  - HWAM A/S, Danmark
- This report summarises the outcomes of Task 1.1 of the project, Screening and evaluation of available gas sensor for use in automated stove control systems

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Background

Background
Basic considerations

- Challenges in stove combustion
  - Batch combustion with rather short duration → significant impact of start & burn-out phases on performance values
  - Constantly changing boundary conditions
  - Unknown user behavior
- Measure: Continuous air supply adjustment (amount & position)
  - Shorten start & burn-out phases with high emissions of carbon monoxide & hydrocarbons
  - Avoid phases with incomplete combustion
  - Higher efficiency by reducing unnecessary excess air
  - React on user induced errors
- Requirement: Determination of current combustion condition
  - Sensors for temperature, pressure, gas components

Background
Selection criteria for gas sensors

- **Costs**
- **Life span**
  - **Ideally replacement is avoided during stove's normal life time**
- **Development status & availability**
  - **Should be available in sufficient numbers and consistent quality**
- **Temperature resistance**
  - **Determine if and on what position a sensor can be placed**
- **Selectivity & Stability**
  - **Signal interference due to other gas components, dust or variations in pressure and temperature; directly and over time**
- **Processing and peripherals**
  - **Beneficial with minimal effort for sensor operation & signal processing**

Background
Measurement principles for gas sensors

- **Solid electrolyte**
  - **Potentiometric & amperometric sensor principle**
  - **Commercially available & widely used**
- **Semiconductors**
  - **MOS (Metal Oxide Semiconductor), MOSFET (metal-oxide-semiconductor field-effect-transistor), etc.**
  - **Commercially available & widely used (especially MOS sensors)**
- **Calorimetric**
  - **Temperature change due to chemical reactions on catalytic detector**
  - **Risk of catalyst poisoning, improvable component selectivity**
- **Optical**
  - **Based on absorption and emission spectrometry**
  - **Improvable in terms of price & miniaturization**

Market research

Market research Questionnaire

- **General Information**
  - Sensor, manufacturer, measured component, state of development, measurement principle
- **Operation characteristics**
  - Measurement range, power consumption, life span, long term drift, temperature range for operation, cross sensitivities, sensor poisoning risks, reaction to dust/tar deposition
- **Sales condition**
  - Estimated costs for sensor alone respectively sensor including signal processing electronics (acquisition of around 1000/year)
- **Others**
  - Experiences & references from usage in wood stoves or other biomass combustion appliances

Market research
Detected sensors (I)

Oxygen sensors

- **Switching type lambda probe OZA685-WW1 (NGK Spark Plug Co., Ltd.)**
- **Broadband lambda probe ZFAS-U2 (NGK Spark Plug Co., Ltd.)**
- **Broadband lambda probe LSU 4.9 (Bosch)**
- **MF010-O-LC (J. Dittrich Elektronic)**
- **OC2010 (Scantronic)**
- **Heraeus oxygen sensor (Heraeus AG)**

Market research
Detected sensors (II)

- **Sensors for unburnt gases & combination sensors for multiple gases**
  - **CarboSen 1000 (LAMTEC GmbH & Co. KG)**
  - **TGS 816 (FIGARO Engineering inc)**
  - **CO2000 (Scantronic)**
  - **KS1D (LAMTEC GmbH & Co. KG)**
  - **CO/O_2 sensor (SenSic AB)**

Market research
Lambda probe OZA685-WW1 (Switching type)

- **Manufacturer**
  - NGK Spark Plug Co., Ltd.
- **Measurement principle**
  - Solid electrolyte Yttria-stabilized zirconia (YSZ) - potentiometric sensor
- **Component & Range**
  - Oxygen: ca. 1% – Air
- **State of development**
  - commercial
- **Price (Sensor / with electronics)**
  - Sensor ca. 45€ / including optional electronics ca. 70 €
- **Temperature range**
  - Max. temperatures: probe 900°C, housing 600°C, grommet: 210°C

Market research
Lambda probe OZA685-WW1 (Switching type)

- **Life span**
  - **> 10.000h**
- **Cross sensitivities**
  - **H_2 (increase signal) and CH_4 (decrease signal)**
  - **CO and Temperature – no known impact**
- **Long term drift**
  - **no problems reported**
- **Risk for sensor poisoning & Reaction to dust/tar deposition**
  - **no problems reported**
- **Experience**
  - **developed for biomass combustion**
  - **> 200.000h in field at several biomass applications**

Market research
Lambda probe ZFAS-U2 (Broadband type)

ERA-NET Bioenergy

- **Manufacturer**
  - NGK Spark Plug Co., Ltd.
- **Measurement principle**
  - Solid electrolyte YSZ - amperometric sensor
- **Component & Range**
  - Oxygen: λ 0,7 - Air
- **State of development**
  - Commercial
- **Price (Sensor / with electronics)**
  - Sensor ca. 45€ / including electronics ca. 115 €
- **Temperature range**
  - Max. temperatures: probe 950°C, housing 650°C, grommet 240°C

Market research
Lambda probe ZFAS-U2 (Broadband type)

- **Life span**
  - n/a
- **Cross sensitivities**
  - n/a
- **Long term drift**
  - no problems reported
- **Risk for sensor poisoning & Reaction to dust/tar deposition**
  - no problems reported
- **Experience**
  - Used by a few manufacturers of biomass applications
  - Same sensors used in automotive industry in large numbers

Market research
MF010-O-LC (Oxygen sensor)

- **Manufacturer**
  - J. Dittrich Elektronic GmbH & Co. KG
- **Measurement principle**
  - Solid electrolyte YSZ
- **Component & Range**
  - Oxygen: 0,1 – 25 Vol.-%
- **State of development**
  - Commercial
- **Price (Sensor / with electronics)**
  - N/A
- **Temperature range**
  - probe: up to 250°C or 350°C, electronics: -20°C to 60°C

Market research
MF010-O-LC (Oxygen sensor)

- **Life span**
  - **About 5 years on fresh air**
- **Cross sensitivities**
  - **Stoichiometric combustion at Pt-electrode**
- **Long term drift**
  - **n/a**
- **Risk for sensor poisoning & Reaction to dust/tar deposition**
  - **Halogens (F2, Cl2); HCL; HF; SO2; H2S; Freons; CS2; Long time in reducing atmospheres**
- **Experience stoves & other biomass**
  - **Used in project “Holzverbrennung 2015” (AZ27383-24/0)**
  - **Different costumer application**

Market research
OC 2010 (Oxygen sensor)

- **Manufacturer**
  - **ScanTronic ApS**
- **Measurement principle**
  - **Solid electrolyte YSZ (potentiometric sensor)**
- **Component & Range**
  - **Oxygen: 0.5 - 20.9 %**
- **State of development**
  - **Commercial**
- **Temperature range**
  - **probe: up to 600°C**
- **Experience stoves & other biomass**
  - **installed in several small/medium scale boilers (biomass & fossil fuels)**

Market research
Heraeus Oxygen sensor

- **Manufacturer**
  - Heraeus Group
- **Measurement principle**
  - Solid electrolyte YSZ (amperometric sensor)
- **Component & Range**
  - Oxygen: 0,5 – 25 (100)Vol%
- **State of development**
  - Developed
- **Temperature range**
  - probe: up to 400°C
- **Experience stoves & other biomass**
  - Evaluated in a research project

Market research
CarboSen 1000 (CO_e sensor)

- **Manufacturer**
  - LAMTEC GmbH & Co. KG
- **Measurement principle**
  - Solid electrolyte YSZ (Non Nernst Sensor)
- **Component & Range**
  - CO_e : 0 - 3000 ppm (best 0-1000 ppm), also available up to 2% CO
- **State of development**
  - Commercial
- **Temperature range**
  - probe: up to 450°C
- **Experience stoves & other biomass**
  - Evaluated for example in several research projects

Market research
TGS 816 (CO_e sensor)

- **Manufacturer**
  - FIGARO Engineering inc
- **Measurement principle**
  - Metal Oxide Semiconductor (SnO_2)
- **Component & Range**
  - CO_e: 0 - 10,000 ppm (various other types with specific selectivity's)
- **State of development**
  - Commercial (more than 200 Mio. TGS sensors sold worldwide)
- **Temperature range**
  - probe: up to 200°C
- **Price (Sensor / with electronics)**
  - Sensor < 40€

Market research
CO 2000 (CO_e sensor)

- **Manufacturer**
  - **ScanTronic ApS**
- **Measurement principle**
  - **Metal Oxide Semiconductor Ga_2O_3**
- **Component & Range**
  - **CO_e: 0 - 10,000 ppm**
- **State of development**
  - **Commercial**
- **Temperature range**
  - **probe: up to 300°C**
- **Experience stoves & other biomass**
  - **Evaluated for example in some research projects**

Market research
Kombi Probe KS1D

- **Manufacturer**
  - **LAMTEC GmbH & Co. KG**
- **Measurement principle**
  - **Solid electrolyte YSZ / Combined Nernst- and Non Nernst Sensor**
- **Component & Range**
  - **O_2 : 0-21 Vol % & CO_e : 0 - 3.000 ppm**
- **State of development**
  - **Developed**
- **Temperature range**
  - **For flue gas temperatures up to 450°C**
- **Price (Sensor / with electronics)**
  - **Sensor 100-200 € / including electronics 600-1.000 €**

Market research
Kombi Probe KS1D

- **Life span**
  - **Depends on biomass**
- **Long term drift**
  - **none**
- **Cross sensitivities**
  - **Impact on Oxygen from CO_2, CO, CH_4, SO_2, NO: < 0,1 Vol %**
  - **Impact on CO_e from CO_2, O_2 : < 30 ppm**
- **Risk for sensor poisoning & Reaction to dust/tar deposition**
  - **Risks at long term CO & HC exposure to more than 1.000 ppm**
  - **Response time is increasing in case of dust/tar deposition**
- **Experience stoves & other biomass**
  - **10 year experiences in big biomass furnaces; Some testing in stoves**

Market research
SenSic CO/O_2 sensor

- **Manufacturer**
  - SenSic AB
- **Measurement principle**
  - Catalytic layer integrated with semiconductor component (Silicon carbide high temperature MOSFET)
- **Component & Range**
  - CO_e & O_2 combined signal: Range settable, best resolution at low CO
- **State of development**
  - Developed
- **Temperature range**
  - Temperature will have impact on sensitivity to CO & O_2
- **Price (Sensor / with electronics)**
  - Sensor ca. 110 €

Market research
SenSic CO/O_2 sensor

- **Life span**
  - **N/A**
- **Cross sensitivities**
  - **Cross-sensitive mainly to unsaturated/long-chained hydrocarbons**
- **Long term drift**
  - **N/A**
- **Risk for sensor poisoning & Reaction to dust/tar deposition**
  - **Risks at long term exposure to high HCL, SO_2 amounts**
  - **Fly-ash might cause clogging & block active sensor area**
- **Experience stoves & other biomass**
  - **Evaluated during some research projects, including field tests in district heating plants**

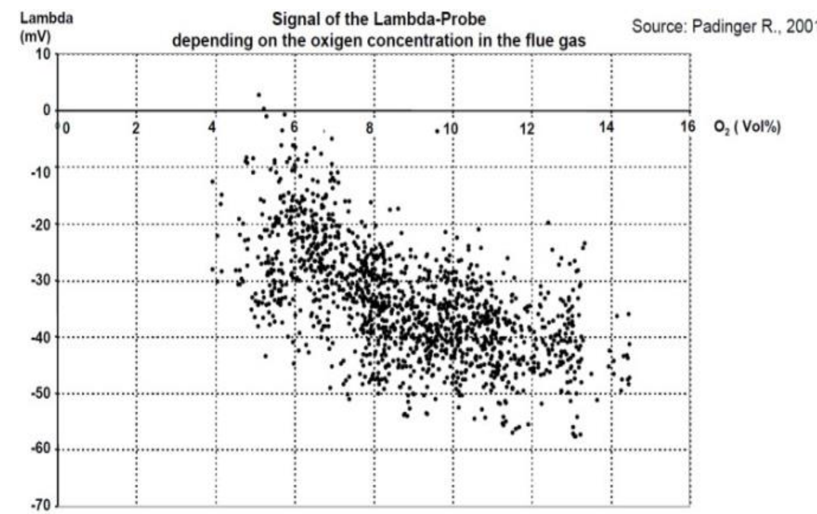
Literature review

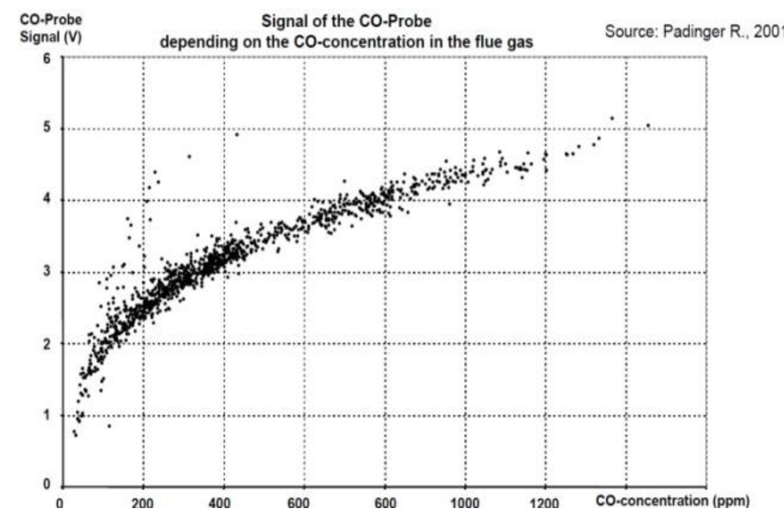
Literature review
Summary

- Limited (but growing) number of sensors, especially for unburned gases
- Most research projects were focusing on operation concept, less on sensor evaluation
  - Main focus on boiler development, but some stove projects
- Long development & implementation time span for new sensors
- Oxygen sensors
  - In general god accuracy & little cross sensitivity
- 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
  - Utilization in operation concept successfully proven

Literature review (selected studies)
Padinger 2001

- **Project topic**
  - **Design & Evaluation of automatic control system for a 50 kW wood chip boiler**
- **Sensors evaluated**
  - **O_2 sensor: Bosch LSM11**
  - **CO sensor: Figaro TGS 816**
- **Results**
  - **Comparison of LSM11 signals at boiler operation with O_2 from analyzer instrument shows significant scatter**
  - **Comparison of TGS 816 signals at boiler operation with CO analyzer instrument shows good correlation**
  - **Control system based on CO sensor signals alone successfully proven (gradient based control)**





Literature review (selected studies)
Eskilsson & Tullin 2001

Project topic

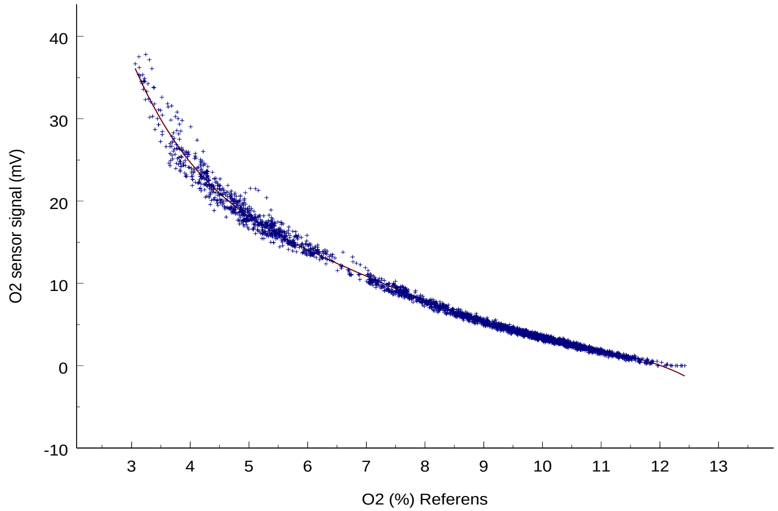
- **Gas sensor test in a 12 kW pellet burner under different operation modes**
- **Sensors installed in bypass after cooling**

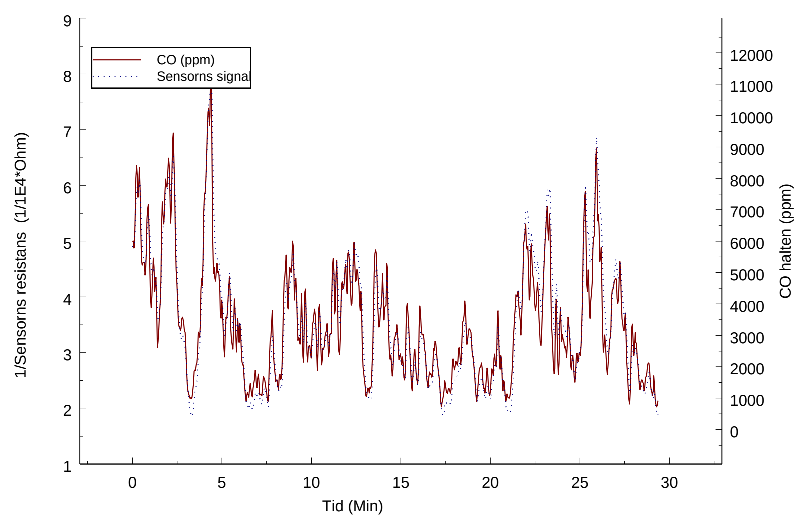
Sensors evaluated

- **O_2 sensors: Bosh LSM11**
- **CO sensors: Steinel SGAS 220**

Results

- **LSM11**
  - Good correlation of sensor signal with oxygen values from standard analyzer
- **SGAS 220**
  - Good correlation of sensor signal and CO concentration in flue gas
  - Signal slightly depended on O_2 concentration





Source: Eskilsson & Tullin 2001

Literature review (selected studies)
Svensson 2003

- **Project topic**
  - **Test of sensors installed in flue gas duct of a 400 kW pellet burner**
  - **Different load modes tested (full & part load)**
- **Sensors evaluated**
  - **O_2 sensors: Bosch LSM11 & lambda probe from unknown manufacturer**
- **Results**
  - **LSM11**
    - Good correlation between sensor signals & O_2 analyzer instrument
    - Noticeable signal fluctuations (assumingly due to turbulent flow conditions)
    - No aging effects & only small influence of particle deposit observed during project
    - Considered to be suitable for intended use in automated control system
  - **2nd lambda probe (unknown manufacturer)**
    - Problems with signal stability, drift and response time
    - Change in signal sensitivity over time (presumable due to particle deposit)
    - Inoperative after two month

Literature review (selected studies)
Eskilsson & Rönnbäck 2004

Project topic

- **Long time sensor test (about 3 month) in a small district heating pellet boiler**
- **Sensors installed in flue gas duct (directly and after a particle filter)**

Sensors evaluated

- **CO Sensors: SGAS 220, CarboSen 1000 & Lamtec CO sensor**

Results

- **Sensors directly installed in flue gas duct**
  - Sensor 1 inoperative after 2 weeks (presumable due to particle deposit)
  - Sensor 2 not working correctly over whole time (presumably caused by high flue gas velocity)
  - Sensor 3 indicated CO concentration trend, but over time significant change in signal characteristics with decrease in minimum detection limit and detection sensitivity (presumable due to particle deposit)
- **2 Sensor installed after a particle filter**
  - Worked satisfactory
  - Both sensors indicate CO concentration trend
  - Noticeable change in signal characteristics over time

Literature review (selected studies)
Padban et al. 2004

Project topic

- **Evaluation of different control strategies using gas sensors in a 220 kW based pellet boiler**

Sensors evaluated

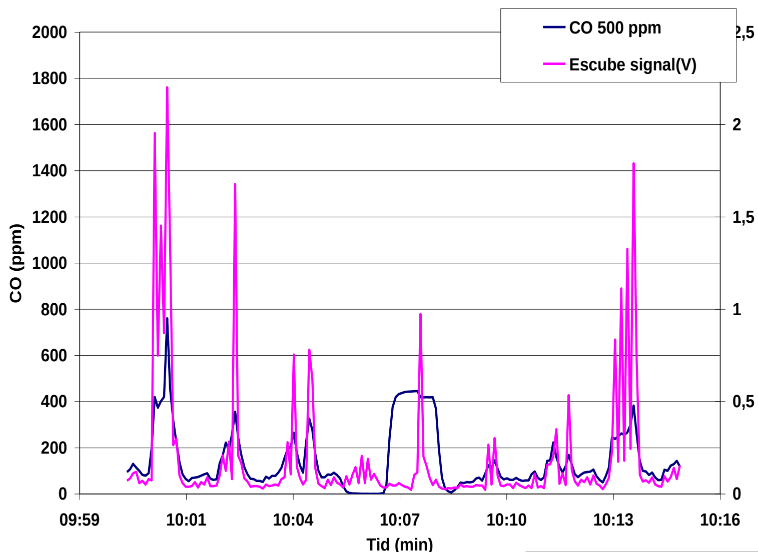
- **O_2 sensors: Lambda probe (switching type)**
- **CO Sensors: SGAS 220, CarboSen 1000, SIC FE**

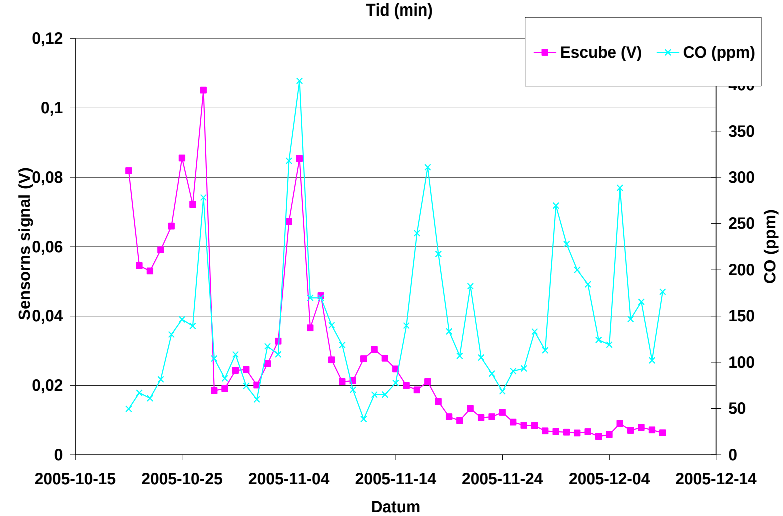
Results

- **Lambda probe**
  - Very good correlation between sensor signal and oxygen value from standard analyzer
- **SGAS 220**
  - Good correlation to CO concentration, noticeable variation in base signal & sensitivity
- **Carbosen 1000**
  - Good correlation to CO concentration, stable signal without large variation in base signal
- **SiC FE**
  - Good correlation to CO concentration, minor variation in base signal

Literature review (selected studies)
Eskilsson & Tullin 2006

- **Project topic**
  - **Long time field test (up to 2 month) in 3 district heating plants (80 kW - 4 MW)**
  - **Sensors installed in flue gas channel with different particle protection layouts**
- **Sensors evaluated**
  - **CarboSen 1000 & Scantronic CO 2000**
- **Results**
  - **CarboSen 1000**
    - All sensors operable under campaign
    - Drift in signal characteristics & base signal (not uniform for different sensors)
  - **CO 2000**
    - 3 (out of 4) inoperable after campaign (two due to corrosion)
    - 4th sensor operable under campaign, but with drift in base signal





Source: Eskilsson & Tullin 2006

Literature review (selected studies)
Struschka et al. 2009

- **Project topic**
  - **Field tests of sensors in 4 different appliances (pellet boiler, wood boiler & wood stove)**
  - **Long time test for about 3-4 month, including logging of sensor signals**
  - **Comparison of sensor signals with conventional gas analysis before and after test campaign during operation at wood fired lab appliances**
- **Sensors evaluated**
  - **Combination sensor for O_2 and NOx (NGK)**
  - **CO Sensor (CarboSen)**
- **Results**
  - **Base and span drift for both sensors**
    - Adjustment for base drift during campaign when possible
    - Adjustment for span drift afterwards at lab for evaluation purposes
  - **Good correlation between adjusted sensor signals and corresponding values from standard gas analyzers**

Literature review (selected studies) Körlof & Wilhelmson 2009

Project topic

- **Development of a control system for a 23 kW pellet burner**
- **Short term test in different load modes**

Sensors evaluated

- **O_2 sensors: Bosch LSU 4.9**
- **CO Sensors: CarboSen 1000 & SGAS 220**

Results

- **LSU 4.9**
  - Very good conformity for sensor signal with O_2 values from standard analyzer instrument
  - Linear correlation between signals and O_2 concentration
- **CarboSen 1000 & SGAS 220**
  - Good conformity for sensor signals with CO values from standard analyzer instrument
  - Carbosen 1000 slightly more accurate than SGAS 220 at lower CO values

Literature review (selected studies) Kohler et al. 2009/2011

Project topic

- **Development of a control system for wood burning appliances (7 kW Wood stove, 15 kW tile stove inset, 24 kW wood boiler & 15 kW pellet boiler)**
- **Sensor evaluation in test gas rig**

Sensors evaluated

- **O_2 sensors: Dittrich MFO10-O**
- **CO Sensors: CarboSen 1000**

Results

- **Gas sensors suitable for automated control system (sensor installed in flue)**
- **CarboSen 1000**
  - Differing signal sensitivity to unburnt components (e.g. significant higher sensor signal at exposure to H_2 than for exposure to same amount of CO)
  - Cross sensitivity to O_2
  - Reduced sensitivity with time (lower sensor signal at same CO values)

Literature review (selected studies)
Kohler et al. 2010/2013

Project topic

- **Development wood boiler control system incl. control of sensors in test gas rig**

Sensors evaluated

- **O_2 sensors: Bosch LSU 4.9 & Dittrich MF420**
- **Combination sensor for O_2 and CO: Lamtec KS-1D**
- **CO Sensors: CarboSen 1000 & Figaro TGS 823**

Results

- **O_2 determination**
  - Excellent signal stability and reproducibility for all sensors
  - No cross sensitivity to CO & moisture for LSU 4.9 & MF420; but some for KS-1D
- **CO determination**
  - Noticeable cross sensitivity to O_2 (signal increase when O_2 decreases)
  - Significant cross sensitivity to moisture for TGS 823 (signal increase with higher moisture)
  - Noticeable moisture impact on KS-1D & Carbosen 1000 (more clearly at higher CO values)
  - Change in signal sensitivity for CarboSen 1000 over time (exposed to propene, flue gas)

Literature review (selected studies)
Reference list (I)

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Literature review (selected studies) Reference list (II)

- T. Körlof & P. Wilhelmson, ”Robust reglering av pelletsbrännare - En förstudie,” Luleå tekniska universitet, 2009.
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- H. Kohler, R. Herwig & T. Leize, ”Holzverbrennung 2015 - Konzeption, Darstellung und Untersuchung eines extrem emissionsarmen Stückholz-Heizkessels, Berichtsteil zu den Arbeitspaketen des ISIS,” ISIS Hochschule Karlsruhe, 2013.

Sensor evaluation

Sensor evaluation
Overview

Sensors tested at RISE

- **Lambda probe OZA685-WW1 (NGK)**
- **Lambda probe ZFAS-U2 (NGK)**
- **SenSic CO/O_2 sensor**

Sensors tested at BIOS

- **Combination probe KS1D (Lamtec)**

Sensor evaluation

RISE

Sensor evaluation at RISE
Sensor selection

- **Lambda probe OZA685-WW1 (switching type)**
  - **3 units (used over complete evaluation period)**
  - **Operated with Lambda Transmitter (LT-OZA)**
- **Lambda probe ZFAS-U2 (broadband type)**
  - **3 units (used over complete evaluation period)**
  - **Operated with Lambda system control (LSC)**
- **SenSic CO/O_2 sensor**
  - **3 units in total (one used in first evaluation phase & two in second)**
  - **Operated with SenSic electronics**

Sensor evaluation at RISE
OZA685-WW1

Potentiometric solid electrolyte sensor

- **Heated YSZ ceramic permeable for oxygen ions**
- **Platinum electrodes on two separated sides (sample gas and reference/air)**
- **Different oxygen partial pressure induce oxygen ion transport between electrodes, generating an electric potential difference (specific to oxygen difference, thus usable as sensor signal)**

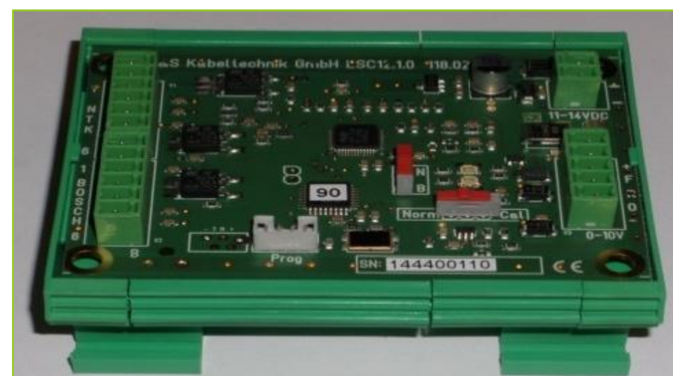
Operation notes

- **Passive measurement – no active control needed**
- **4 cable probe (2 for heating current, 2 for signal)**
- **Feeding voltage between 11-14 V (will affect signal characteristics)**
- **Probe signal around -10 till 60 mV in oxygen range of interest (abrupt voltage rise at zero oxygen level)**
- **Lambda Transmitter amplifies probe signal to an output of 0-10V (adjustable)**

Note: YSZ = Yttria-stabilized zirconia, zirconium dioxide (ZrO_2) added with yttrium oxide (Y_2O_3)

Sensor evaluation at RISE
ZFAS-U2

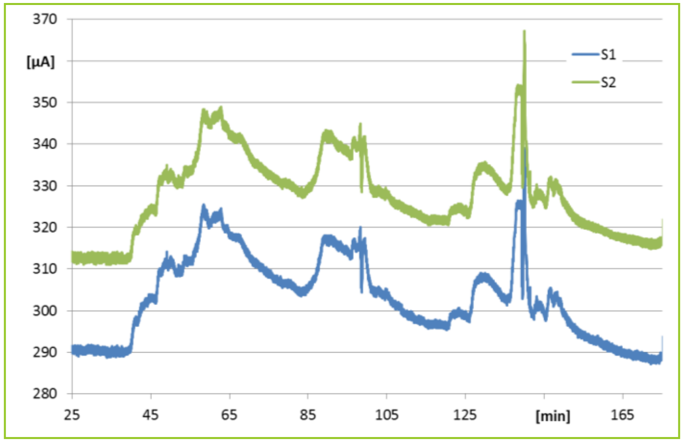
- **Amperometric solid electrolyte sensor**
  - **Heated YSZ ceramic permeable for oxygen ions**
  - **Platinum electrodes on two separated sides (sample gas and a reference chamber)**
  - **A pumping current will force oxygen ions into/from reference chamber to obtain a defined voltage between reference chamber and sample side**
  - **Magnitude of pumping current depends on oxygen difference, thus can be used as sensor signal**
- **Operation notes**
  - **Active measurement, specific control chip is needed**
  - **6 cable probe, connected to Lambda system control**
  - **Feeding voltage 12 V**
  - **LSC operates probe (heating ceramic, adjust pumping current, generates output signal)**
  - **Output signal 0-10V**



Note: YSZ = Yttria-stabilized zirconia, zirconium dioxide (ZrO_2) added with yttrium oxide (Y_2O_3)

Sensor evaluation at RISE
SenSic CO/O_2 sensor

- **Silicon carbide high temperature MOSFET**
  - **Sensor surface with a catalytic metal layer**
  - **Unburned gas components will react on surface, changing the electrical current through the transistor, which can be used as sensor signal**
- **Operation notes**
  - **Active measurement, evaluation electronics needed**
  - **Electronics operates probe (regulates temperature on surface, records sensor signals & generates output signal)**
  - **Feeding voltage 12V**
  - **Probe has two sensors, each generating an own signal in µA range, amplified to an output signal of 4-20 mA (resolution window adjustable)**
  - **Temperature settings at sensor surface will affect signal characteristics (CO & O_2 sensitivity)**



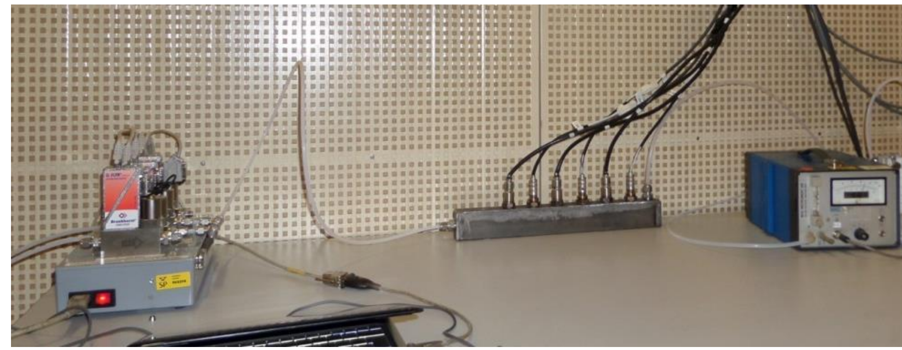
Note: MOSFET = Metal Oxide Semiconductor Field Effect Transistor

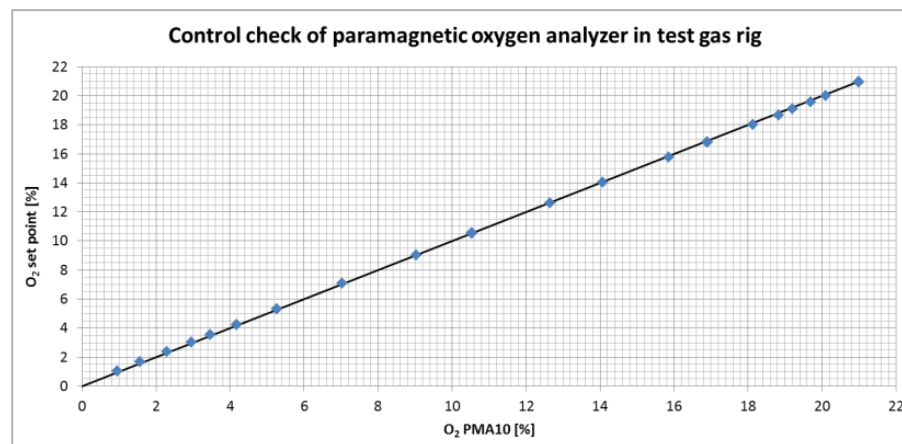
Sensor evaluation at RISE
Procedure

- **Initial check of lambda probes in test gas rig**
  - **Determination of signal characteristics**
- **1st evaluation period**
  - **About 300h stove operation, mainly according to instructions (33 test days, 259 batches, bark free birch wood with moisture content 10-25%)**
  - **Constant logging of sensor signals and recurring comparative measurement campaigns with standard gas analyzers**
- **Intermediate control check of lambda probes in test gas rig**
- **2nd evaluation period**
  - **About 250h stove operation, mainly according to instructions (26 test days, 211 batches, birch wood with bark, moisture content 10-25%)**
  - **Constant logging of sensor signals and recurring comparative measurement campaigns with standard gas analyzers**
- **Final control check of lambda probes in test gas rig**

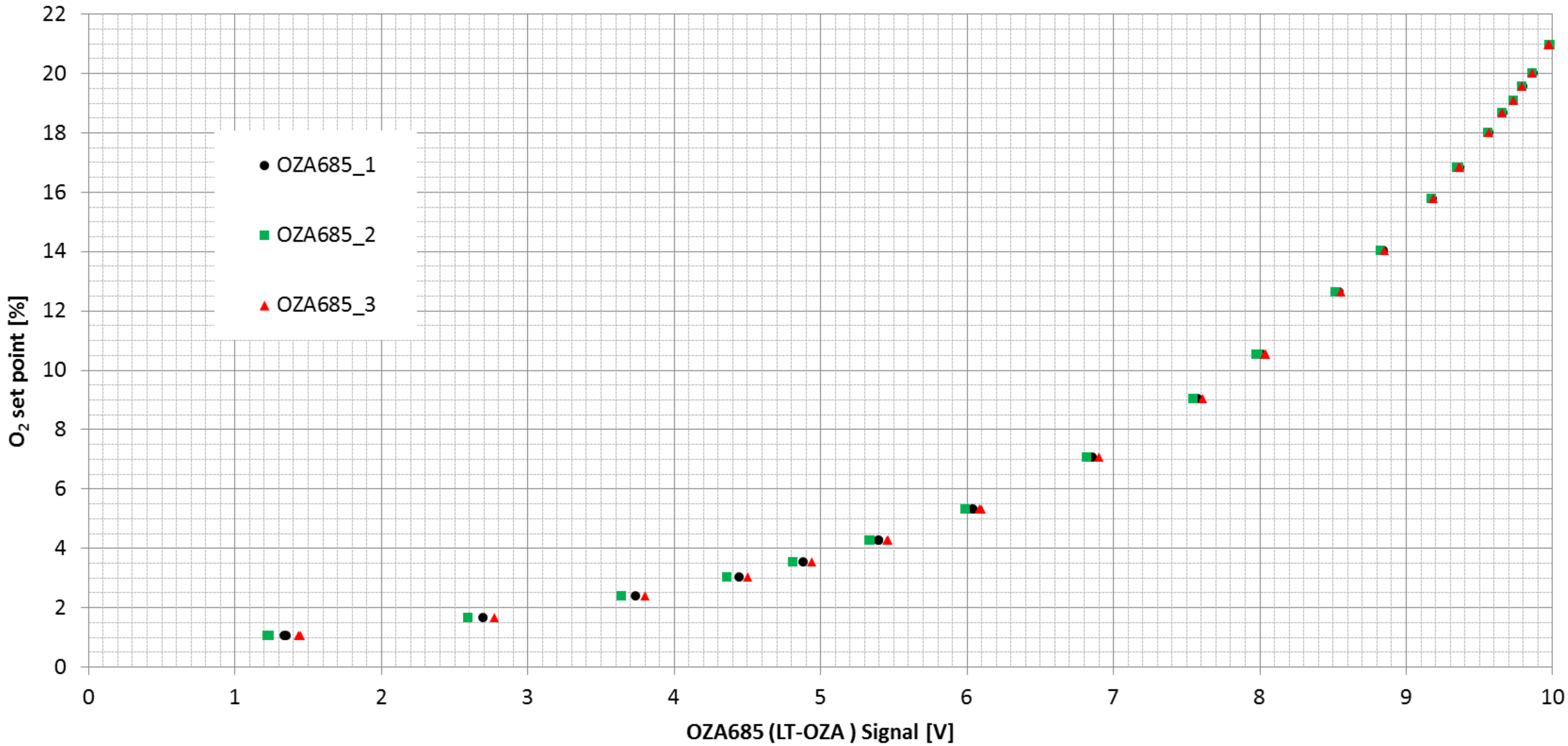
Sensor evaluation at RISE
Initial check in test gas rig

- Exposure to different oxygen levels by mixing compressed air with nitrogen
- Check probe signals for
  - Correlation to oxygen concentration
  - Stability
  - Repeatability
  - Response time
- Control of O_2 set points with paramagnetic oxygen analyzer (PMA10)



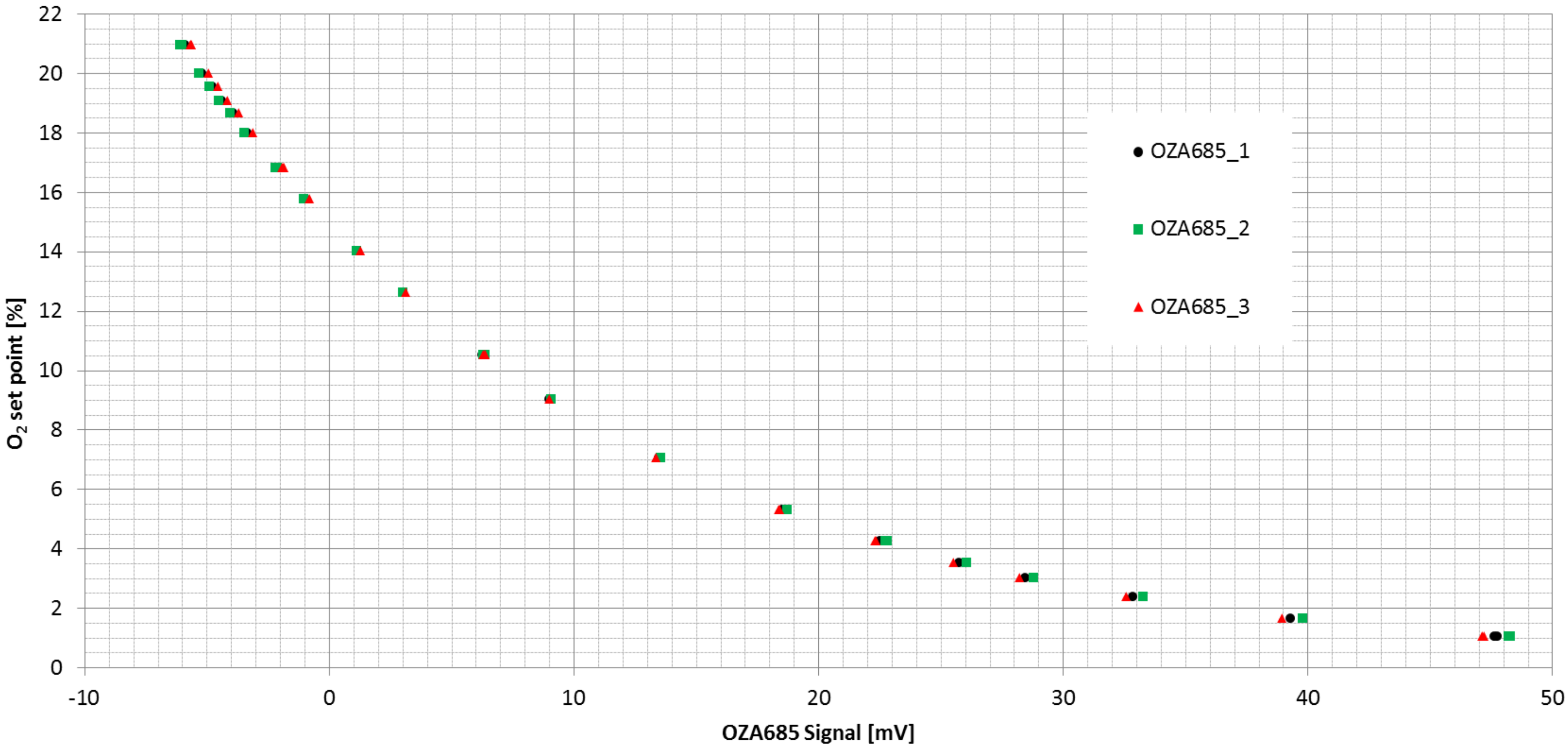


Sensor evaluation at RISE
OZA685-WW1 signal vs O_2 concentration (I)



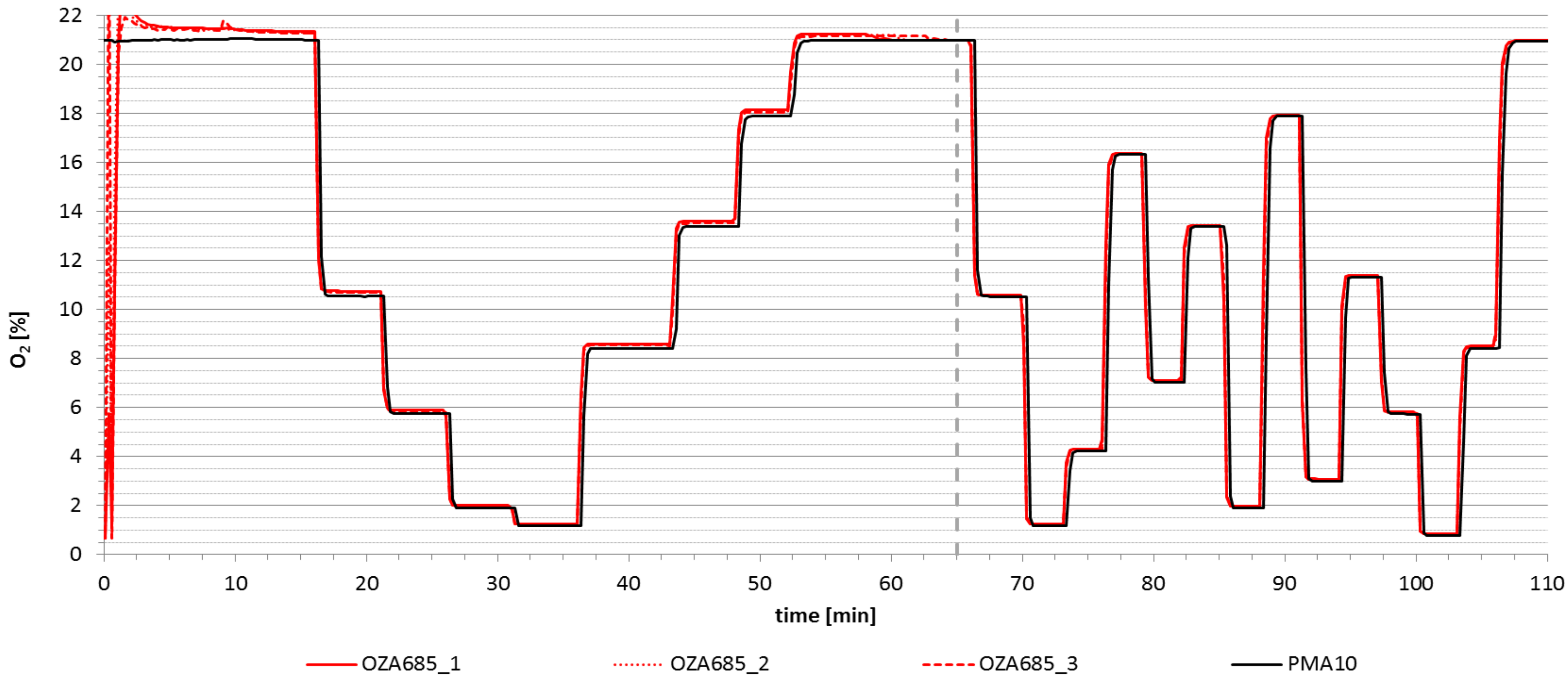
Notes:
- Feeding voltage 12V
- Sensor signal from Lambda transmitter (LT-OZA)

Sensor evaluation at RISE
OZA685-WW1 signal vs O_2 concentration (II)



Notes:
- Feeding voltage 12V
- Direct probe signals

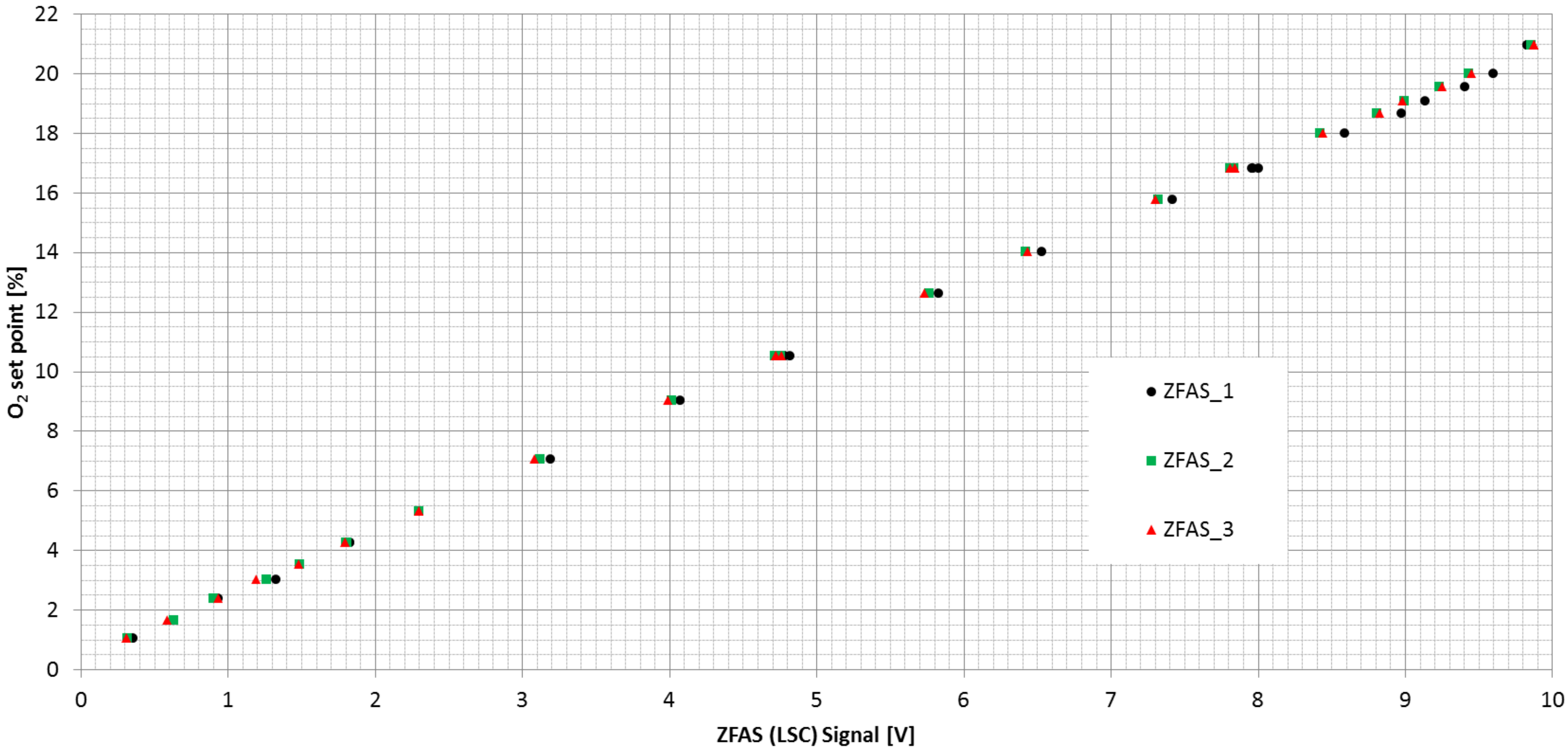
Sensor evaluation at RISE
Initial check OZA685-WW1



Notes:

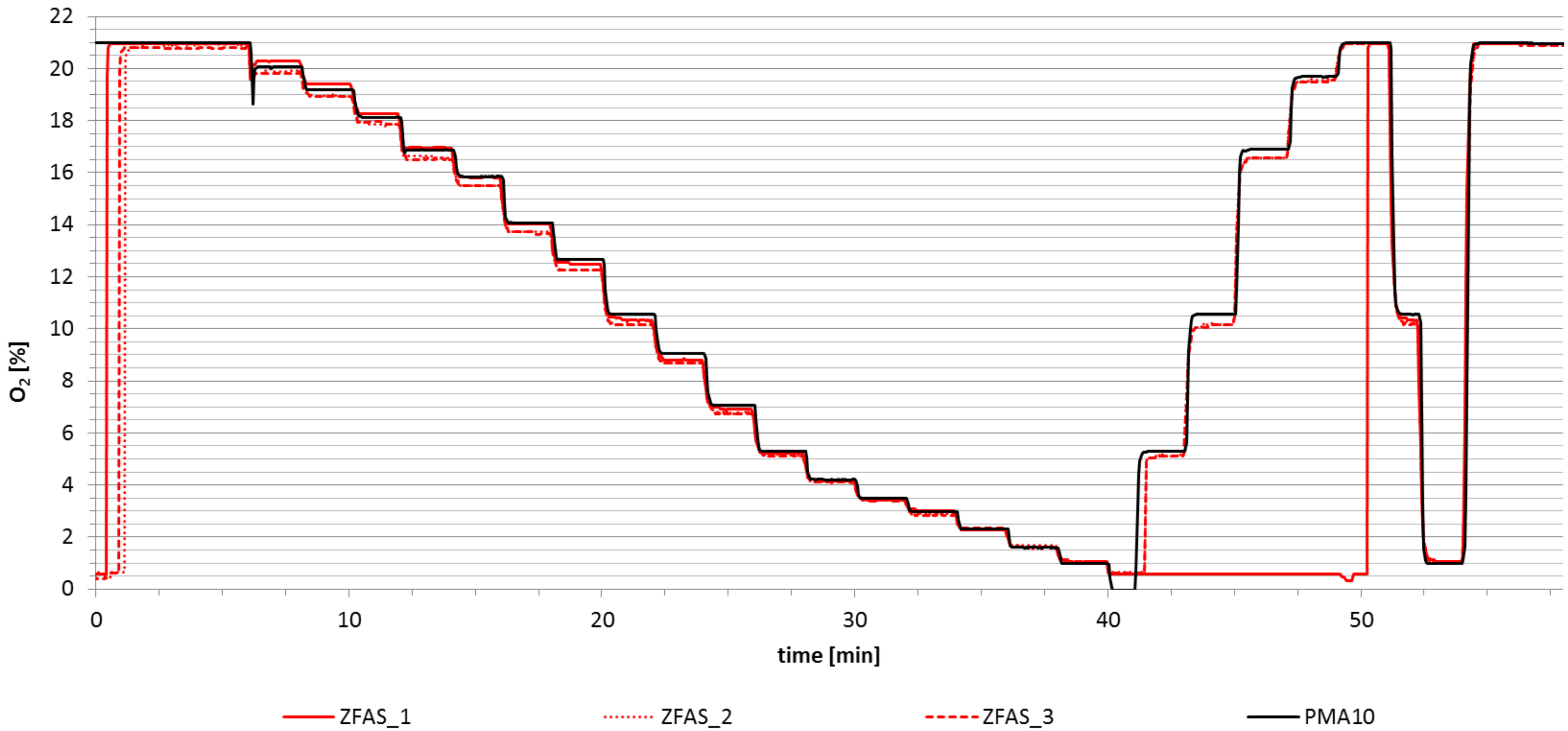
- Probes unused; Feeding voltage 12V
- Start of control check ca. 15 min after power on
- Paramagnetic oxygen analyzer values as comparison (equal set points)
- Lambda transmitter signals adjusted to match air condition prior second phase of control check (unadjusted in first phase)

Sensor evaluation at RISE
ZFAS-U2 signal vs O_2 concentration



Notes:
- Feeding voltage 12V
- Sensor signal from Lambda system control (LSC)

Sensor evaluation at RISE
Initial check ZFAS-U2



Notes:
- Probes unused; Feeding voltage 12V
- Start of control check ca. 5 min after power on
- Paramagnetic oxygen analyzer values as comparison (equal set points)
- Probe ZFAS_1 went to failure mode at zero oxygen, fixed with restart

Sensor evaluation at RISE
Conclusions initial check

- **OZA685-WW1 (switching type probe)**
  - **Similar signals for all three probes**
  - **Exponential correlation between probe signal and O_2**
  - **Transmitter Signal (LT-OZA) adjustable, provide calibration possibility**
  - **Stable & repeatable signals**
  - **Fast response to changes in oxygen**

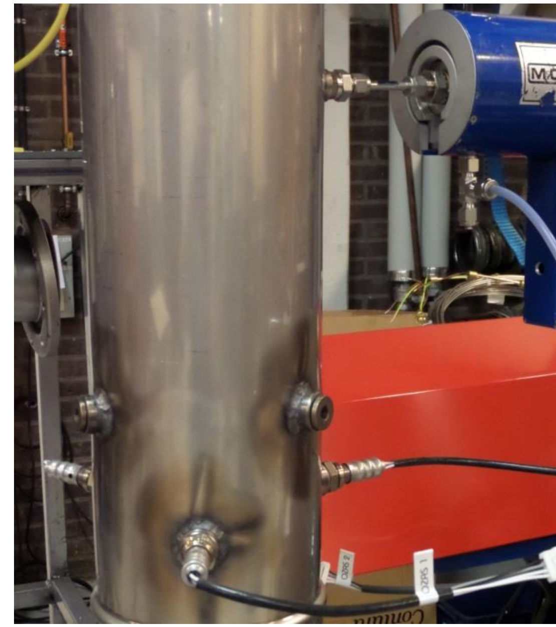
- **ZFAS-U2 (broadband probe)**
  - **Similar signals for all three probes**
  - **Linear correlation between probe signal and O_2**
  - **Stable & repeatable signals**
  - **Fast response to changes in oxygen**

Sensor evaluation at RISE
Test stand 1st evaluation period (I)

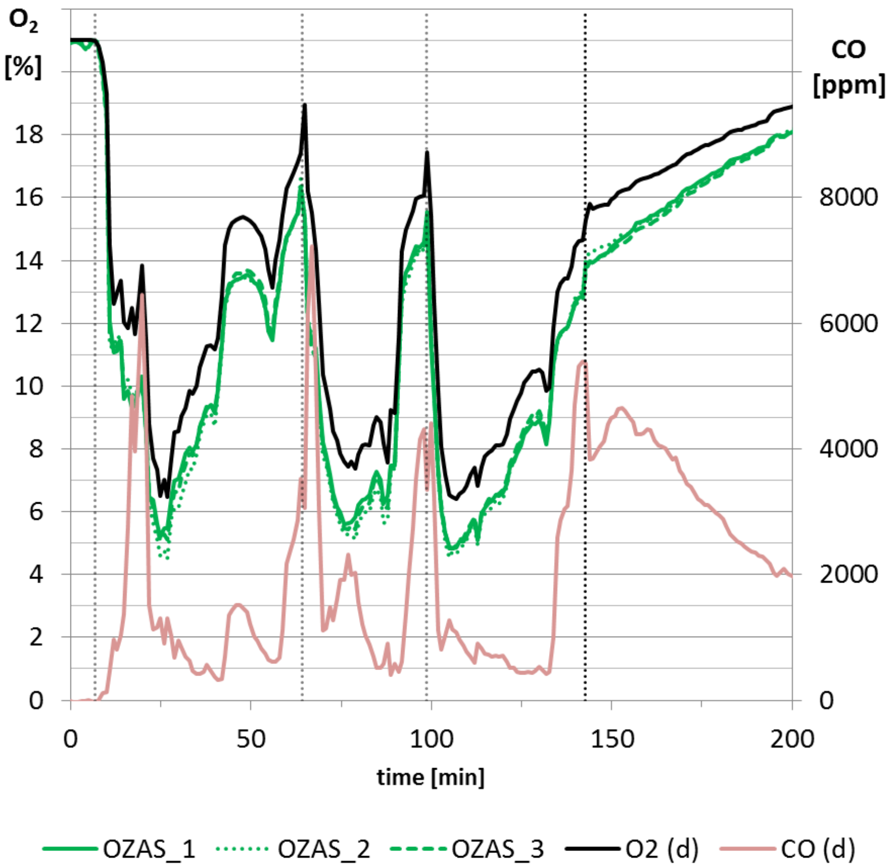
- **Stove**
  - **Contura 556**
- **Sensor placement**
  - **Lambda probes placed evenly around in flue in two levels (OZA685-WW1 on lower level)**
  - **Sensic probe in upper part of flue**
- **Sensor signals**
  - **Start 1st Sensic sensor (SenSic_2) on day 2**
  - **Start logging direct OZA685-WW1 probe signals on day 7**
  - **Start ZFAS probes on day 21**

Sensor evaluation at RISE
Test stand 1st evaluation period (II)

- **Standard gas analysis**
  - **Sampling position directly above lambda probes**
  - **Sampling probe according to EN13240 (average sampling)**
- **Gas analyzers**
  - **M&C PMA 10 (paramagnetic oxygen analyzer)**
  - **Emerson NDIR analyzer X-Stream XEGC (CO, CO_2)**
  - **JUM FID 3-300A (hydrocarbons)**
  - **FTIR Gas Analyzer BOMEM 9100 (CO, CO_2, H_2O, various hydrocarbons)**



Sensor evaluation at RISE
1st evaluation period Day 1



	Batch		Ignition	2	3
Gas Analyzers	CO_2	%	7,4	9,2	10,3
	O_2	%	12,9	11,1	10,0
	CO at 13% O_2	mg/m^3_N	1718	2096	1374
	$O_{2,w}$ (EN13240)	%	11,9	10,1	9,0
O_2 OZA685	OZA685_1	%	11,1	9,2	8,2
	OZA685_2	%	10,9	8,8	8,2
	OZA685_3	%	11,1	9,0	8,3

Notes:
- Analyzers used: PMA10, X-Stream XEGC
- Consider also for comparison: different sampling locations, cross sensitivities for probes & analyzer, different gas condition (dried gas for standard analyzer)

Sensor evaluation at RISE
1st evaluation period Day 2

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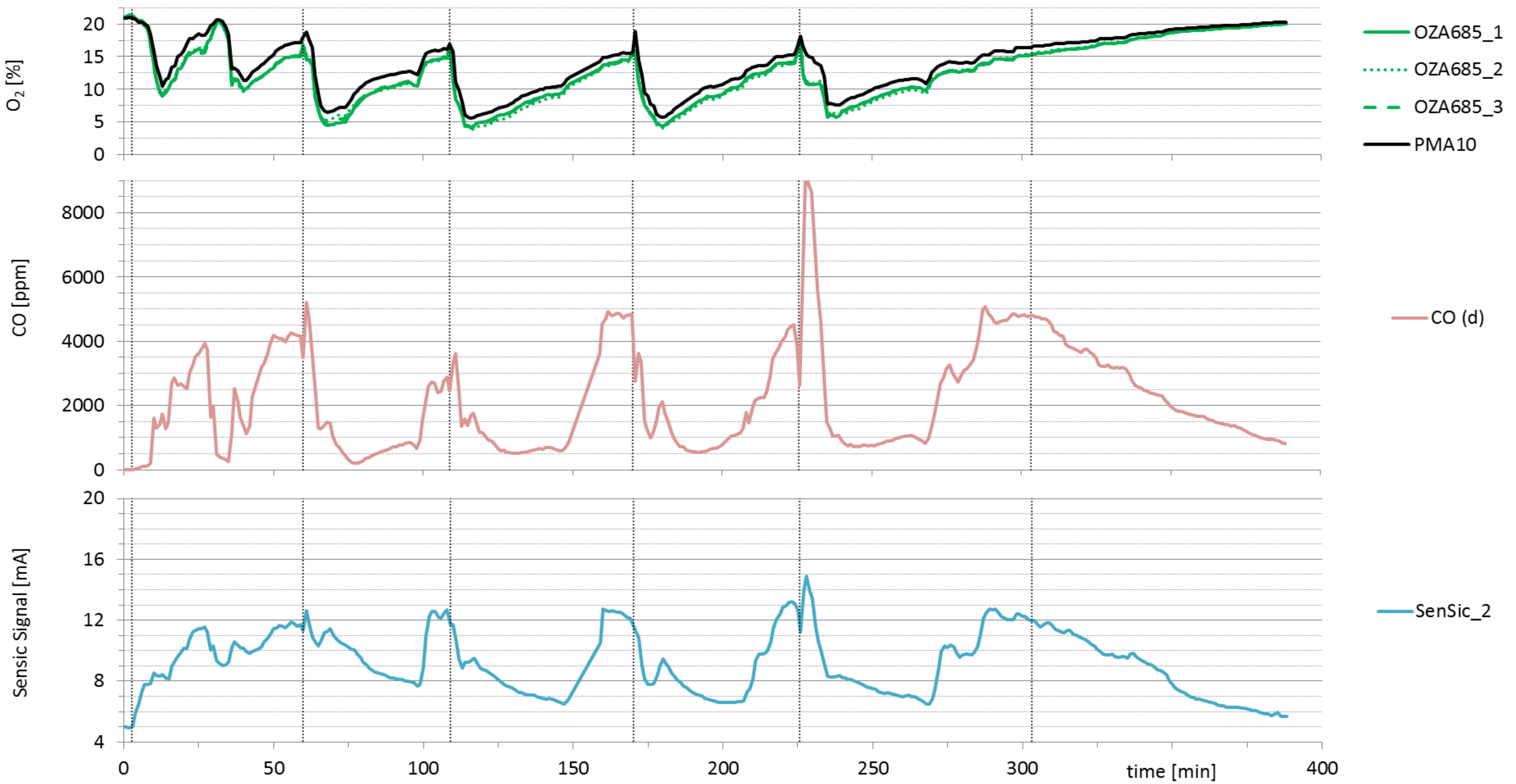
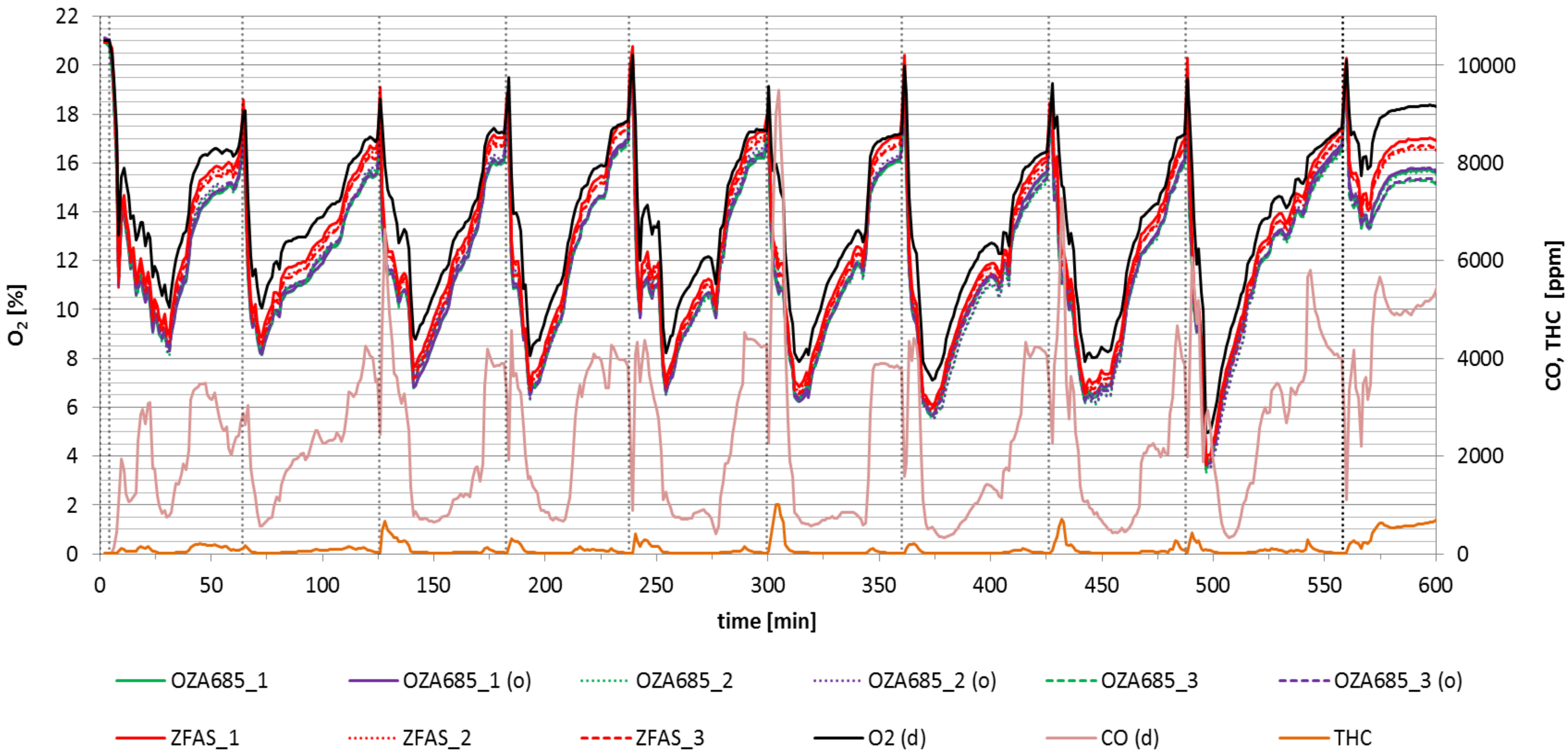


Notes:
- Analyzers used: PMA10, X-Stream XEGC
- Sensor SenSic_2 operated at 200°C
- Consider also for comparison: different sampling locations, cross sensitivities for probes & analyzer, different gas condition (dried gas for standard analyzer)

Sensor evaluation at RISE
1st evaluation period Day 26 (I)



Notes:
- Analyzers used: PMA10, X-Stream XEGC, FID
- Consider also for comparison: different sampling locations, cross sensitivities for probes & analyzer, different gas condition (dried gas for standard analyzer)

Sensor evaluation at RISE
1st evaluation period Day 26 (II)

	Batch		Ignition	2	3	4	5	6	7	8	9
Gas Analyzers	CO_2	%	5,9	6,4	6,9	6,8	6,9	7,3	7,9	7,8	7,2
	O_2	%	14,6	13,9	13,5	13,6	13,5	13,0	12,4	12,6	13,1
	CO at 13% O_2	mg/m^3_N	3190	3191	2957	3505	3025	3000	2247	2473	3697
	OGC at 13% O_2	mg/m^3_N	193	123	198	127	124	191	64	154	124
	$O_{2,w}$ (EN13240)	%	13,7	13,0	12,5	12,7	12,6	12,1	11,4	11,6	12,1
O_2 OZA685	OZA685_1	%	12,7	12,0	11,5	12,0	11,8	11,2	10,9	10,8	11,6
	OZA685_1 (o)	%	12,7	12,1	11,6	12,0	11,8	11,2	11,0	10,9	11,7
	OZA685_2	%	12,8	12,2	11,8	12,0	11,9	11,3	10,6	10,8	11,4
	OZA685_2 (o)	%	12,9	12,3	11,9	12,1	12,0	11,4	10,7	10,9	11,4
	OZA685_3	%	12,7	12,1	11,7	12,0	11,8	11,3	10,8	10,8	11,5
	OZA685_3 (o)	%	12,8	12,2	11,7	12,0	11,9	11,3	10,8	10,8	11,5
O_2 ZFAS	ZFAS_1	%	13,5	13,0	12,4	12,7	12,6	12,0	11,5	11,6	12,2
	ZFAS_2	%	13,3	12,7	12,2	12,5	12,4	11,8	11,1	11,3	11,9
	ZFAS_3	%	13,2	12,6	12,1	12,5	12,3	11,7	11,3	11,3	12,0

Notes:
- Time average values for single batches
- Oxygen level in wet gas calculated according to EN13240 using wood moisture & hydrogen content

Sensor evaluation at RISE
1st evaluation period Day 26 (III)

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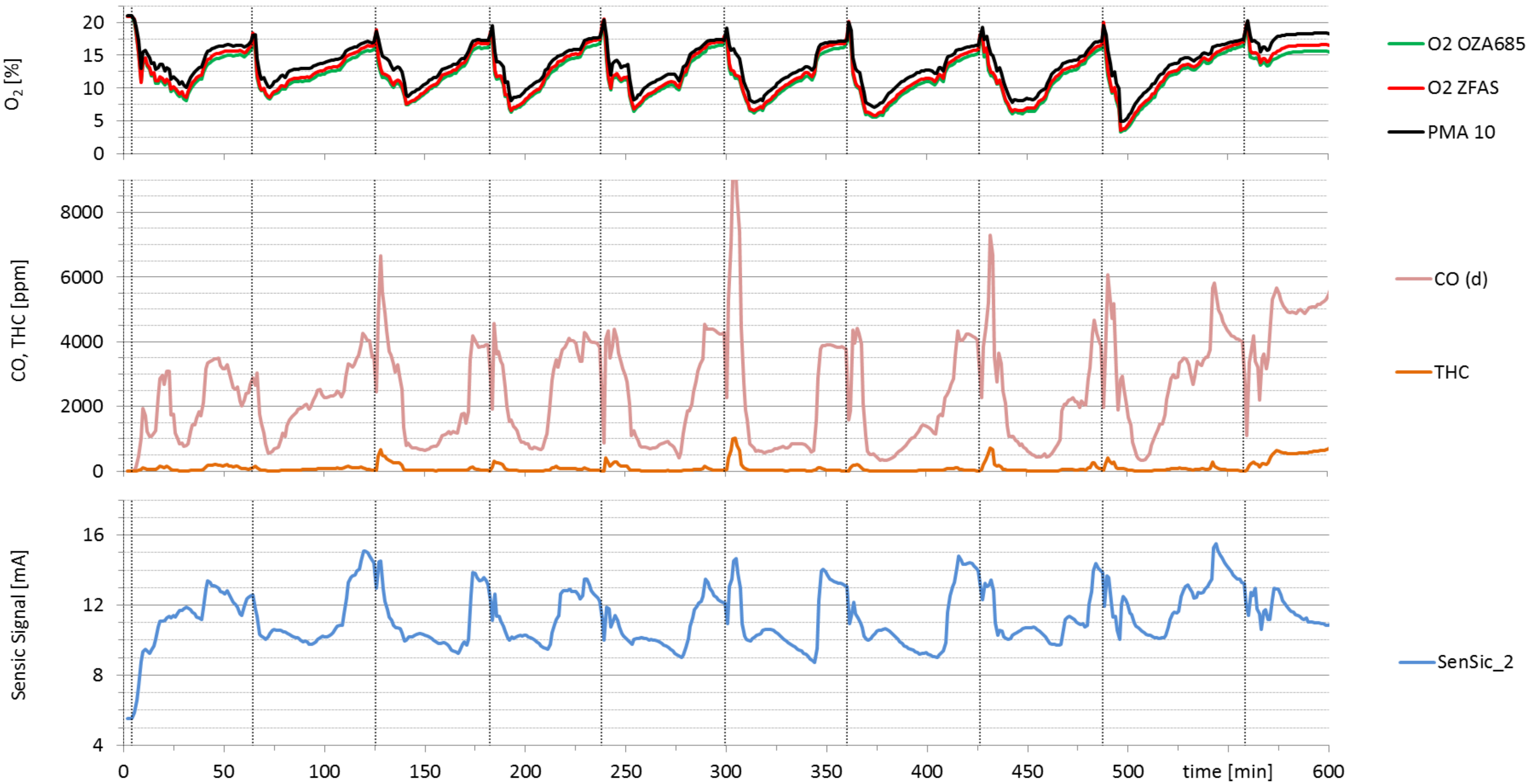


Notes:
- Analyzers used: PMA10, X-Stream XEGC, FID
- Sensor SenSic_2 operated at 200°C
- Consider also for comparison: different sampling locations, cross sensitivities for probes & analyzer, different gas condition (dried gas for standard analyzer)

Sensor evaluation at RISE
End of 1st evaluation period

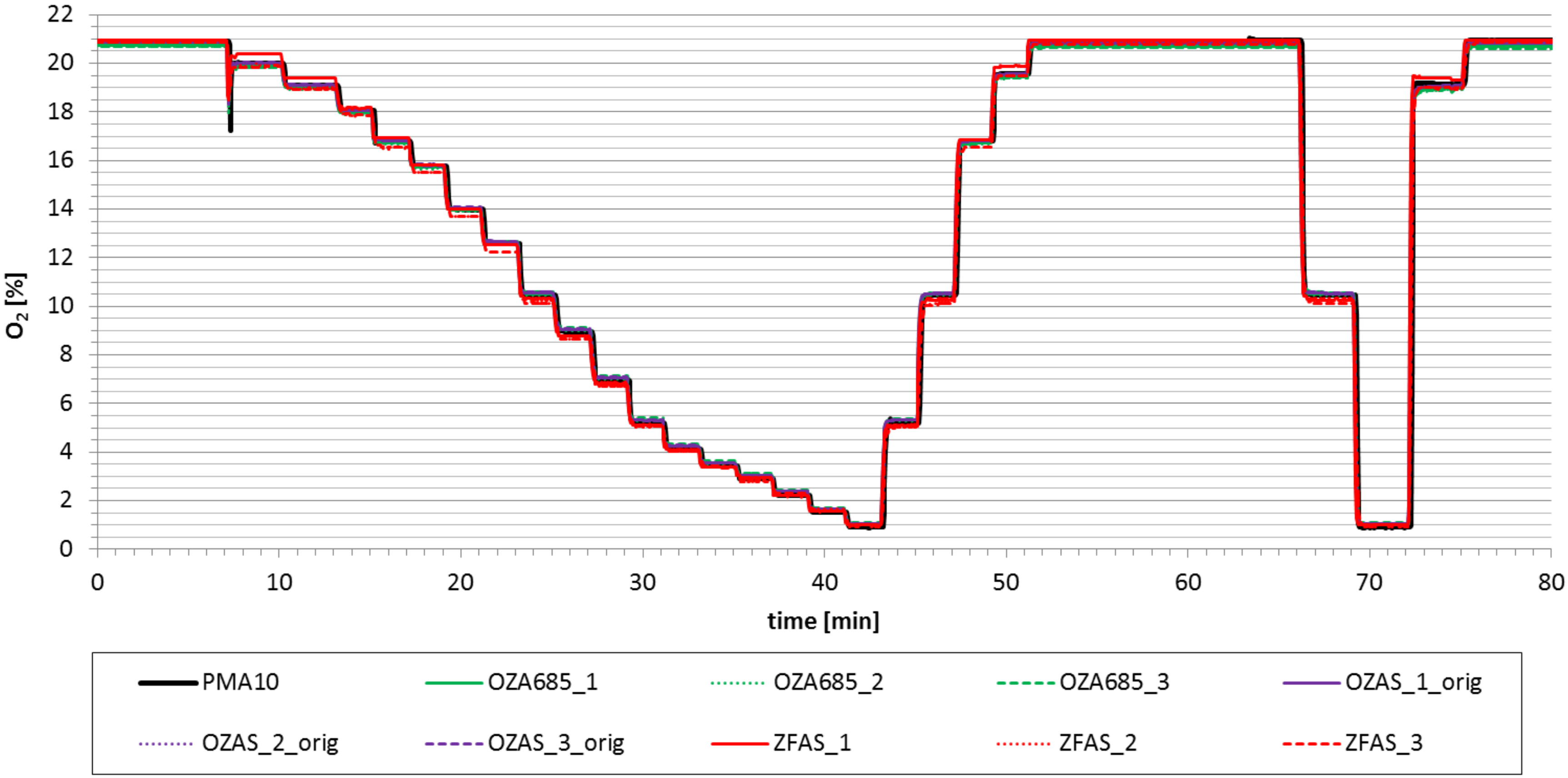
Lambda probe condition at end of 1st evaluation period






Notes:
- OZA685-WW1 in operation for 300h, ZFAS-U2 for 130h due to later start
- Loose, non-sticking deposit on probes, easy to remove

Sensor evaluation at RISE
Intermediate control check in test gas rig



Notes:
- Probes uncleaned; Feeding voltage 12V
- Start of control check ca. 1h after power on
- Lambda transmitter signals (switching type probe) not adjusted for control check
- Paramagnetic oxygen analyzer values as comparison (equal set points)
- Control check with cleaned probes gave same results

Sensor evaluation at RISE
Test stand 2nd evaluation period

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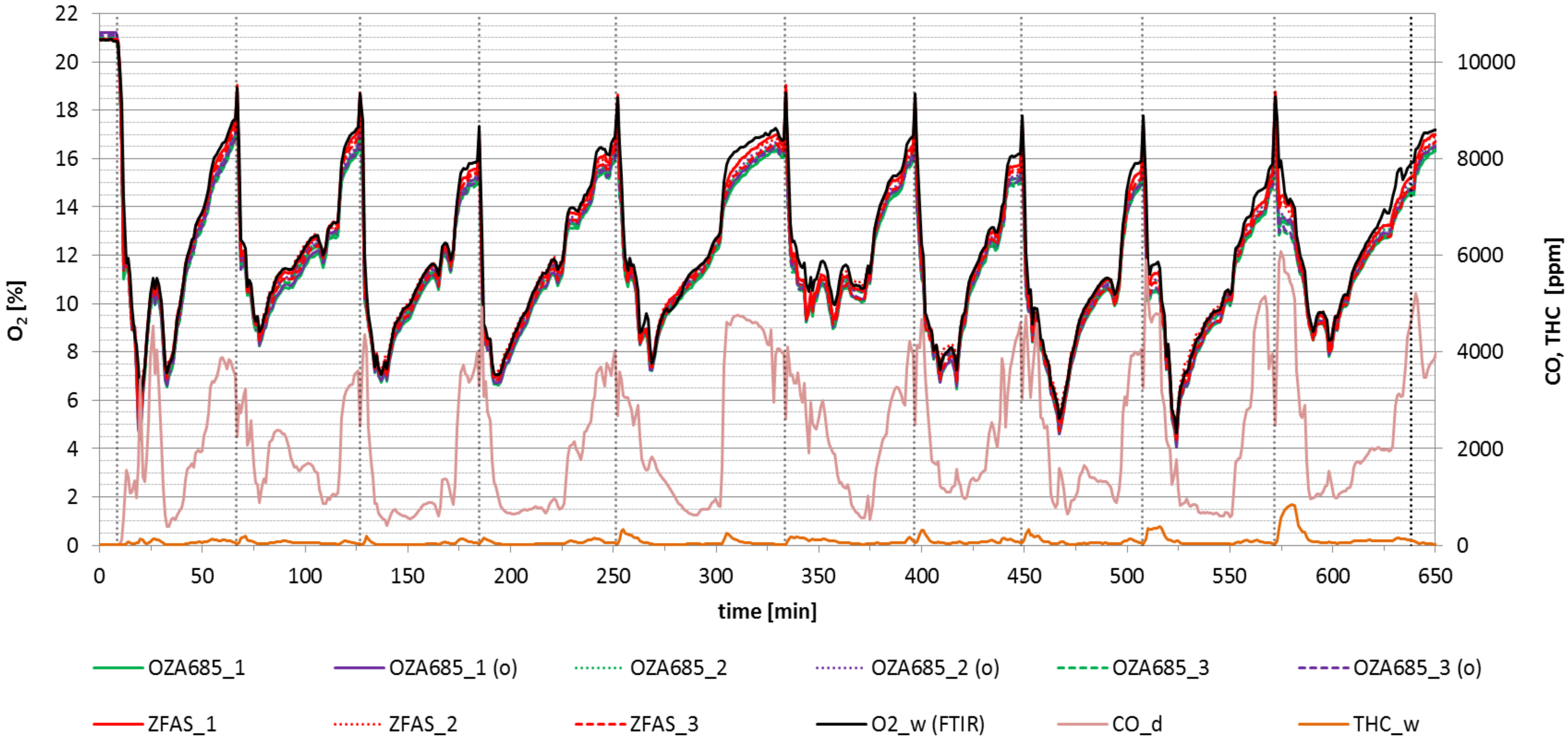
Sensor placement

- **Lambda probes placed evenly around in flue in two levels (OZA685-WW1 on upper level)**
- **SenSic probes in upper part of flue**

Sensor signals

- **Constant logging of all sensor signals during whole period**

Sensor evaluation at RISE
2nd evaluation period Day 50 (I)



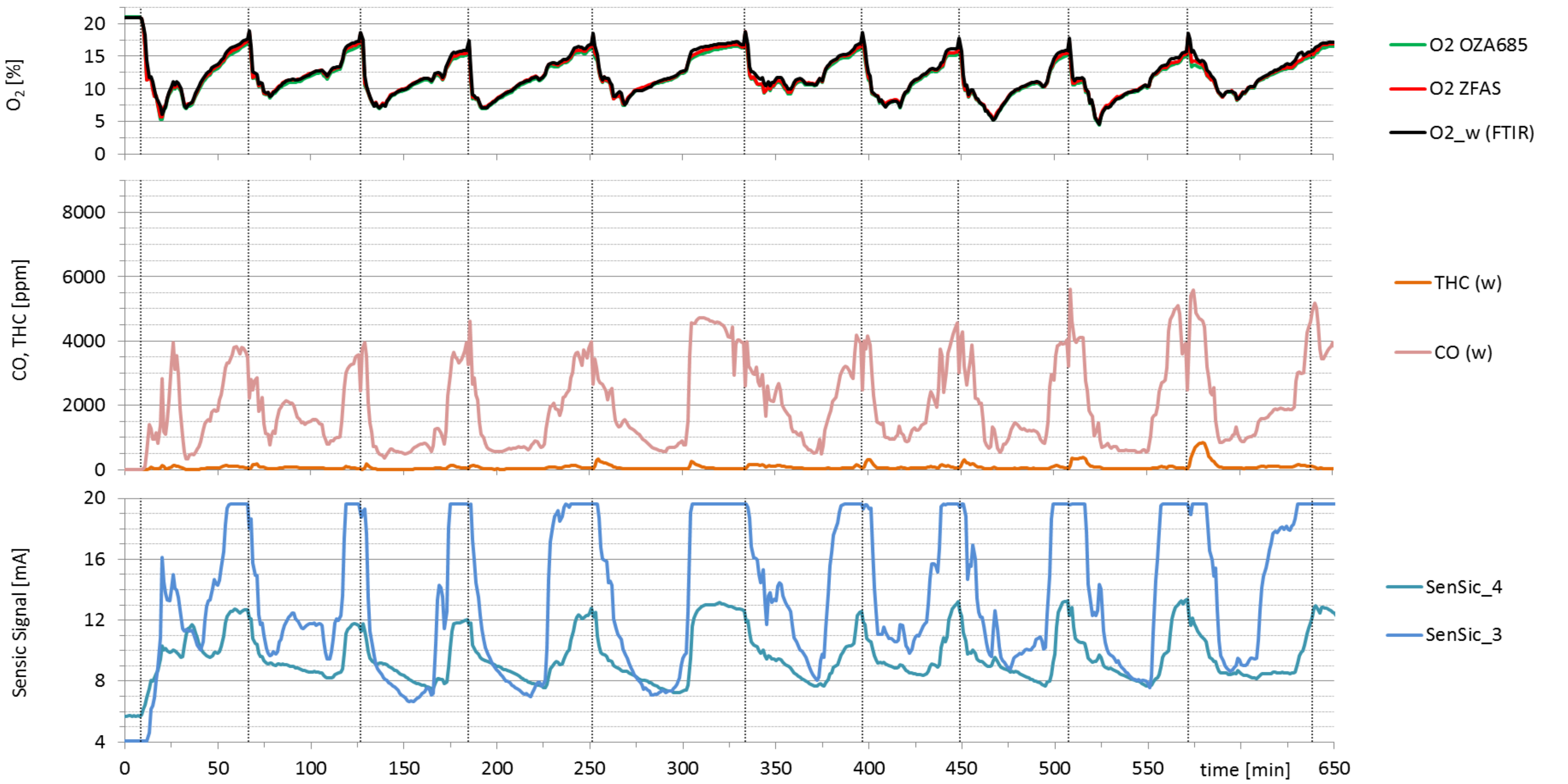
Notes:
- Analyzers used: PMA10, X-Stream XEGC, FTIR
- O2_w (FTIR) calculated by using O_2 (d) from oxygen analyzer and H_2O values from FTIR
- Consider also for comparison: different sampling locations, cross sensitivities for probes & analyzer, different gas condition (dried gas for standard analyzer)

Sensor evaluation at RISE
2nd evaluation period Day 50 (II)

	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

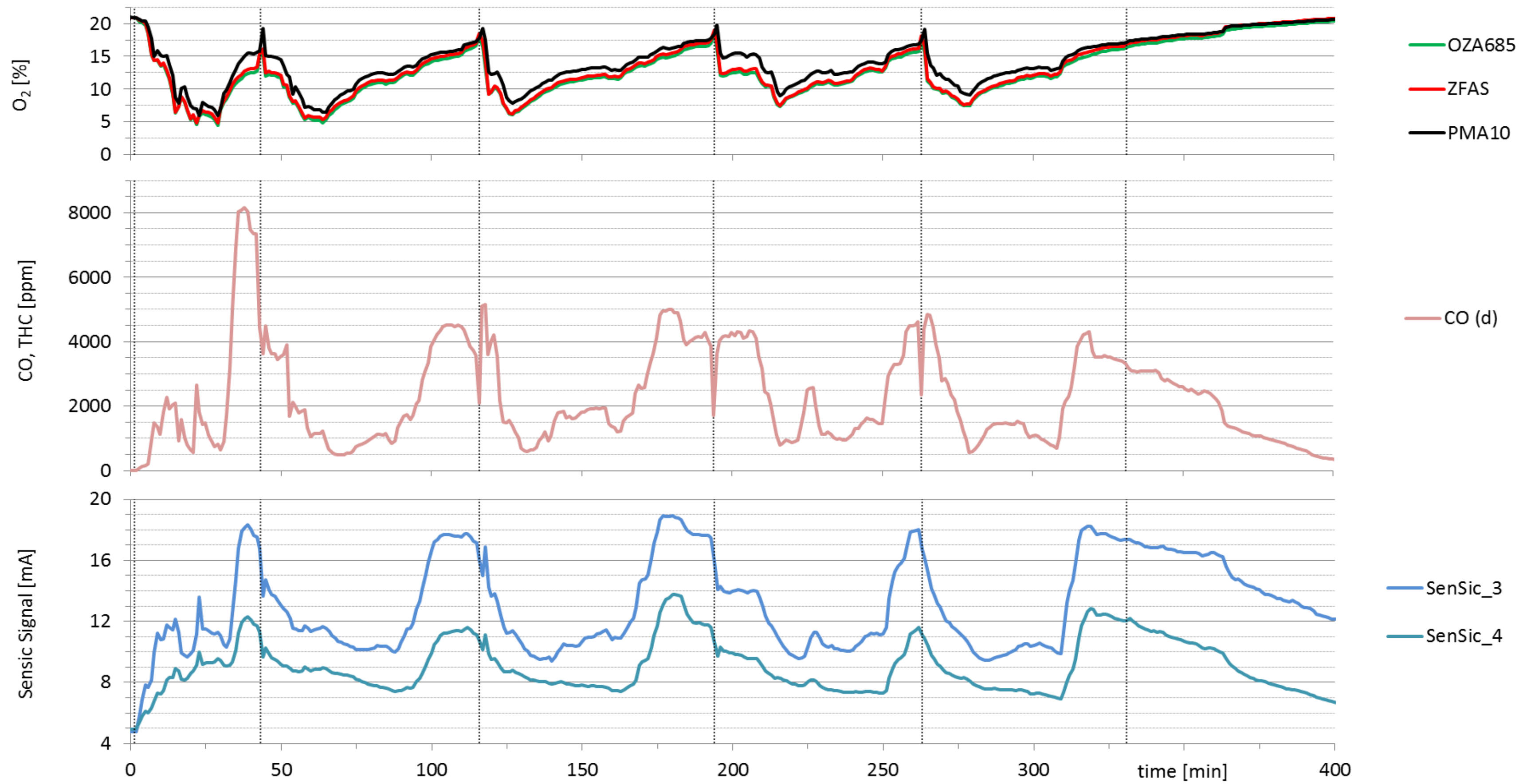
Notes:
- Time average values for single batches
- $O_{2,w}$ (EN13240) calculated according to EN13240 using wood moisture & hydrogen content
- $O_{2,w}$ (FTIR) calculated by using O_2(d) from oxygen analyzer H_2O values from FTIR

Sensor evaluation at RISE
2nd evaluation period Day 50 (III)



Notes:
- Analyzers used: PMA10, X-stream, FTIR
- O2_w (FTIR) calculated by using O_2 (d) from oxygen analyzer and H_2O values from FTIR
- Sensor SenSic_4 operated at 200°C; SenSic_3 at 250°C, SenSic_3 output signal window set too narrow
- Consider also for comparison: different sampling locations, cross sensitivities for probes & analyzer, different gas condition (dried gas for standard analyzer)

Sensor evaluation at RISE
2nd evaluation period Day 59



Notes:
- Analyzers used: PMA10, X-stream
- 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)

Sensor evaluation at RISE
End of 2nd evaluation period

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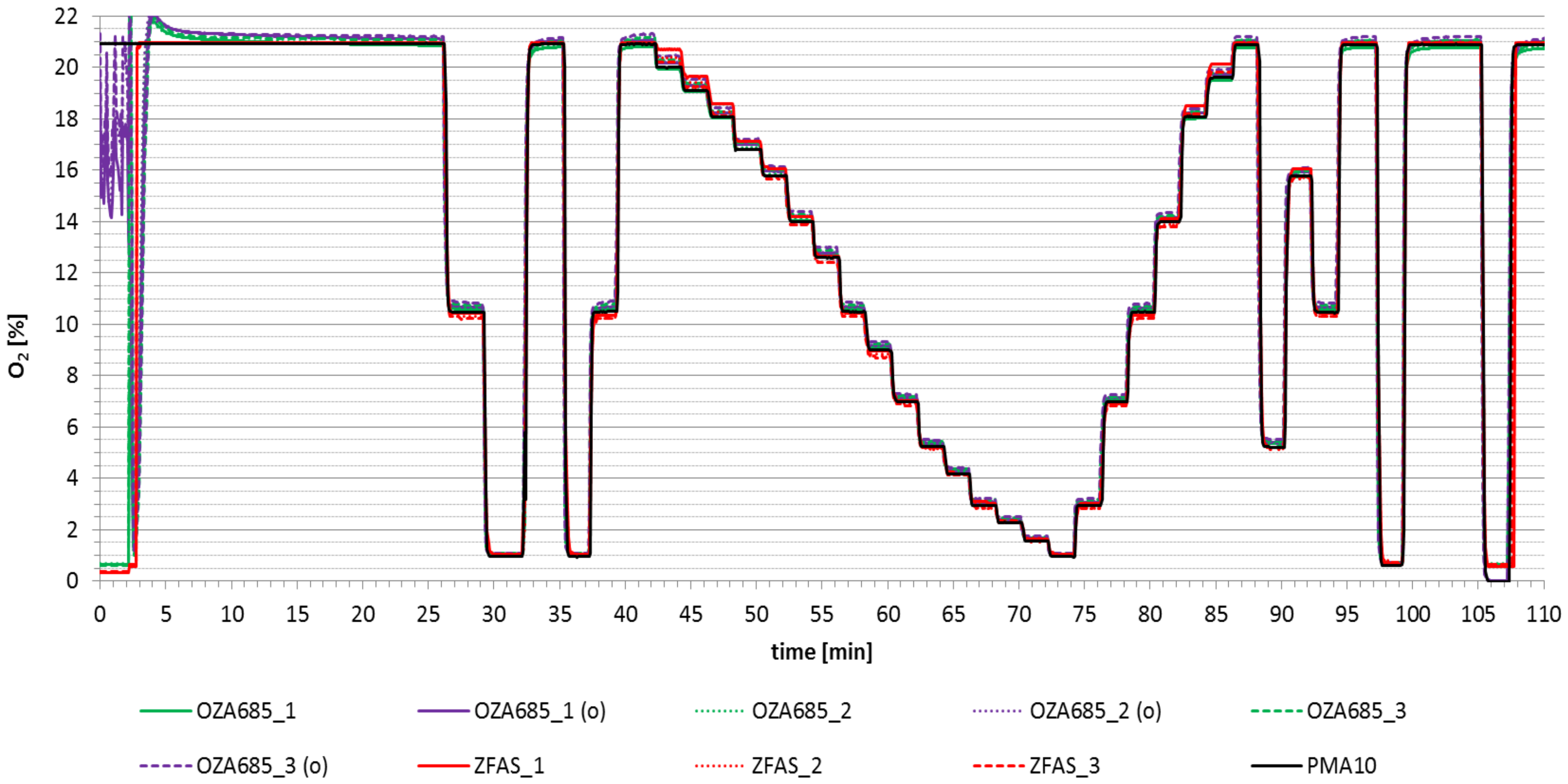
Probe condition at end of 2nd evaluation period

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

Sensor evaluation at RISE
Final control check in test gas rig



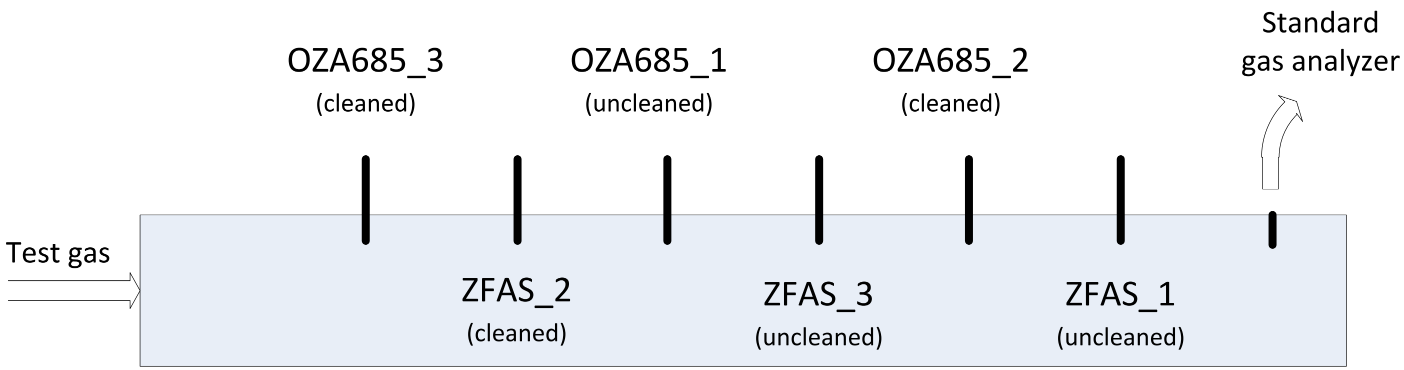
Notes: Probes uncleaned; Feeding voltage 12V
Start of control check ca. 25 min after power on
Lambda transmitter signals (switching type probe) not adjusted
Paramagnetic oxygen analyzer values as comparison (equal set points)

Sensor evaluation at RISE
Lambda probes cross sensitivity check (I)

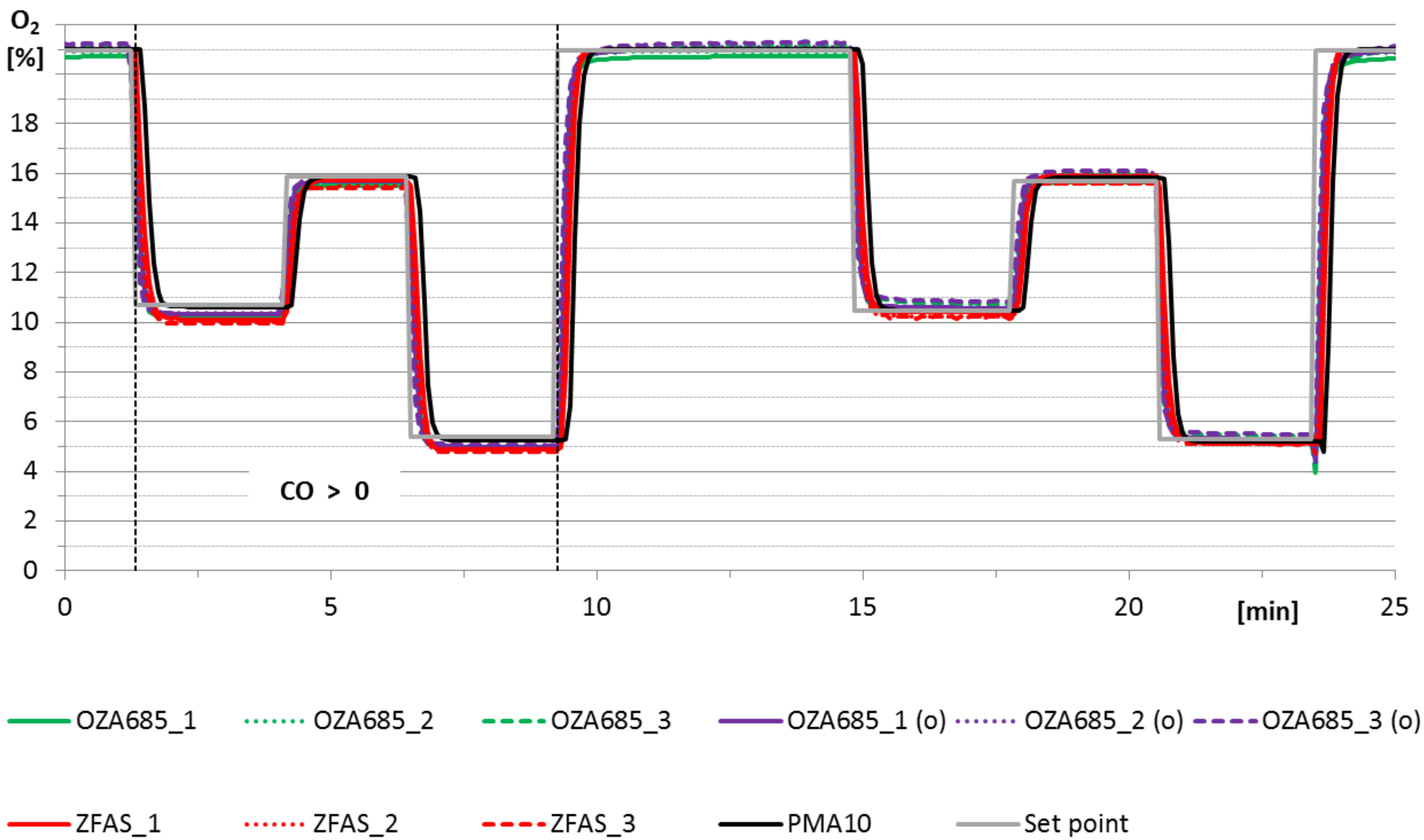
Test condition for cross sensitivity check

- **At end of evaluation period, after final control check**
- **Test gas rig used**
- **Lambda probes exposed to various oxygen levels by mixing compressed air with nitrogen with addition of carbon monoxide, methane and propane**
- **Paramagnetic oxygen analyzer as comparison & control**

Placement & condition of probes

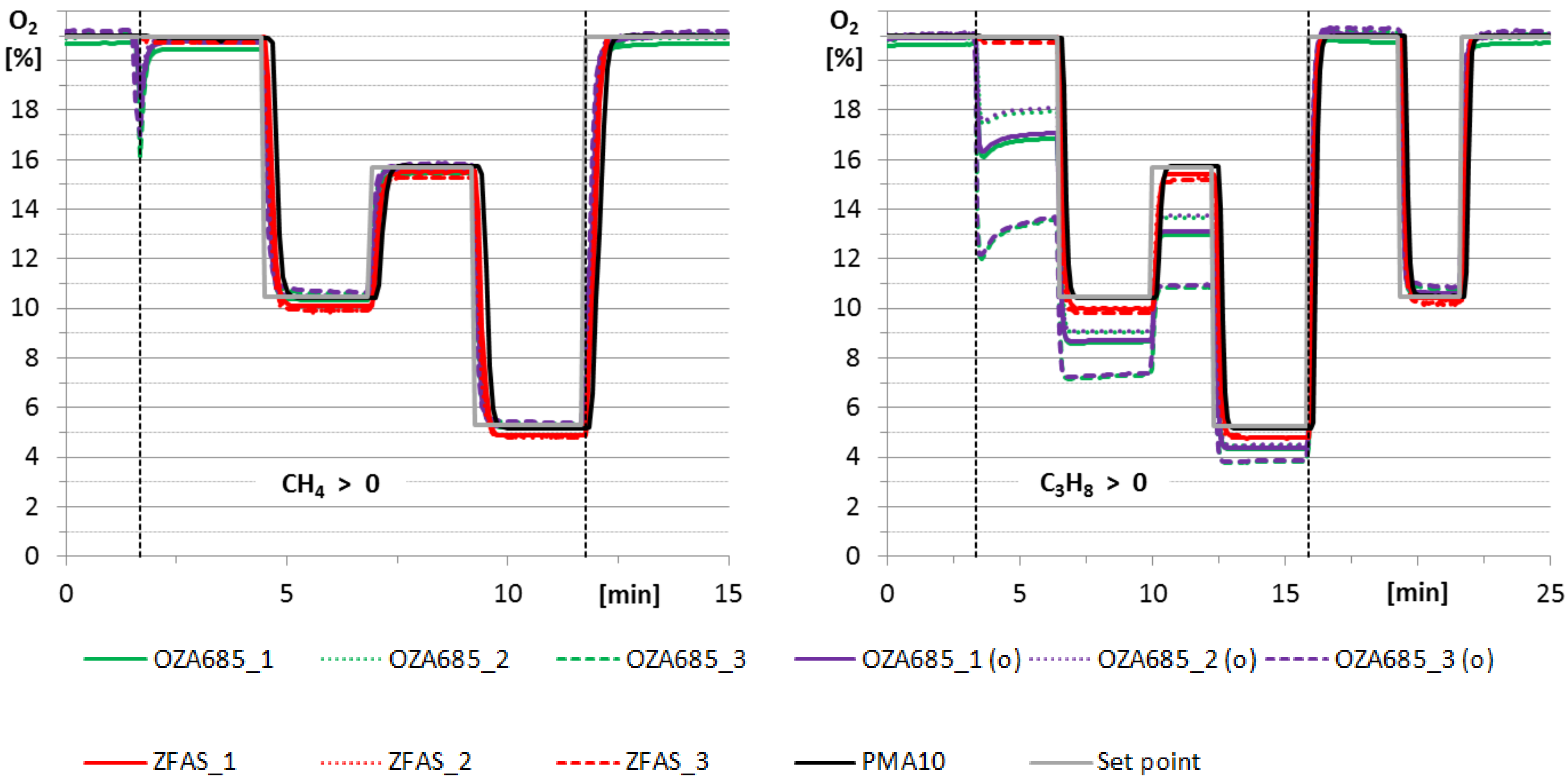


Sensor evaluation at RISE
Lambda probes cross sensitivity check (II)



Notes: Feeding voltage 12V
Carbon monoxide levels 8000/4000/8000 ppm

Sensor evaluation at RISE
Lambda probes cross sensitivity check (III)

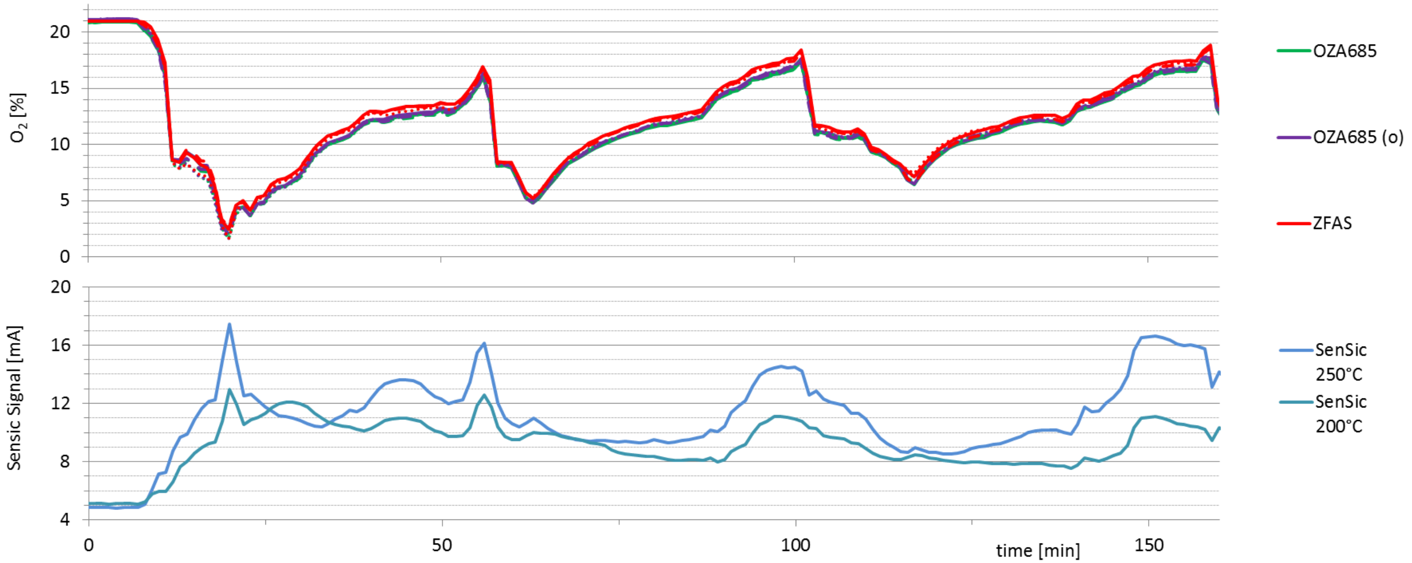


Notes: Feeding voltage 12V
Methane level 1000 ppm; propane level 1000 ppm;
Consider probe position for evaluation (OZA685_3, ZFAS_2, OZA685_1, ZFAS_3, OZA685_2, ZFAS_1)

Sensor evaluation at RISE
Results & Conclusions (I)

Overall

- All probes with fast and reproducible response to gas concentrations changes
- Reliable determination of current combustion condition only based on sensor signals at all times during whole evaluation period



Sensor evaluation at RISE
Results & Conclusions (II)

Lambda probes

- **O_2 detection**
  - **Highly accurate determination of O_2 concentration within the whole oxygen range when comparing probe signals with set point values in test gas rig**
  - **Only minor deviation comparing probe O_2 values during stove operation with values from standard analyzer, with Broadband type ZFAS-U2 slightly more accurate than switching type OZA685-WW1**
  - **Deviation during stove operation mainly due to cross sensitivities to hydrocarbons & carbon monoxide (see deviation especially at start/end of batches & other phases with high HC/CO emissions as well as cross sensitivity check)**
- **Long term durability**
  - **No aging effect observed during long term evaluation**

Sensor evaluation at RISE
Results & Conclusions (III)

Lambda probes

- **Long term durability (cont.)**
  - **Probe signal characteristics at end of evaluation period unchanged compared to unused probes**
  - **Particle deposit during evaluation period did not affect probe functionality**
- **Conclusion**
  - **Both types suitable for automatic control systems**
  - **Broadband type ZFAS-U2 with slight advantage in O_2 determination accuracy (mainly at existence of high concentration of HC/CO)**
  - **Switching type with advantage in cost and simplicity of implementation (especially with possibility to use probe directly without any additional evaluation electronics)**

Sensor evaluation at RISE
Results & Conclusions (IV)

SenSic CO/O_2 sensor

- **CO/O_2 detection**
  - **Reliable detection of CO gradients & overall CO magnitudes (allow e.g. successful identification of batch ignition & start of char coal burn-out)**
  - **Significant impact of oxygen concentration on sensor signal complicates determination of specific CO concentration, especially at low CO ranges**
  - **Oxygen impact can be reduced by increasing sensor temperature (will also affect CO resolution capacity)**
  - **Combination of two sensors running at different temperatures could be used to improve CO concentration accuracy & enable O_2 determination**
- **Long term durability**
  - **Noticeable signal drift during first hours of sensor operation (possible to handle with electronics)**

Sensor evaluation at RISE
Results & Conclusions (V)

SenSic CO/O2 sensor

- **Long term durability (cont.)**
  - **No probe failure during operation, but some problems with single sensor channels (two sensors on one probe)**
  - **Improvable electronics**
    - One probe failure during re-placement (likely due to ground problems when reconnecting electronics to power)
    - Minimization of electronics unit for use in stove sector
- **Conclusions**
  - **Sensor usable for stove operation**
  - **But with current costs for sensor and electronics still too expensive for stoves in ordinary price range (especially when considering requirement of O_2 determination through second or external sensor)**

Sensor evaluation

BIOS

Methodology - Description of sensor tested (I)

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
  - Sensor output: O2: 4-20 mA; COe: 4-20 mA
- **Development state & price**
  - Developed
  - Single unit: 100-200 € (sensor) / 600-1.000 € (sensor + converter)

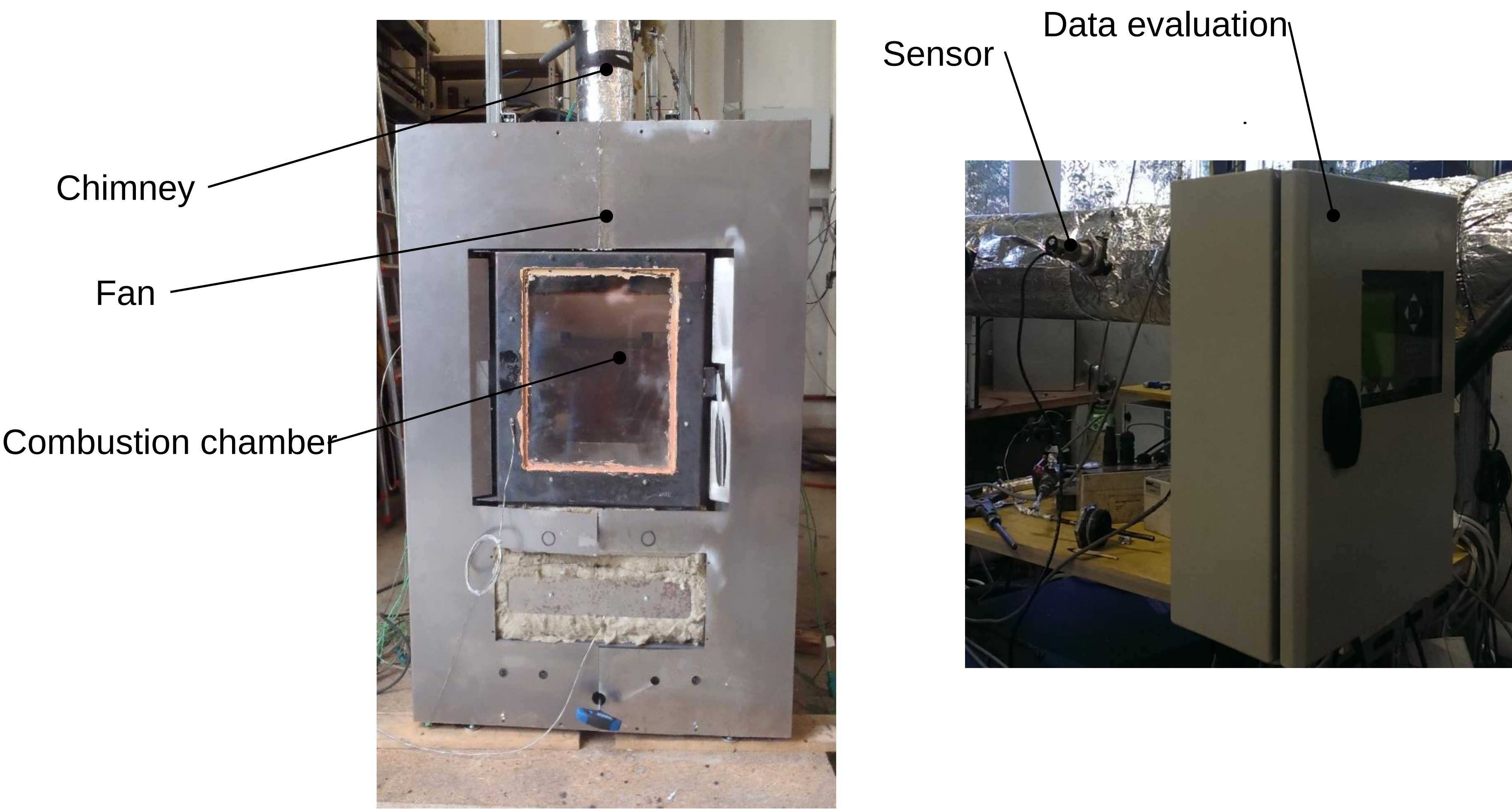
Methodology - Description of sensor tested (II)

Combination probe KS1D (Lamtec)

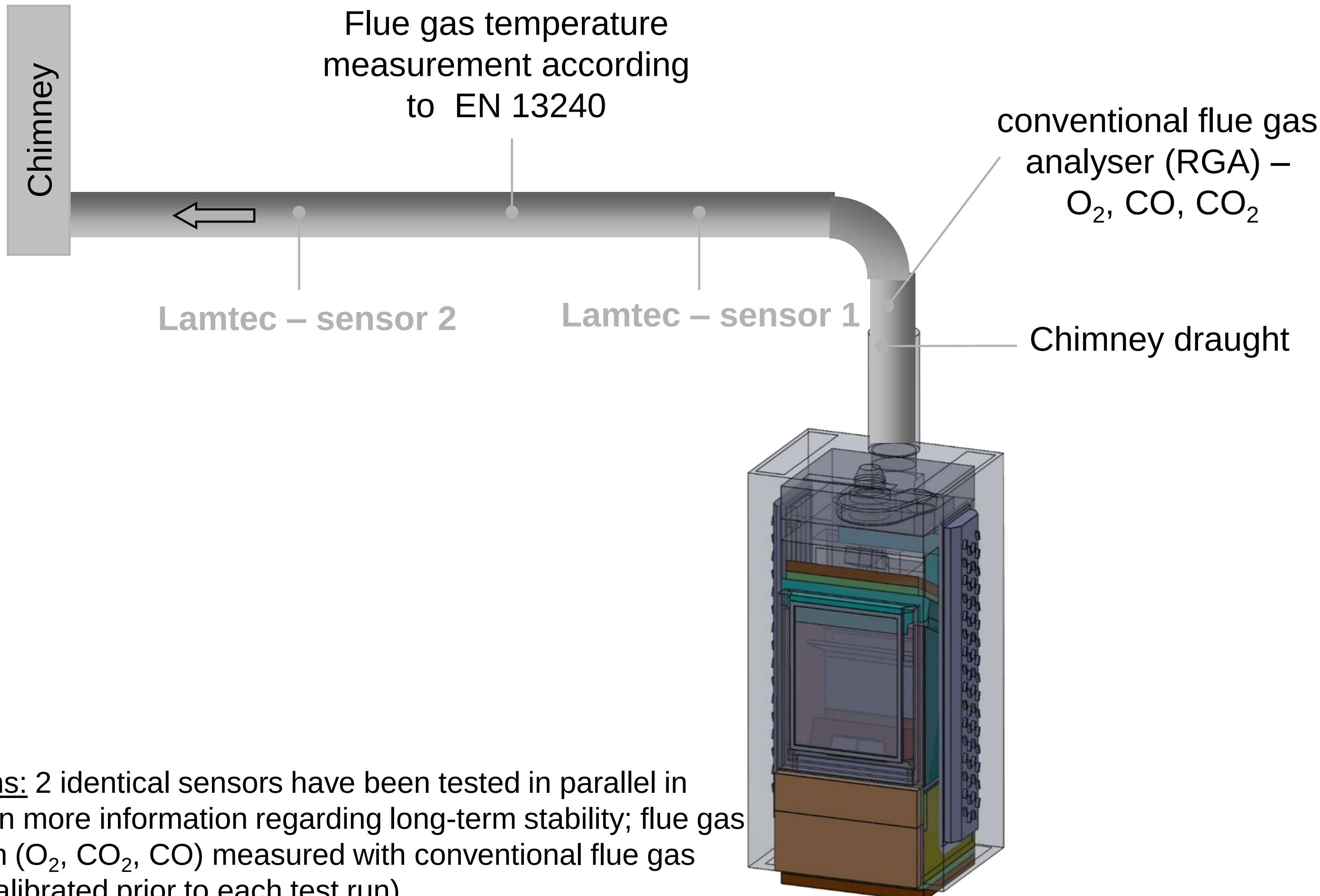
- **Characteristics**
  - **Temperature of flue gas at probe: up to 350°C**
  - **Cross sensitivities: CO_2/CO/CH_4/SO_2/NO < 0,1 Vol% O_2 CO_2/O_2 < 30 ppm COe**
  - **Sensor poisoning: SO_2/HCl yes, but no experience; hydrocarbons > 1000ppm**
- **Calibration**
  - **O_2: calibrated with dry ambient 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**

Methodology -
Description of chimney and pellet stoves applied

- **The combination probe KS1D has been tested at an adapted 8 kW logwood chimney stove.**



Methodology -
Test stand set-up



<u>Explanations:</u> 2 identical sensors have been tested in parallel in order to gain more information regarding long-term stability; flue gas composition (O_2, CO_2, CO) measured with conventional flue gas analyser (calibrated prior to each test run)

Methodology - General test stand set-up

- **Continuous measurements**
  - **Flue gas composition (O_2, CO, CO_2) – measured with conventional flue gas analyser (Emerson NGA 2000) (only during selected measurement days)**
  - **Combustion chamber temperature and flue gas temperature according to EN 13240 (with suction pyrometer)**
  - **Chimney draught**
  - **Output signal (mA) of sensor tested**
- **Discontinuous measurements and analyses**
  - **TSP emission measurements according to VDI 2066 (only during selected measurement days)**
  - **Mass of fuel applied**
  - **Analyses of selected fuel samples**

Explanations: The logwood chimney stove has been used for different test run campaigns. Only relevant data of these test runs will be shown within this presentation.

Methodology -
Test run methodology

- **General operation conditions**
  - **Constant draught of 12 Pa at the chimney**
  - **Test fuel:**
    - **hardwood (beech) without bark, triangle shape**
- **Overall procedure**
  - **Logwood chimney stove operation over 12 weeks (approx. 255 h)**
  - **Performance of several dedicated one-day measurement series with emission measurements within the test run campaigns performed**

Combination probe KS1D – Overview

- The long-term operation of the logwood chimney stove for the evaluation of the combination probe KS1D started in week 35/2015 (25/08/2015 / day 1) at the test stand of BIOS in Graz and lasted till week 49/2015 (04/12/2015). The long-term operation has been performed within the catalyst testing campaigns (see WP2.2). Two identical sensors have been tested in parallel.

- In addition, test runs including flue gas measurements have repeatedly been performed within the long-term operation of the chimney stove in order to check the performance of the sensor.

- In total 47 test runs with 273 batches have been performed. The overall operation time of the logwood chimney stove can be amounted to approx. 255 hours. One sensor has been tested for approx. 150 hours.

Fuel applied

Beech logs without bark		
Moisture content [1]	wt% wet basis	10.1-14.4
Ash content	wt% dry basis	0.47
Ash content (CO_2-free)	wt% dry basis	0.40
Gross calorific value [2]	MJ/kg dry basis	19.3
Net calorific value	MJ/kg wet basis	15.3
C	wt% dry basis	48.6
H	wt% dry basis	6.20
N	wt% dry basis	<0.1
Ca	mg/kg dry basis	995
K	mg/kg dry basis	981
Mg	mg/kg dry basis	221
Si	mg/kg dry basis	105
Al	mg/kg dry basis	48
P	mg/kg dry basis	37
Na	mg/kg dry basis	10
S	mg/kg dry basis	87
Cl	mg/kg dry basis	25

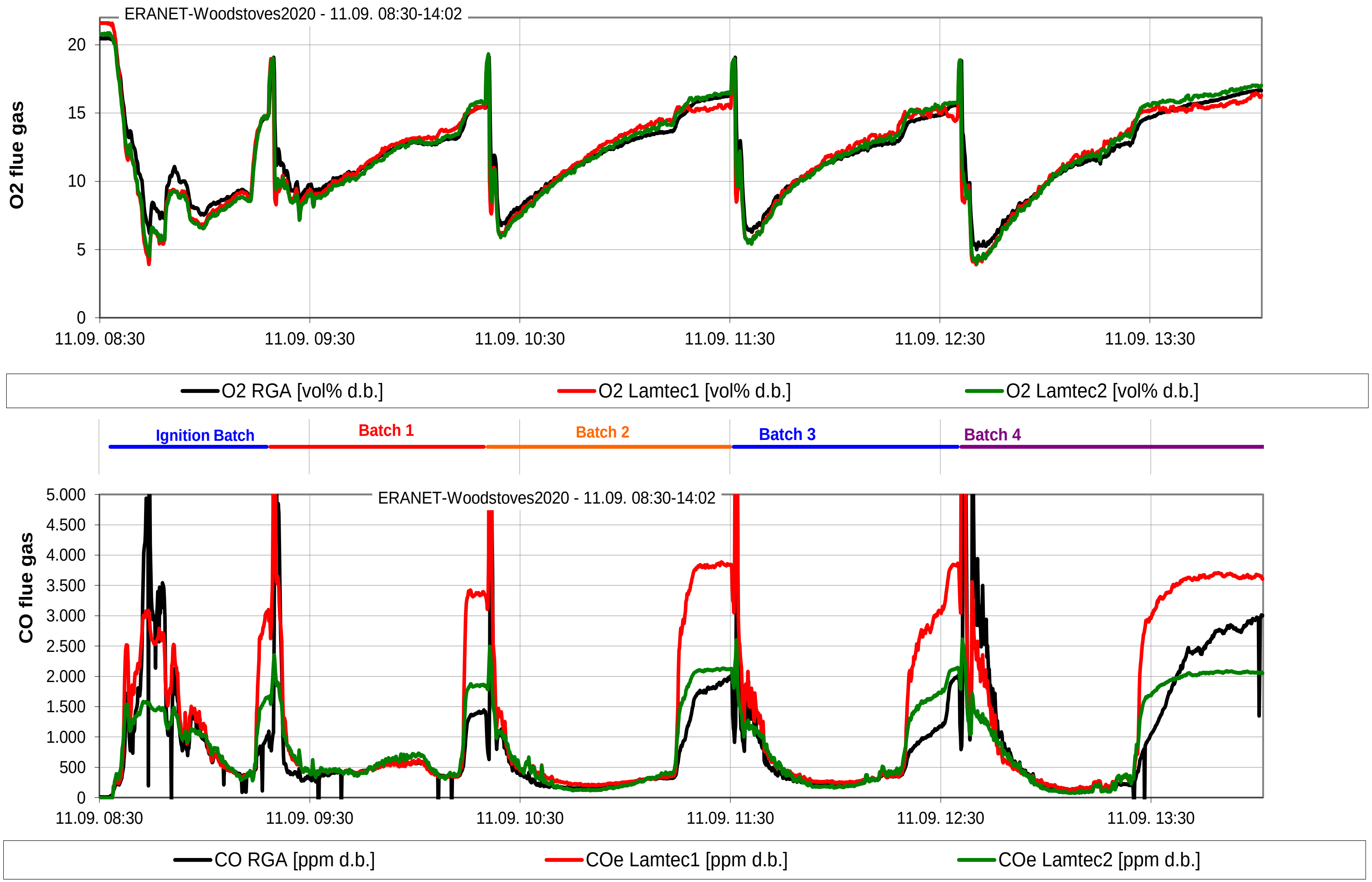
According to comparisons with database values the fuel applied can be evaluated as typical beech wood without bark

[1] mean value: 11.7 wt% w.b. (27 samples)
[2] calculated according to Gaur

General aspects

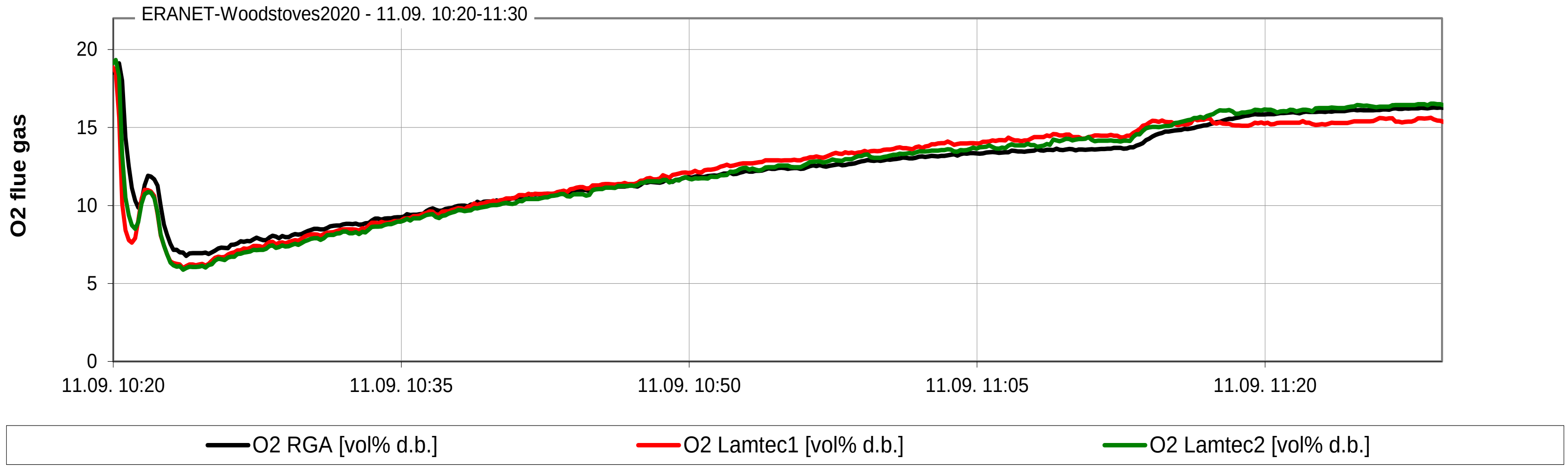
- **General remarks regarding the data presented on the next slides**
  - **O_2 contents in vol% are related to dry flue gas**
  - **As the sensors measure the O_2 content in the wet flue gas the measured value is calculated on dry basis based on the moisture content and the elemental composition of the fuel used.**
  - **CO emissions in ppmv are related to dry flue gas**

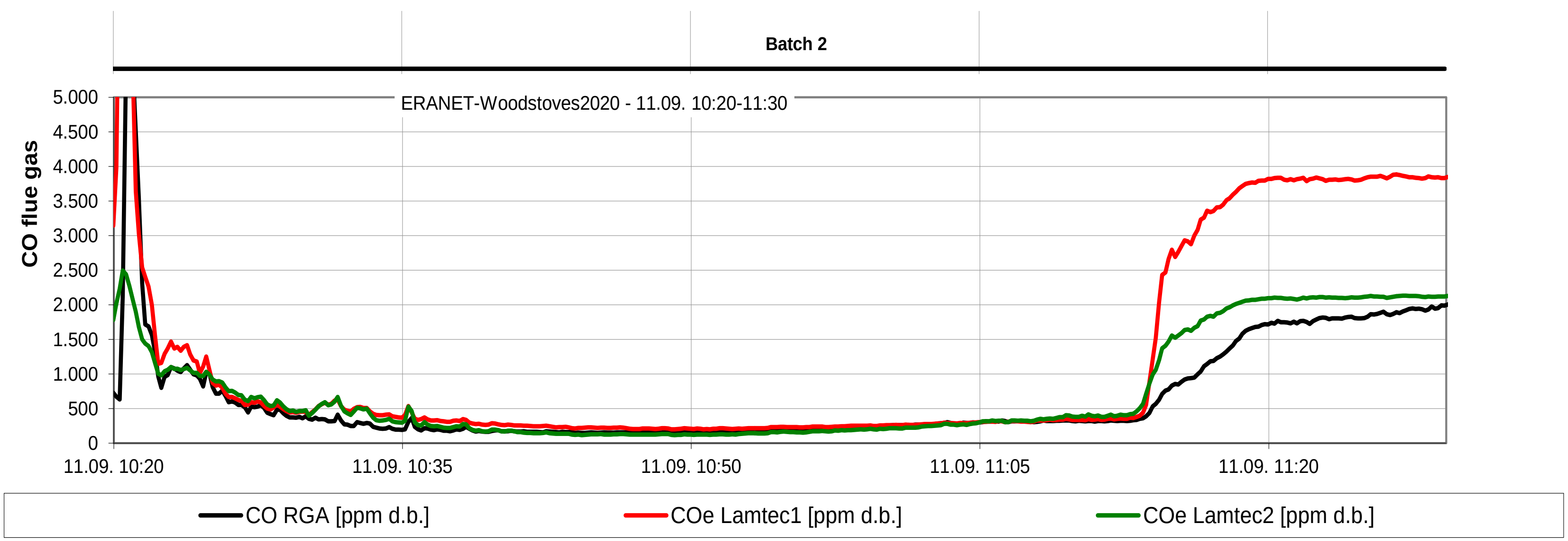
Combination probe KS1D – O_2 and CO trends – day 13



Explanations: O_2 and CO emissions related to dry flue gas

Combination probe KS1D – O_2 and CO trends – batch 2 of day 13

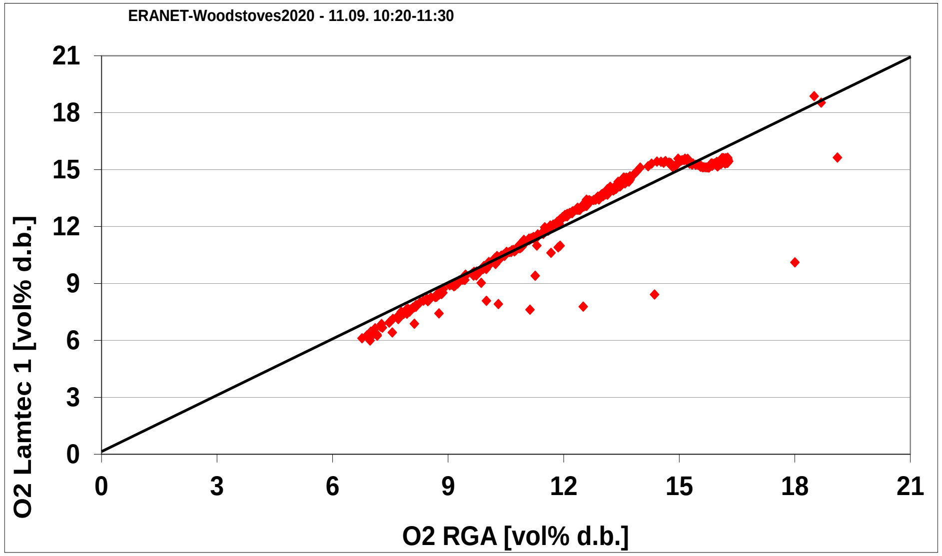


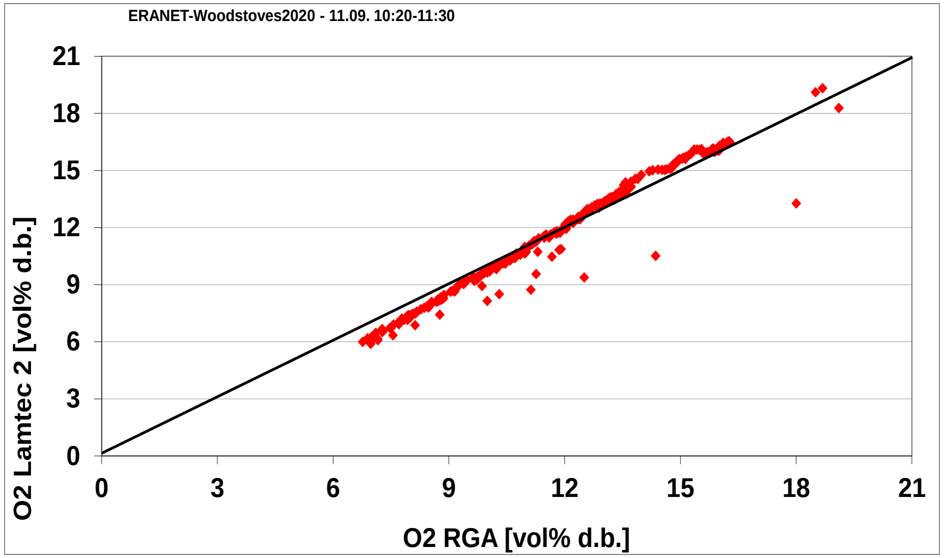


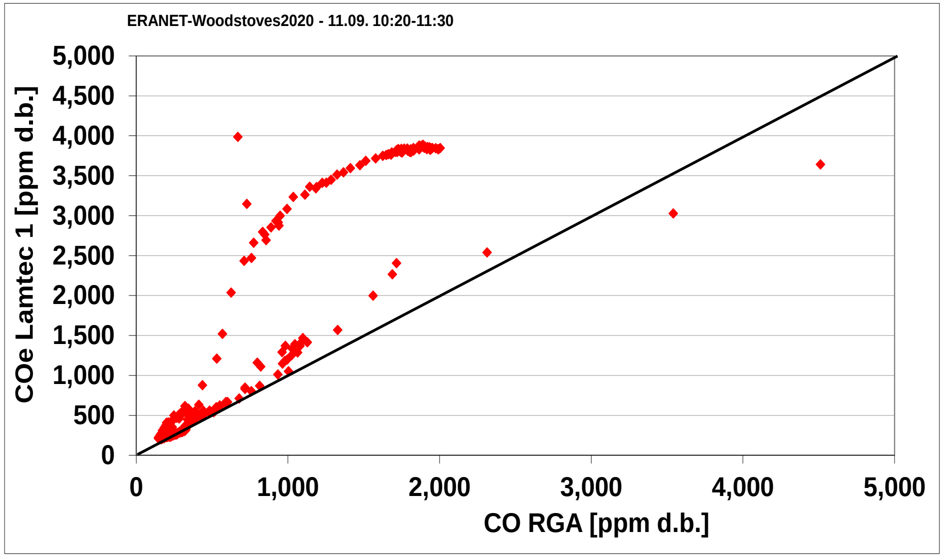
Explanations: O_2 and CO emissions related to dry flue gas

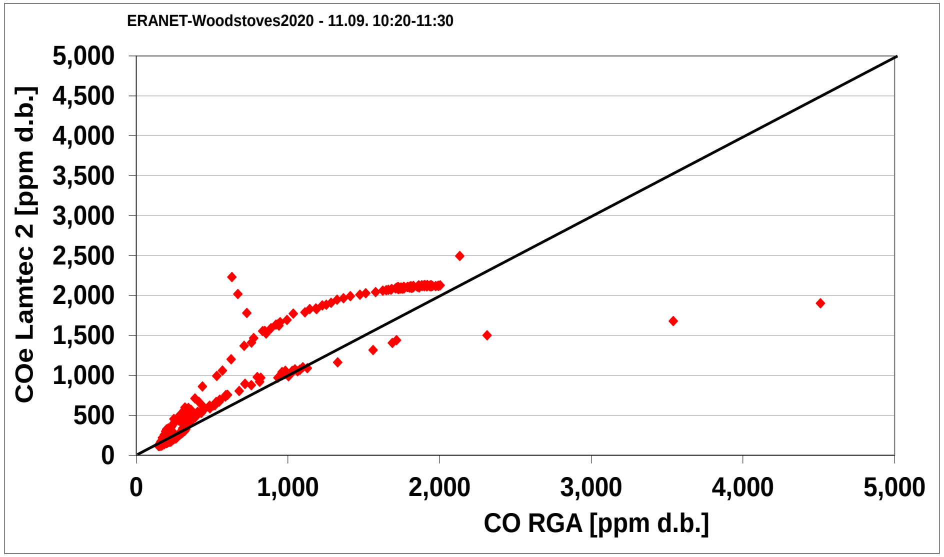
Combination probe KS1D –

O_2 and CO Lamtec vs. O_2 and CO conventional RGA – day 13







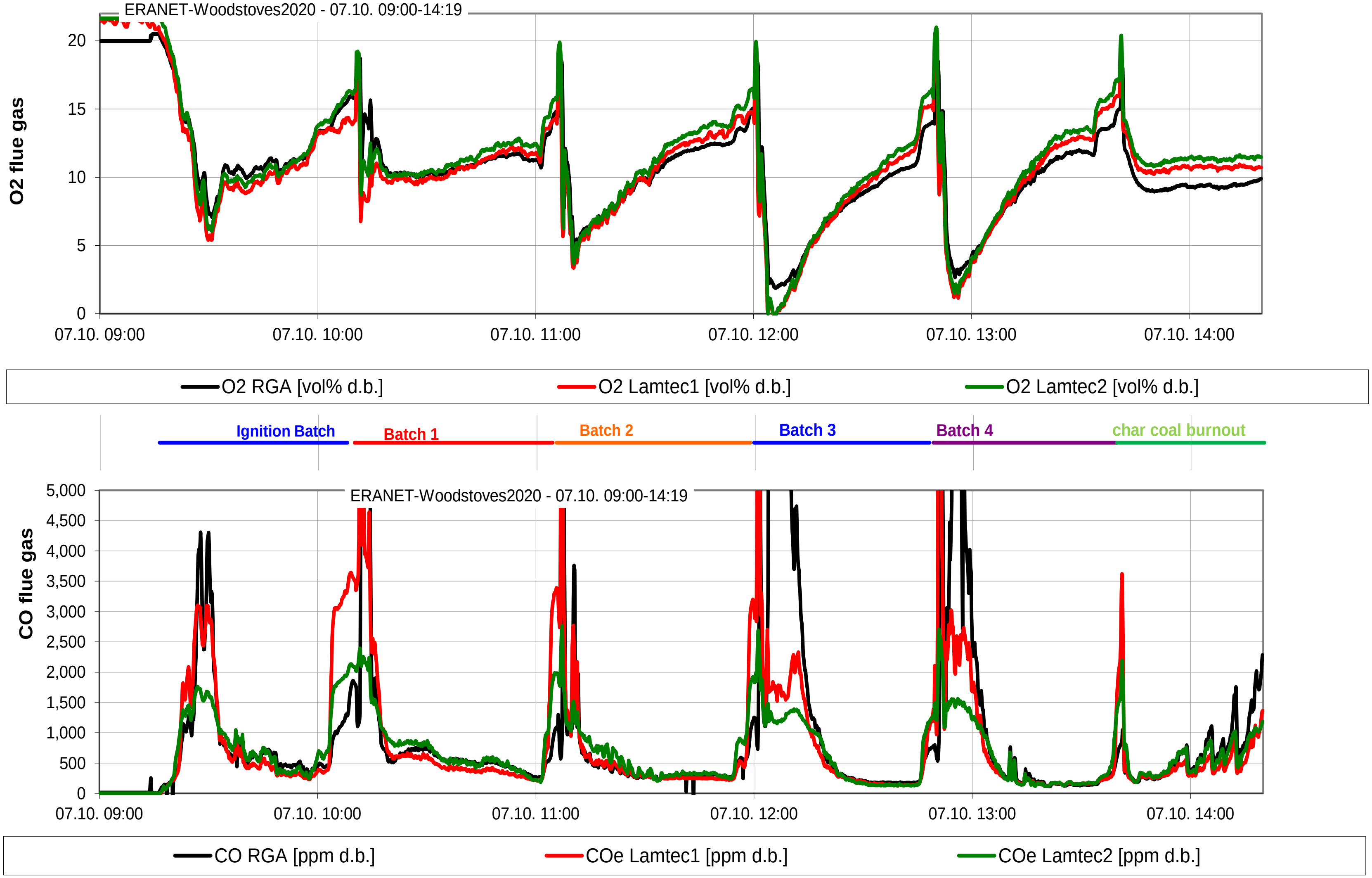


Combination probe KS1D – operation parameters – day 13

period		Ignition Batch	Batch 1	Batch 2	Batch 3	Batch 4
from	unit	11.09 08:33:19	11.09 09:18:56	11.09 10:20:55	11.09 11:31:08	11.09 12:36:00
to		11.09 09:17:56	11.09 10:19:55	11.09 11:30:08	11.09 12:35:00	11.09 14:02:28
duration	[h]	0.7	1.0	1.2	1.1	1.4
mean measurement values - ERANET-Woodstoves2020						
O2 RGA	[vol% d.b.]	10.42	11.89	12.19	11.73	12.21
O2 Lamtec1	[vol% d.b.]	9.62	11.83	12.19	11.79	12.11
O2 Lamtec2	[vol% d.b.]	9.46	11.60	12.15	11.72	12.34
CO RGA	[ppm d.b.]	1,216.52	677.24	662.73	663.90	1,385.24
COe Lamtec1	[ppm d.b.]	1,382.64	975.06	1,230.10	1,205.45	1,922.58
COe Lamtec2	[ppm d.b.]	972.88	722.92	742.45	775.40	1,108.56
O2 deviation Lamtec1	[%]	7.68	0.49	0.04	-0.52	0.83
O2 deviation Lamtec2	[%]	9.19	2.43	0.34	0.08	-1.04
CO deviation Lamtec1	[%]	-13.66	-43.98	-85.61	-81.57	-38.79
CO deviation Lamtec2	[%]	20.03	-6.75	-12.03	-16.79	19.97

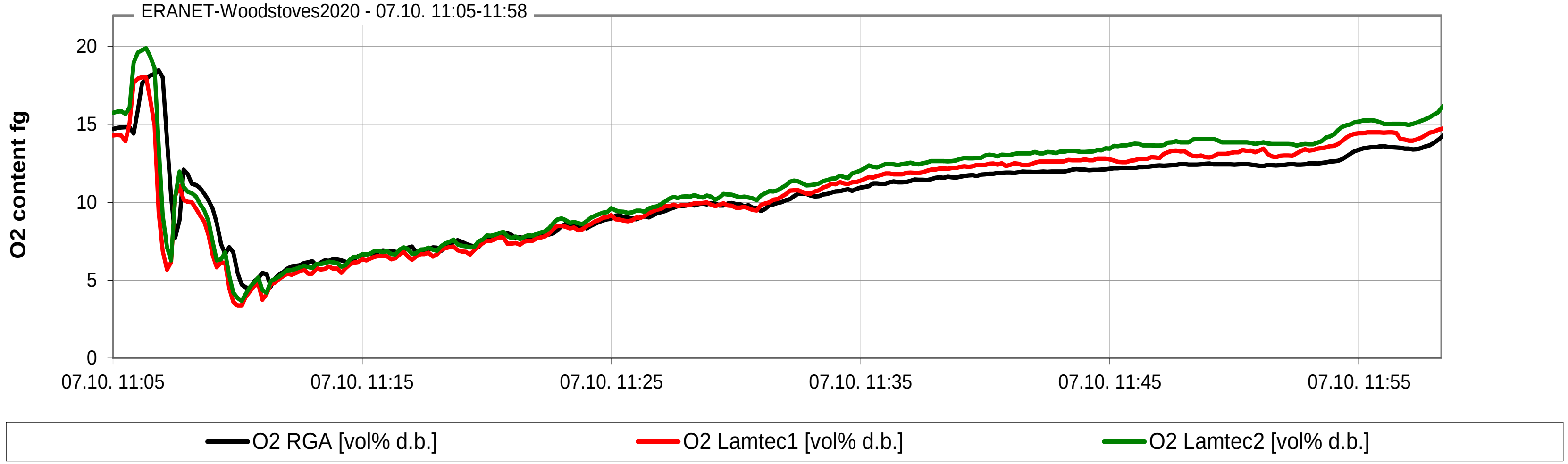
Explanations: O_2 deviation calculated as [1-(O_2 Lamtec)/ (O_2 flue gas)]*100 in %; CO deviation calculated as [1-(COe Lamtec)/ (CO flue gas)]*100 in %

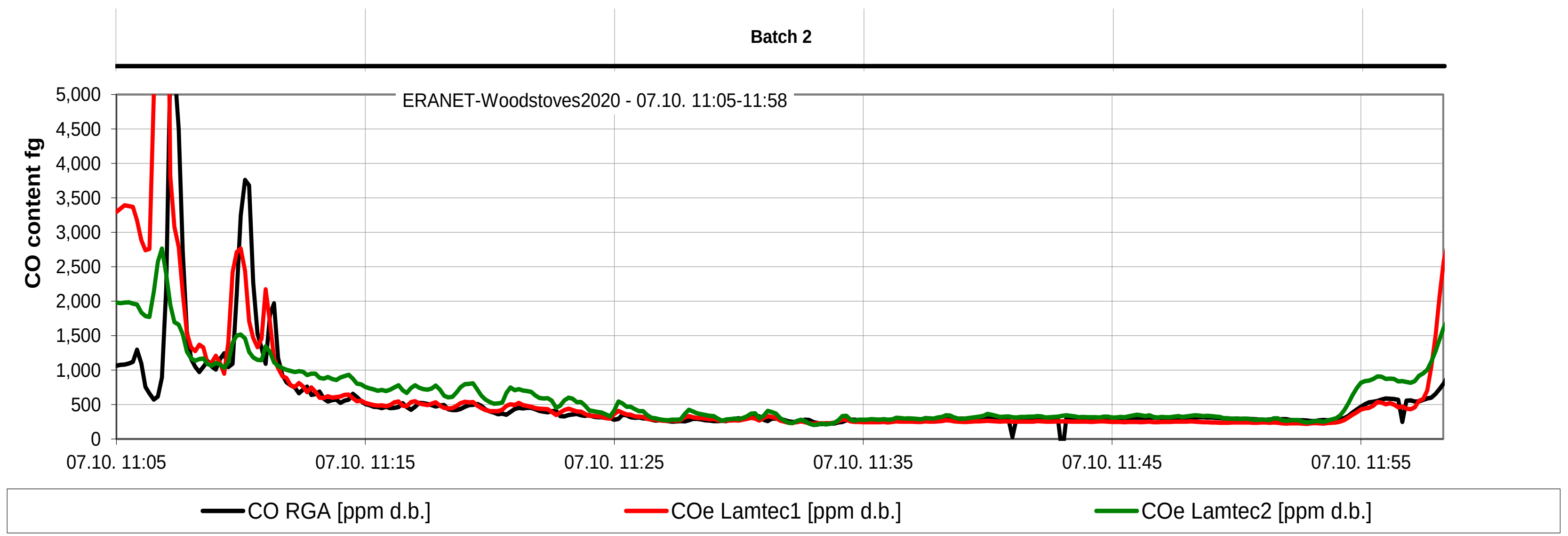
Combination probe KS1D – O_2 and CO trends – day 26



Explanations: O_2 and CO emissions related to dry flue gas

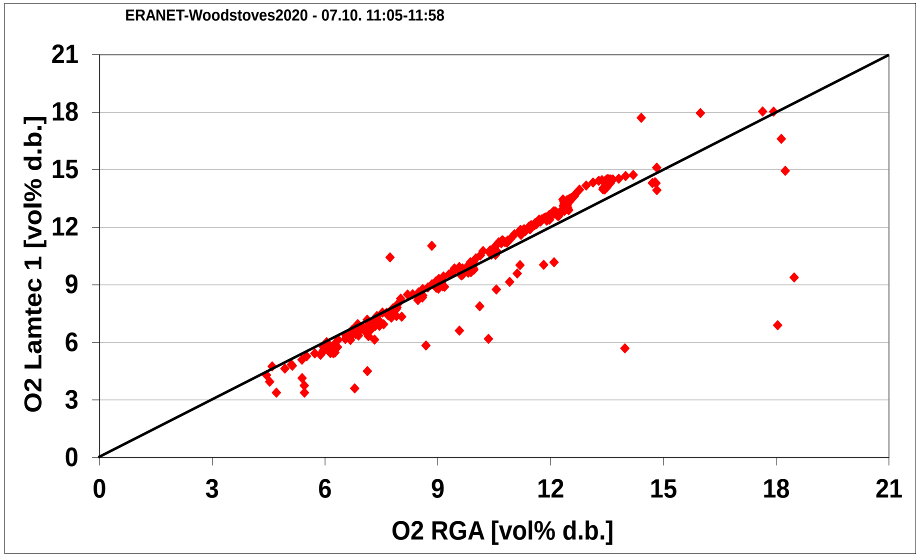
Combination probe KS1D – O_2 and CO trends – batch 2 of day 26

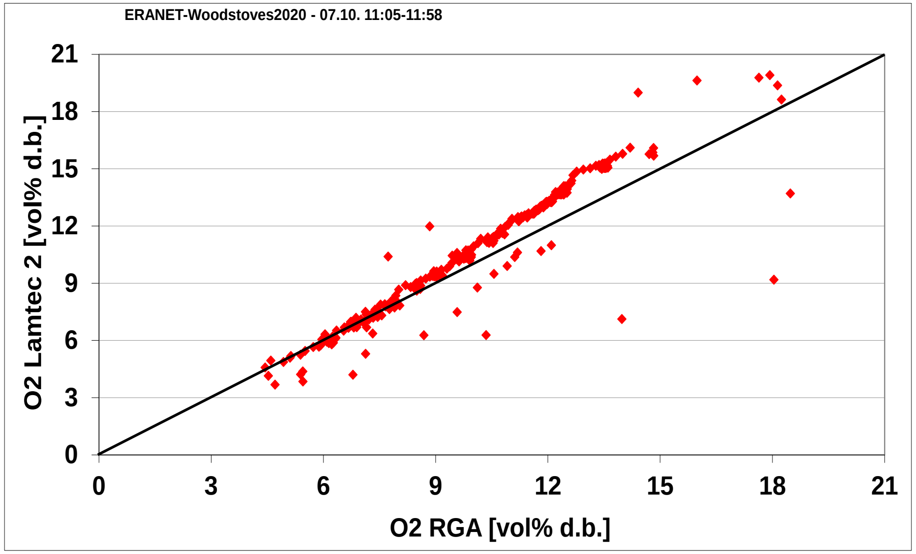


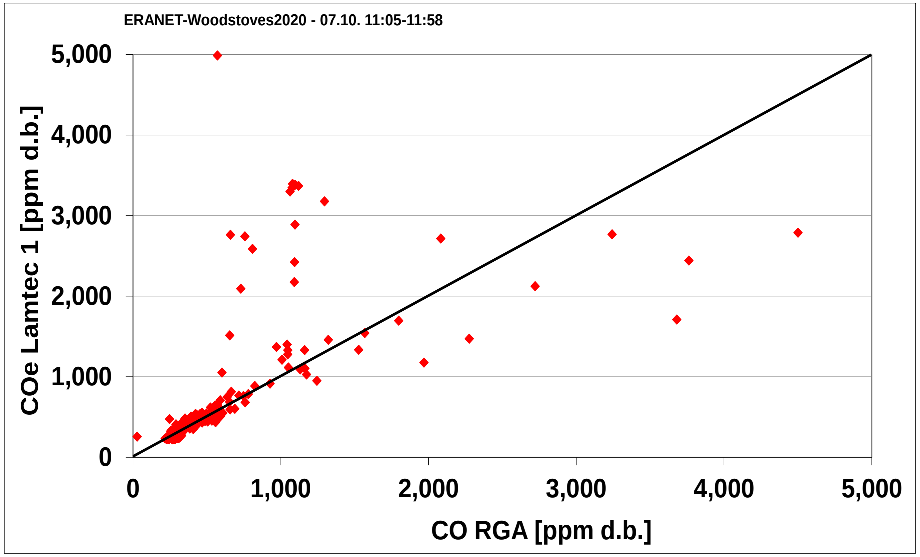


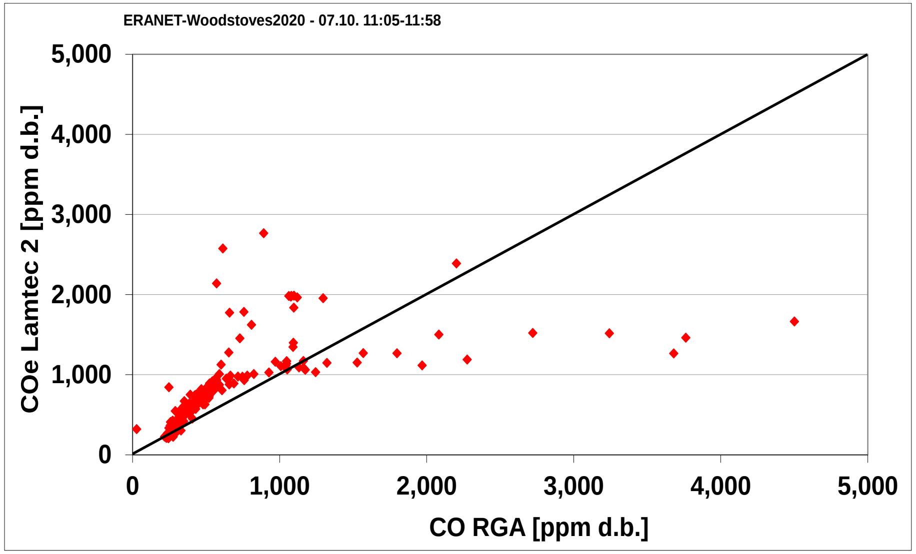
Explanations: O_2 and CO emissions related to dry flue gas

Combination probe KS1D –
O_2 and CO Lamtec vs. O_2 and CO conventional RGA– day 26







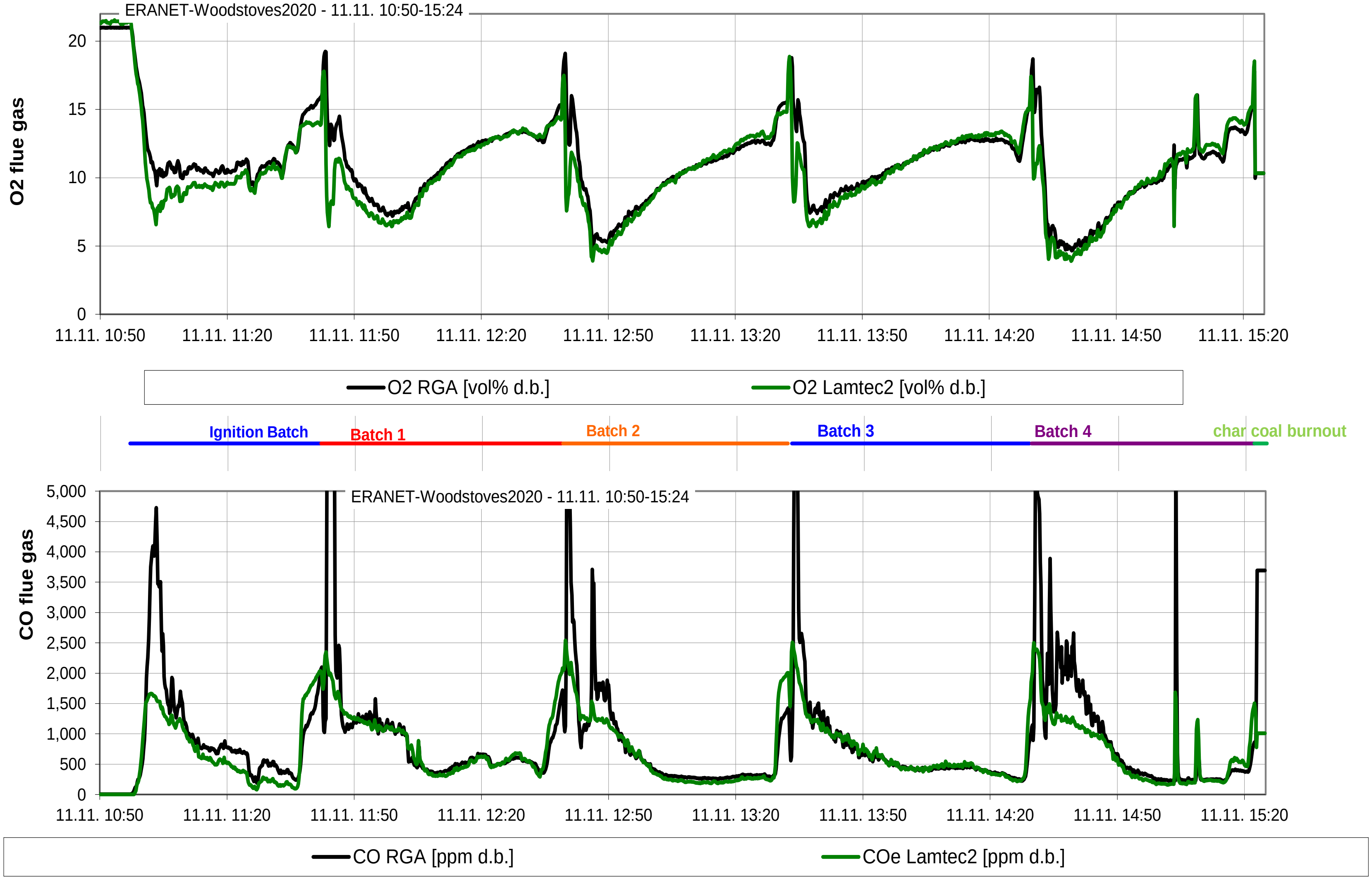


Combination probe KS1D – operation parameters – day 26

period		Ignition Batch	Batch 1	Batch 2	Batch 3	Batch 4
from	unit	07.10 09:16:19	07.10 10:09:56	07.10 11:05:21	07.10 11:59:39	07.10 12:48:57
to		07.10 10:07:56	07.10 11:04:21	07.10 11:58:39	07.10 12:47:57	07.10 13:39:24
duration	[h]	0.9	0.9	0.9	0.8	0.8
mean measurement values - ERANET-Woodstoves2020						
O2 RGA	[vol% d.b.]	12.25	11.39	10.35	7.84	9.39
O2 Lamtec1	[vol% d.b.]	11.42	10.88	10.40	7.71	9.57
O2 Lamtec2	[vol% d.b.]	12.16	11.60	11.01	8.21	10.15
CO RGA	[ppm d.b.]	895.17	906.43	530.26	1,922.05	1,175.70
COe Lamtec1	[ppm d.b.]	999.11	901.46	656.41	952.73	899.23
COe Lamtec2	[ppm d.b.]	831.15	786.16	603.54	691.11	611.12
O2 deviation Lamtec1	[%]	6.74	4.50	-0.55	1.59	-1.92
O2 deviation Lamtec2	[%]	0.72	-1.88	-6.42	-4.76	-8.07
CO deviation Lamtec1	[%]	-11.61	0.55	-23.79	50.43	23.52
CO deviation Lamtec2	[%]	7.15	13.27	-13.82	64.04	48.02

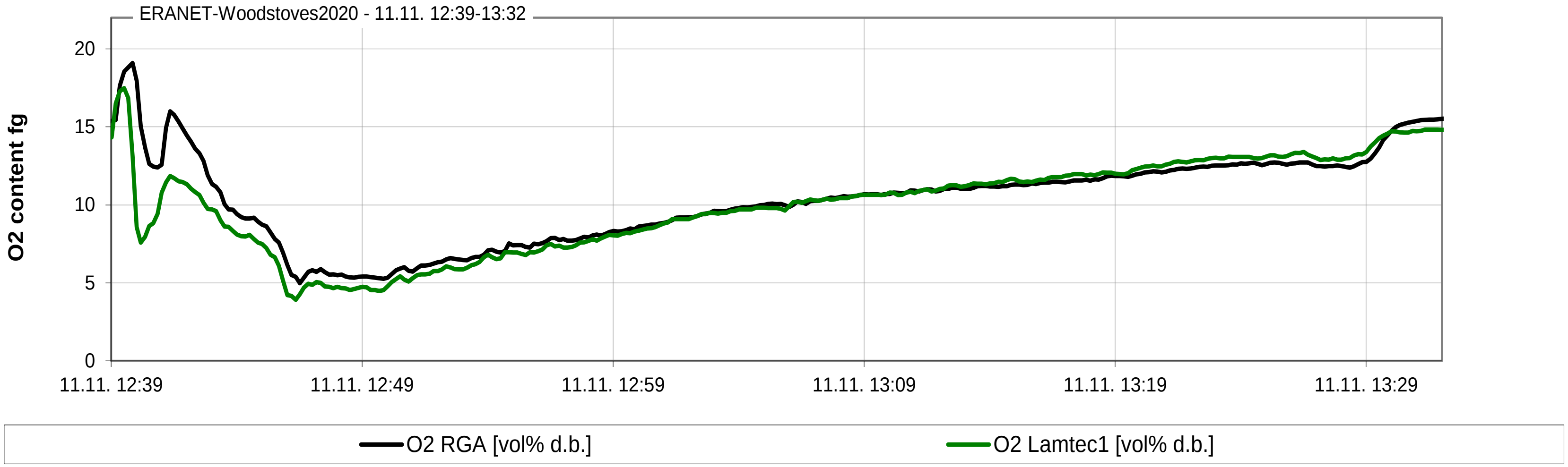
Explanations: O_2 deviation calculated as [1-(O_2 Lamtec)/ (O_2 flue gas)]*100 in %; CO deviation calculated as [1-(COe Lamtec)/ (CO flue gas)]*100 in %

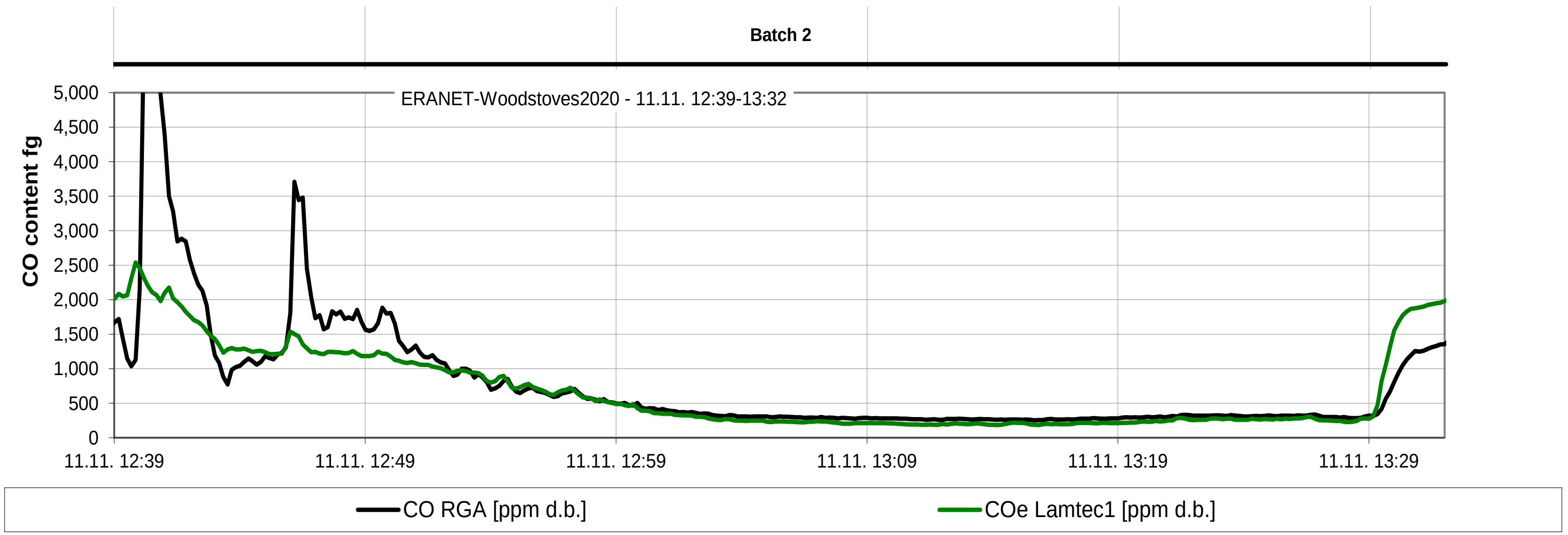
Combination probe KS1D – O_2 and CO trends – day 38



<u>Explanations:</u> O_2 and CO emissions related to dry flue gas

Combination probe KS1D – O_2 and CO trends – batch 2 of day 38

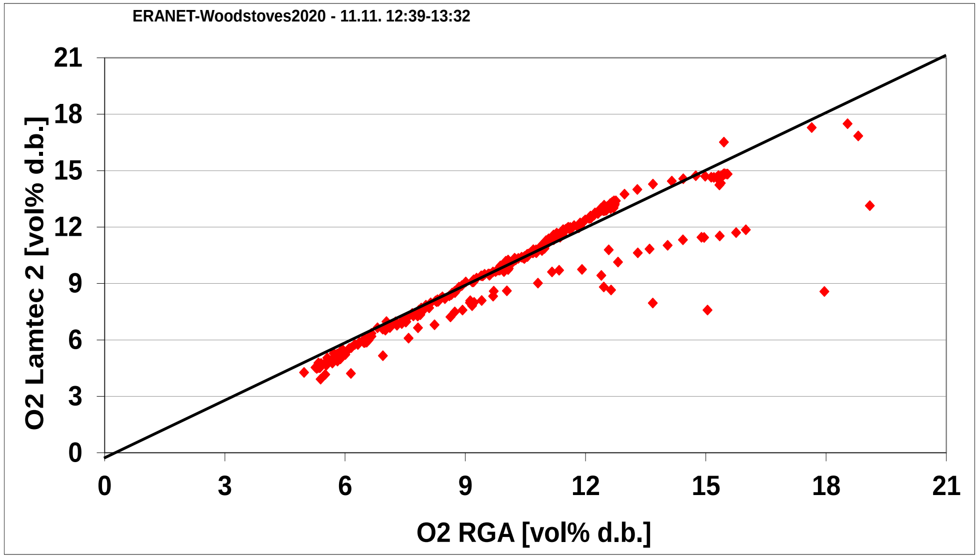


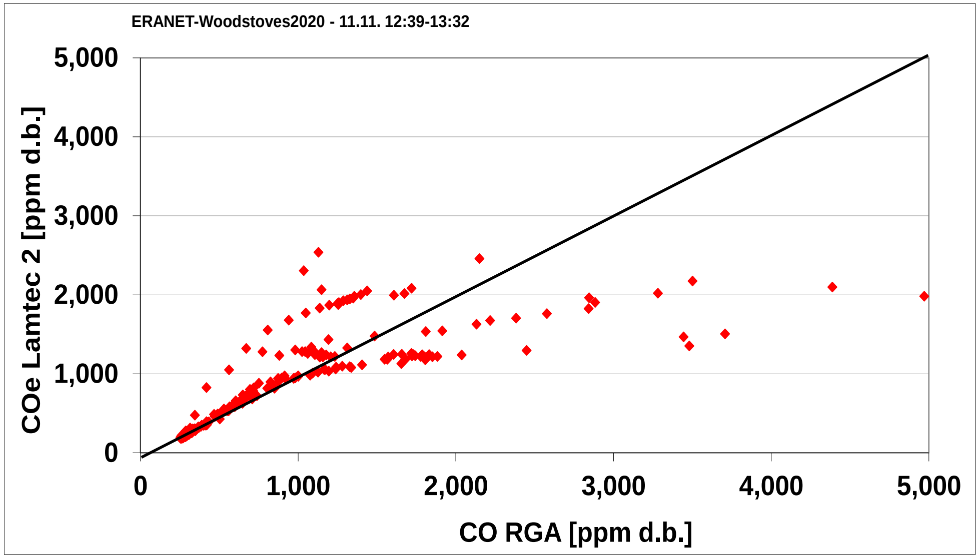


<u>Explanations:</u> O_2 and CO emissions related to dry flue gas

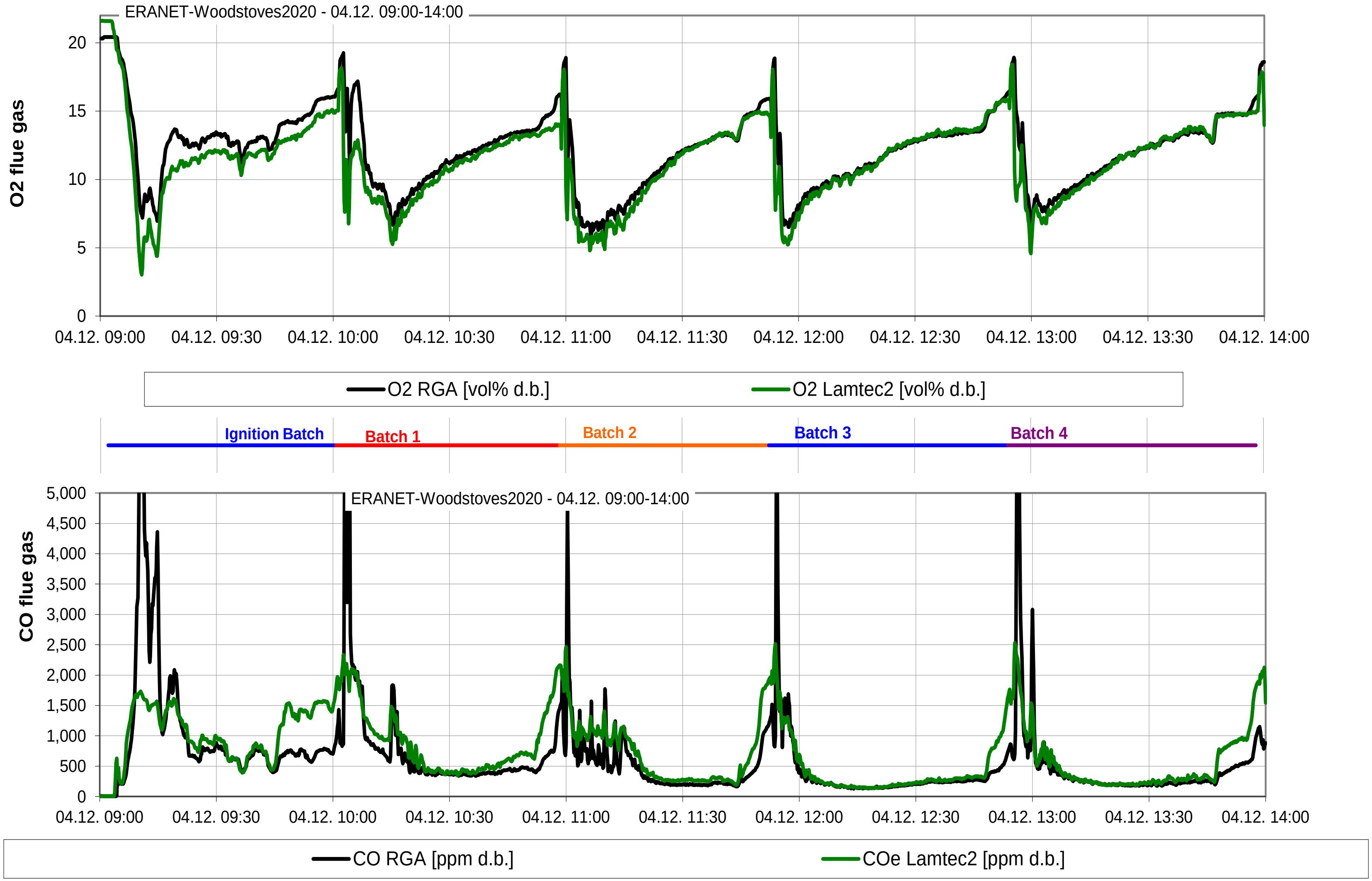
Combination probe KS1D –

O_2 and CO Lamtec vs. O_2 and CO conventional RGA – day 38



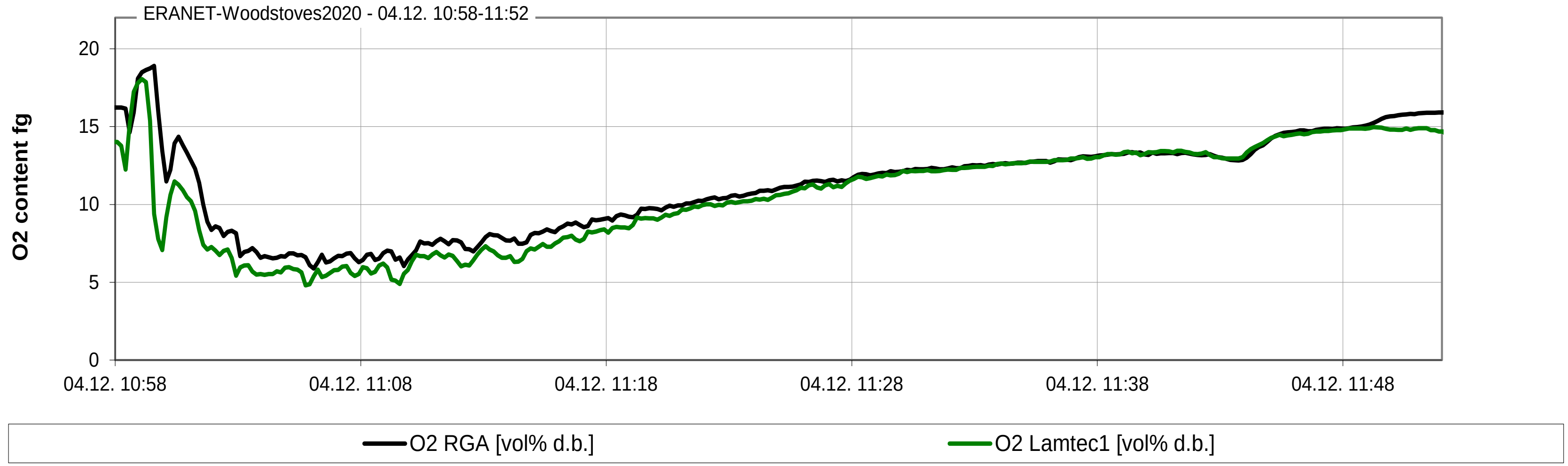


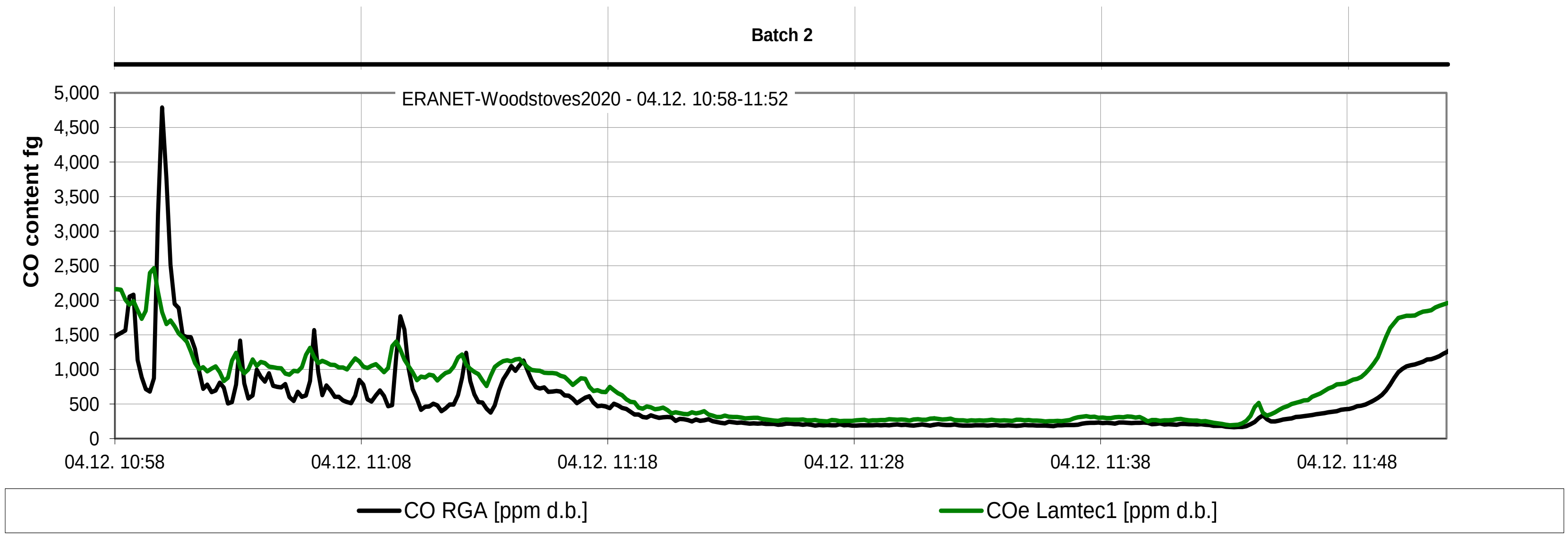
Combination probe KS1D – O_2 and CO trends – day 46



Explanations: O_2 and CO emissions related to dry flue gas

Combination probe KS1D –
O_2 and CO trends – batch 2 of day 46

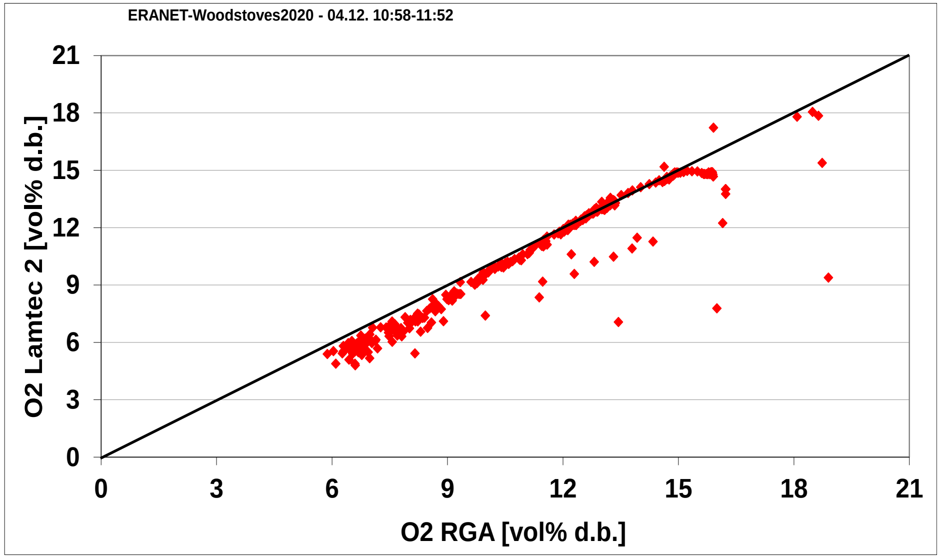


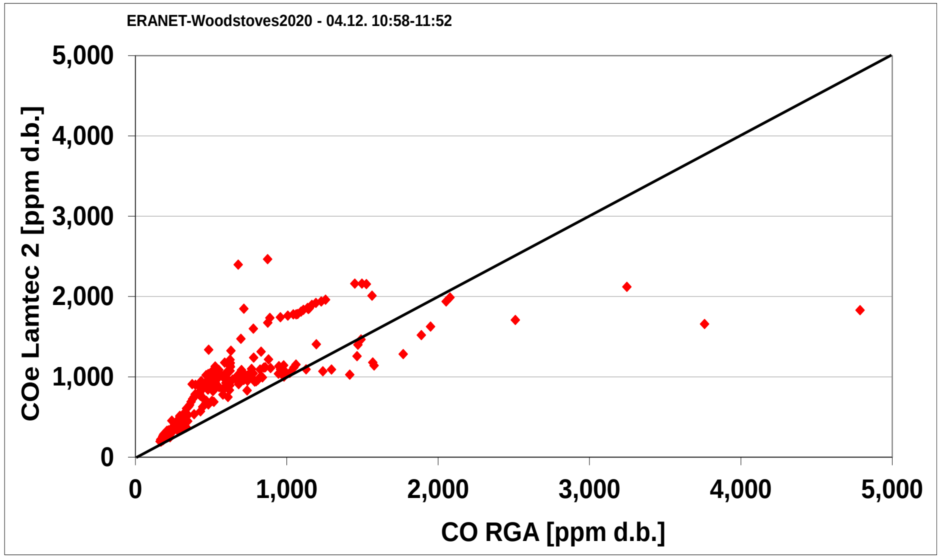


Explanations: O_2 and CO emissions related to dry flue gas

Combination probe KS1D –

O_2 and CO Lamtec vs. O_2 and CO conventional RGA – day 46





Combination probe KS1D – operation parameters – day 46

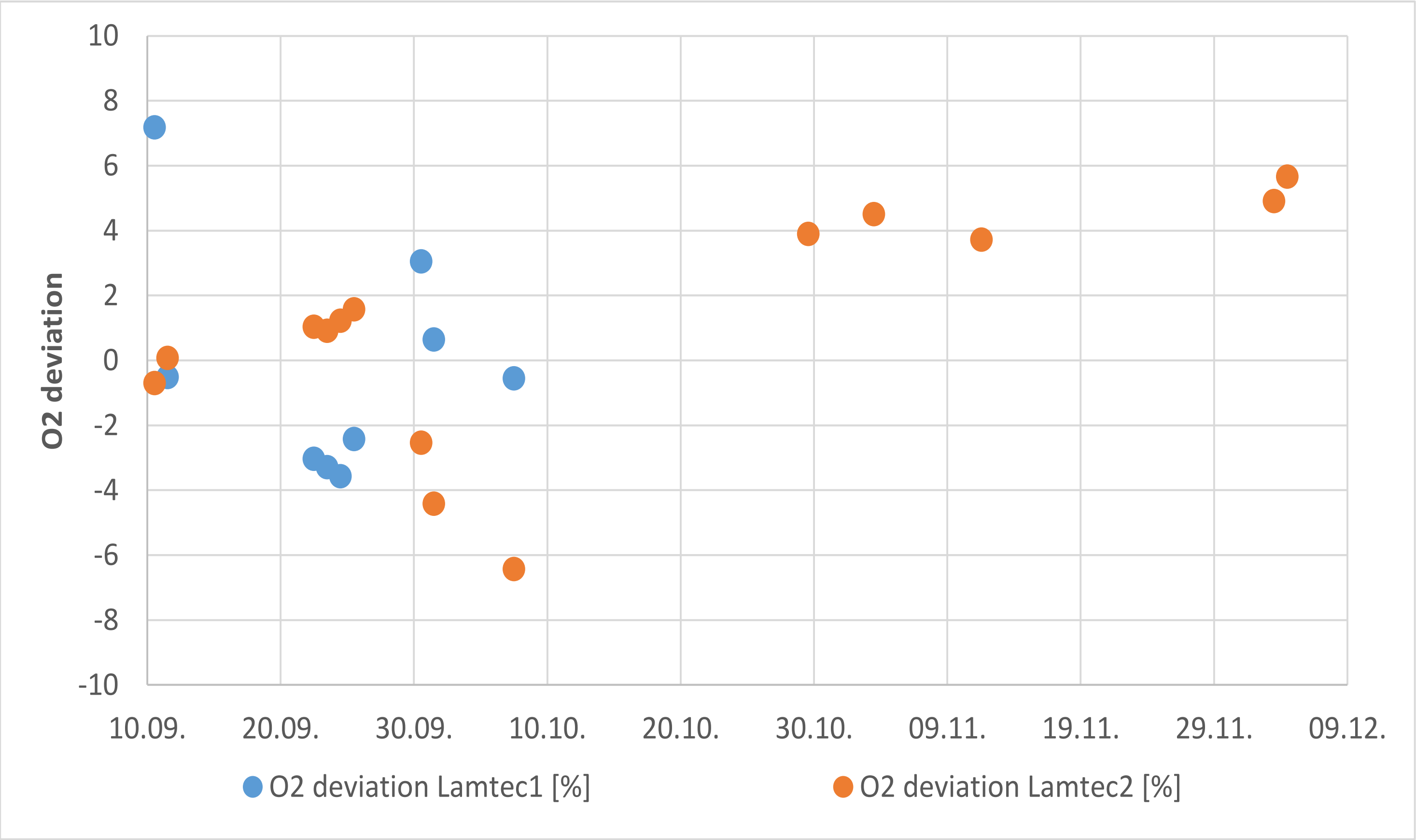
period		Ignition Batch	Batch 1	Batch 2	Batch 3	Batch 4
from	unit	04.12 09:01:59	04.12 10:00:45	04.12 10:58:25	04.12 11:52:27	04.12 12:54:02
to		04.12 10:00:45	04.12 10:58:25	04.12 11:52:27	04.12 12:54:02	04.12 13:58:03
duration	[h]	1.0	1.0	0.9	1.0	1.1
mean measurement values - ERANET-Woodstoves2020						
O2 RGA	[vol% d.b.]	13.49	12.09	11.18	11.86	12.00
O2 Lamtec2	[vol% d.b.]	12.14	11.03	10.55	11.62	11.66
CO RGA	[ppm d.b.]	1,118.48	770.12	529.83	391.92	491.74
COe Lamtec2	[ppm d.b.]	1,052.86	908.94	718.63	453.55	552.64
O2 deviation Lamtec2	[%]	10.00	8.74	5.66	2.03	2.84
CO deviation Lamtec2	[%]	5.87	-18.03	-35.63	-15.73	-12.39

Explanations: O_2 deviation calculated as [1-(O_2 Lamtec)/ (O_2 flue gas)]*100 in %; CO deviation calculated as [1-(COe Lamtec)/ (CO flue gas)]*100 in %

Combination probe KS1D – evaluation (I)

ERA-NET Bioenergy

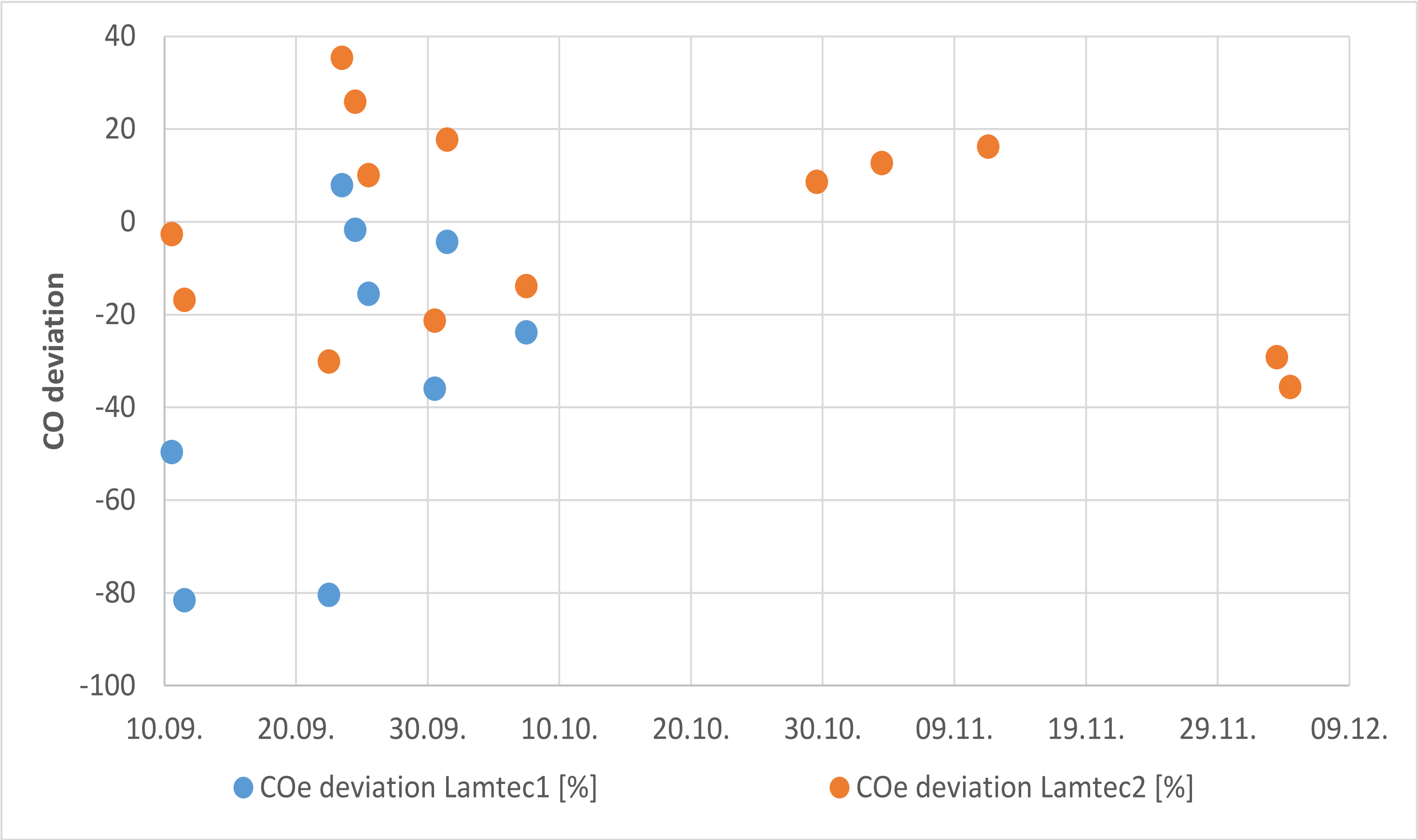
Trends of deviations of O_2 during long-term operation



<u>Explanations:</u> O_2 deviation calculated as [1-(O_2 Lamtec)/ (O_2 flue gas)]*100 in %; Sensor Lamtec1 has only been tested till 07/11/2015

Combination probe KS1D – evaluation (I)

Trends of deviations of CO during long-term operation



Explanations: CO deviation calculated as [1-(COe Lamtec)/ (CO flue gas)]*100 in %; Sensor Lamtec1 has only been tested till 07/11/2015

Combination probe KS1D – evaluation (II)

Sensor before the test runs

Sensor after approx. 255 h of operation

Explanations: no cleaning of sensors has been performed

Combination probe KS1D – Conclusions (I)

- The stove with installed combination probe KS1D was operated for in total 255 hours. Sensor 1 has been tested for approx.150 hours.
- The stove was operated at typical air supply conditions leading to average O_2 contents in the flue gas over a whole batch of between 8 and 13 vol% (dry flue gas, mean values of batches).
- The flue gas temperature at the sensors was in the range of 150 to 170 °C (excluding the ignition batches).
- After an operation time of approx. 255 hours (150 hours for Sensor 1) no deposits have been observed on the sensors during inspection.
- The particulate emissions (TSP) in the flue gas downstream the stove can be amounted to 20 – 35 mg/MJ (35 – 100 mg/MJ for the ignition batches) according to measurements performed during selected test runs.

Combination probe KS1D – Conclusions (II)

Evaluation of O_2:

- **Sensor 1**
  - **The sensor is in good and stable agreement with the O_2 values measured by the conventional flue gas analyser (relative deviation: -4 to +7 %). The sensor can well reproduce the O_2 trend over the entire measurement range. A slightly higher deviation could be observed for O_2 values lower than 5 vol% d.b. and higher than 14 vol% d.b.. However, this deviation is not of relevance as the stove is usually operated at O_2 values between 5 and 14 vol% d.b..**
- **Sensor 2**
  - **The sensor is as well in good and stable agreement with the O_2 values measured by the conventional flue gas analyser (relative deviation: -6 to +2 %). The sensor can well reproduce the O_2 trend over the entire measurement range. A slightly higher deviation could be observed for O_2 values lower than 5 vol% d.b. and higher than 14 vol% d.b.. However, this deviation is not of relevance as the stove is usually operated at O_2 values between 5 and 14 vol% d.b..**

Combination probe KS1D – Conclusions (III)

Evaluation of O_2 (cont.)

- No clear signal drift of the sensors has been observed during the first 150 hours of operation. However, in the long-term operation the deviation of Sensor 2 slightly increases with the operation time.

Evaluation of CO:

- Generally, it has to be mentioned that the COe value of the combination probe KS1D is equivalent to the sum of all combustibles gases. As the CO value is compared / evaluated with CO of the conventional flue gas analyser a basic deviation has to be considered. However, as the sensors have been calibrated based on the CO value of the conventional flue gas analyser and the ratio of the combustibles gases (OGC) is for logwood stoves typically in the range of 10% of the CO emissions the deviation should be rather small.

Combination probe KS1D – Conclusions (IV)

Evaluation of CO (cont.):

- Sensor 1:
  - The sensor supplies stable signals. The relative deviation regarding CO (mean values of batches) in comparison with the measurement values of the conventional flue gas analyser varies between - 80 to +10 %.
  - In general, the sensor can reproduce the CO trend over the entire measurement range. However, for CO values higher than 1,000 ppmv and for O_2 levels above approx. 12 vol% d.b. at the same time (during char coal burnout) the relative deviation significantly increases (up to more than 50%).
  - The deviation can probably be attributed to the fact that the span calibration of the sensor has only been performed at one single point and the internal compensation function of the sensor has only been determined for natural gas and oil burners so far (according to the manufacturer). If this compensation function is determined for biomass combustion systems at different CO and O_2 levels then the deviation can be reduced.

Combination probe KS1D – Conclusions (V)

ERA-NET Bioenergy

Evaluation of CO (cont.):

- **Sensor 2:**
  - **The sensor supplies stable signals. The relative deviation regarding CO (mean values of batches) in comparison with the measurement values of the conventional flue gas analyser varies between -35 to +40 %.**
  - **The sensor can reproduce the CO trend over the entire measurement range. For CO values higher than 1,500 ppmv the relative deviation increases up to 50% (possible reason for deviation see Sensor 1).**
  - **No signal drift of the sensors has been observed during the long-term operation.**
- **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. The sensor can well reproduce the O_2 trend over the entire range of operation of a wood stove.**

Combination probe KS1D – Conclusions (VI)

- Regarding CO some deviations, especially at higher CO levels (> 1,000 ppmv), occur. If the internal compensation function of the sensor would be determined for biomass combustion systems at different CO and O_2 levels then the deviation could most probably be reduced (according to the manufacturer). However, the CO trend is sufficiently well predicted.

- By now the costs of purchase (single unit: 600 – 1,000 € including converter) are too high. 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 to approx. 200 € for a single unit (according to the manufacturer). However, the development costs for the integration of the converter have to be born by the manufacturer of the stove.

- **Due to the recent high costs the combination probe KS1D is not recommended for the integration in the automatic control system of stoves.**

Concluding summery

Final conclusions (I)

- Evaluation confirmed conclusion from other studies regarding gas sensor accuracy at biomass combustion
  - Lambda probes with very accurate oxygen determination
  - SenSic probe with correct identification of CO gradients & ranges
- Evaluated sensors have proven that they can be used for automated stove control systems
  - Control system can rely on sensor signals
  - Probes withstand exposure to temperature, dust load, gas concentration range
- Economic considerations
  - Lambda probes are an affordable choice for utilization of gas sensor based control systems
  - SenSic probe including electronics is at the moment too expensive for a wider use in the stove sector

Final conclusions (II)

- 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. The sensor can well reproduce the O_2 trend over the entire range of operation of a wood stove.
- Regarding CO some deviations, especially at higher CO levels (> 1,000 ppmv), occur. However, the CO trend is sufficiently well predicted.
- By now the costs of purchase (single unit: 600 – 1,000 € including converter) are too high. 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.
- **Due to the recent high costs the combination probe KS1D is not recommended for the integration in the automatic control system of stoves.**