Report on catalysts and foam ceramics

Project ERA-NET Bioenergy "Stove 2020"

Prepared by: Christoph Mandl, Thomas Brunner, Ingwald Obernberger, Robert Mack, Hans Hartmann, Ingmar Schüssler

Date: June 2017

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 aims 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 can be 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 2.2: Integrated high temperature catalysts and Task 2.3: Integrated foam ceramic filters.

Table of Contents

Background and objectives (I)

- In the recent 15 years biomass based room heating systems became more and more popular and the development towards low emission appliances is processing.
- In particular, a further development and optimisation of stoves is necessary in order to achieve low emissions of atmospheric pollutants and particularly to meet stricter emission limits.
- Secondary measures like oxidation catalysts are already applied for emission reduction of wood stoves.
- The catalyst can be integrated into the stove or installed in the flue gas duct downstream the stove (retrofit-option).

Background and objectives (II)

- A catalyst implementation into a stove may have additional advantages:
  - Light-off temperature of catalyst can be reached in short time
  - High operation temperatures of the catalysts may support tar and soot reduction
  - At high operation temperatures a better VOC reduction is expected
  - Reduced risk of tar and soot deposits
- However, suitable materials for a high temperature application are needed as well as a higher pressure drop have to be considered.
- Within Task 2.2 test runs with medium and high temperature catalysts at logwood stoves have been performed by BIOS and RISE. Within Task 2.3 the long-term feasibility of foam ceramic filters or their replacement by a catalyst insert has been evaluated by TFZ.

Catalysts for wood stoves (I)

- The temperature range of the flue gas at the catalyst can vary between 400 – 900°C (depending on the positioning of the catalyst in the stove) or between 200 – 350 °C (if the catalyst is installed in the flue gas duct downstream the stove). For an optimum performance the operation temperature has to be between the ignition and the maximum permissible temperature of the selected catalyst.

- Volume flow: For an optimum emission reduction the whole flue gas has to pass through the catalyst. For wood stoves the flue gas volume flow is typically in the range of 15 – 25 m^3/h (depending on the capacity, temperature and the oxygen content).

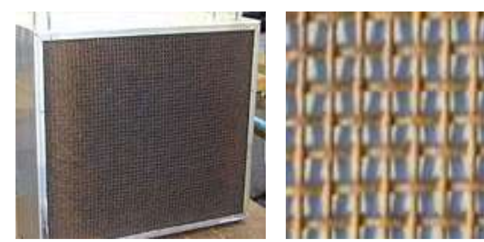
- Typical flue gas composition upstream the catalyst (modern stove):
  - **CO: 500 – 1,000 mg/MJ (reduction by the catalyst expected)**
  - **VOC: < 50 mg/MJ (partial reduction by the catalyst expected)**
  - **TSP: < 50 mg/MJ (partial reduction by the catalyst expected)**
  - **Oxygen: 8 – 12 Vol% dry flue gas**

Catalysts for wood stoves (II)

- The most common catalytic procedure to reduce emissions from stoves is the heterogeneous catalysis. At this type of catalysis the phase of the catalyst differs from that of the reactants:
  - catalyst → solid
  - reactants → gaseous
- The basic structure of solid catalysts consists of metals (most common is iron alloy) or ceramics (e.g. aluminium oxide, zirconium oxide)
- Regarding the structure solid catalysts for emission reduction can be divided into:

Packed beds

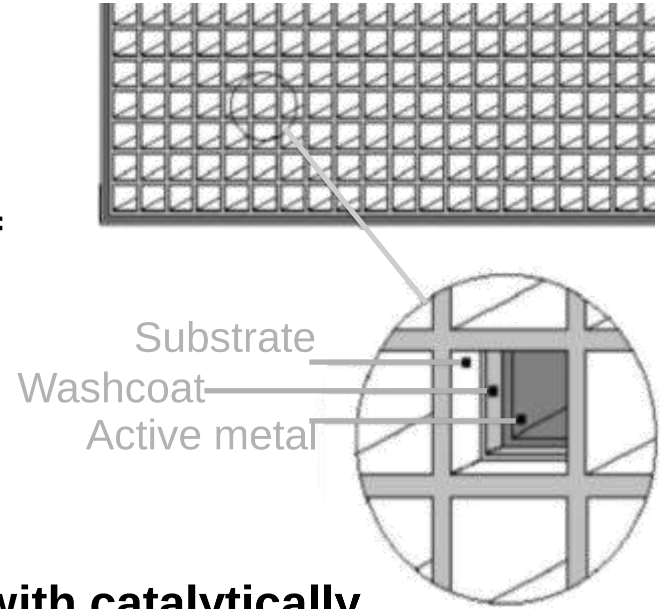
Monoliths (honeycomb or foam structure)



Networks/ wire meshes

Catalysts for wood stoves (III)

Components of solid catalysts:



- **Substrate: Carrier material for the washcoat and the active metal. The structure of the catalyst is defined by the material and production process of the substrate.**
- **Washcoat: To increase the surface of the catalyst a washcoat (powder suspension of metal oxides) is spread and dried on the substrate.**
- **Active metal: The surface is impregnated/coated with catalytically active components Thereby the following main activities of the metals occur:**
  - **Rh > Pd > Pt → oxidation of CO**
  - **Pt > Rh > Pd → oxidation of VOC**
  - **Rh > Pd > Pt → oxidation of NO**
- **At high operation temperatures also metals like Ni, Cu and Mg can achieve considerable conversion rates.**

Results of the test runs with a logwood stove and different catalysts

Prepared by: Christoph Mandl, Thomas Brunner, Ingwald Obernberger (BIOS BIOENERGIESYSTEME GmbH)

Contents

- **Objectives**
- **Methodology**
  - Description of the chimney stove and the test stand
  - Description and characterisation of the catalysts applied
  - Test run procedure
- **Results and conclusions of the test runs**
  - Metal based catalysts
  - Foam ceramics with and without catalyst
- **Recommendations**

Objectives (I)

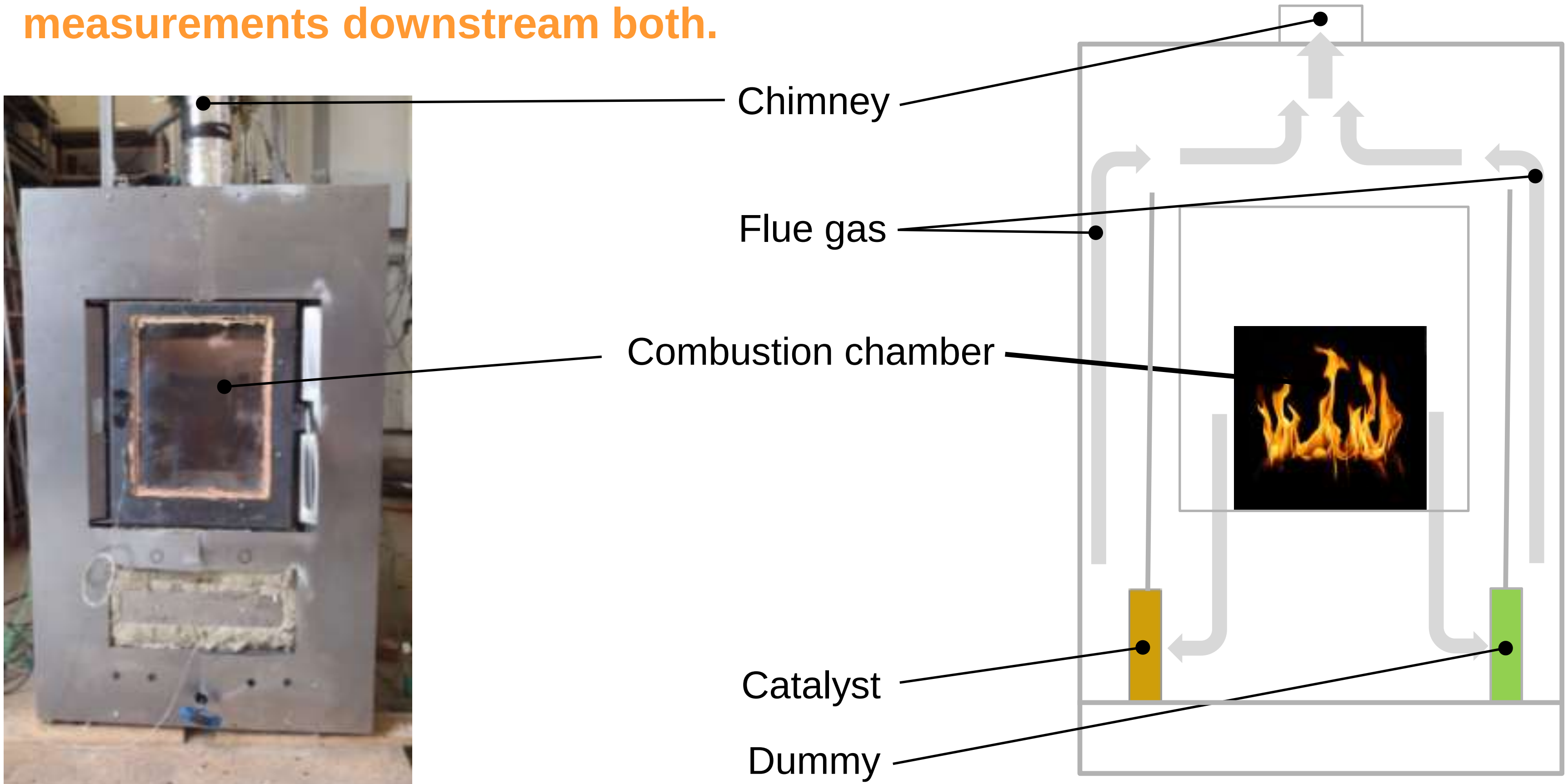
- **Performance of test runs with different high temperature catalysts at a low-emission logwood stove**
  - **Long-term (2 or 3 weeks) operation of the stove with each catalyst**
  - **Performance of dedicated testing campaigns with emission measurements**
- **Different catalysts applied at different stove positions have been tested:**
  - **Metal based honeycomb catalyst installed at the outlet of the post combustion chamber – mounting position I**
- **In addition, BIOS provided data derived from test runs with foam ceramics performed within a national project**
  - **Foam ceramic with and without catalyst installed at the outlet of the main combustion chamber – mounting position II**

Objectives (II)

- Evaluation of the performance of the catalysts in terms of CO and OGC emission reduction
- Evaluation of the long-term operation performance of the catalysts
- Evaluation of the effects of catalyst cleaning after 2 weeks of operation on the emission reduction and the pressure drop caused by the catalyst
- **The evaluations have been performed based on data available from the test runs within the project as well based on additional data derived from the national project of BIOS.**

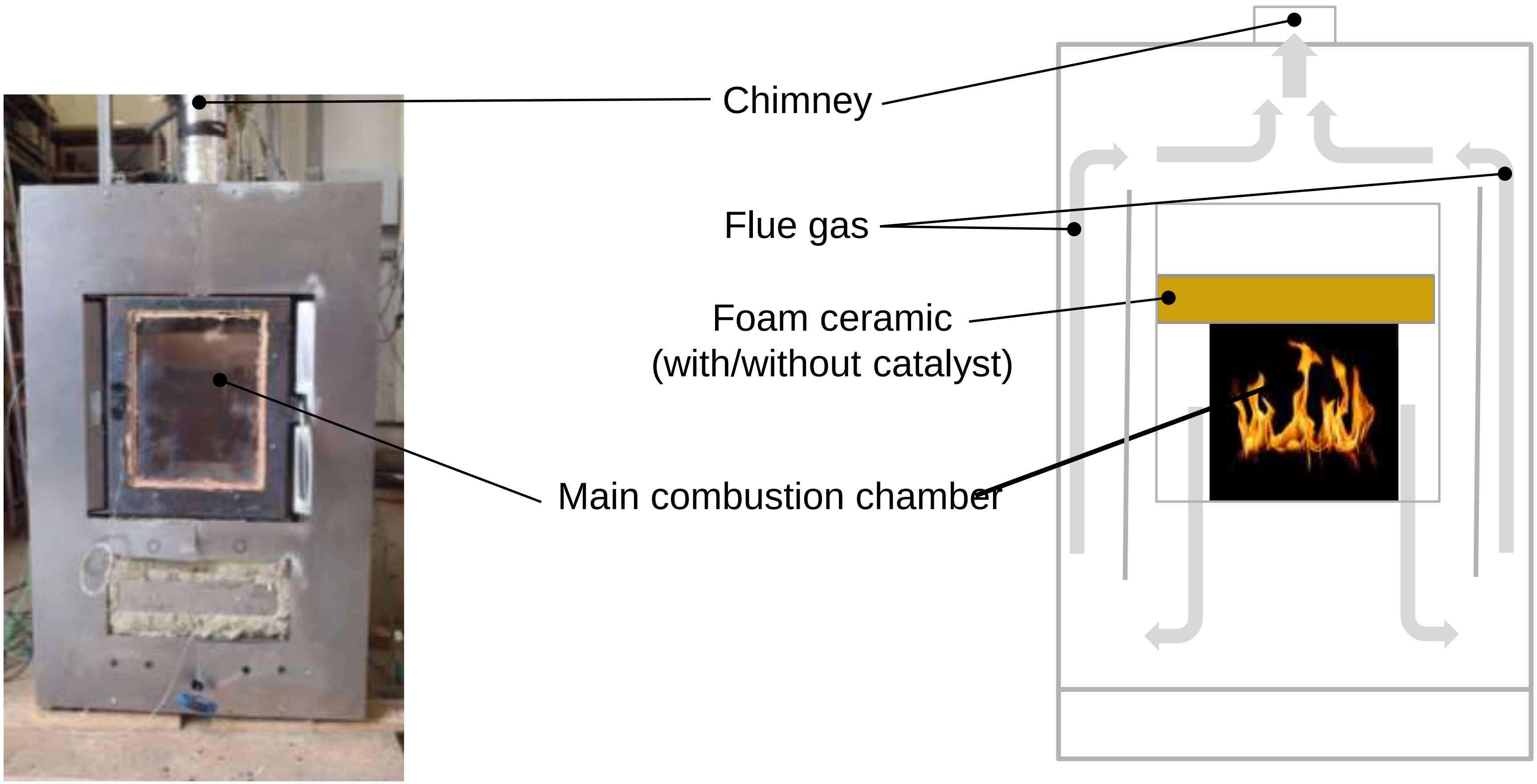
Methodology -
Description of the chimney stove applied – catalyst position I

- **Specially adapted 8 kW logwood chimney stove with 2 flue gas pathways downstream the main burning chamber.**
- **The two flue gas pathways allow for the implementation of a catalyst and of a dummy (substrate without washcoat and catalytic coating) and parallel measurements downstream both.**

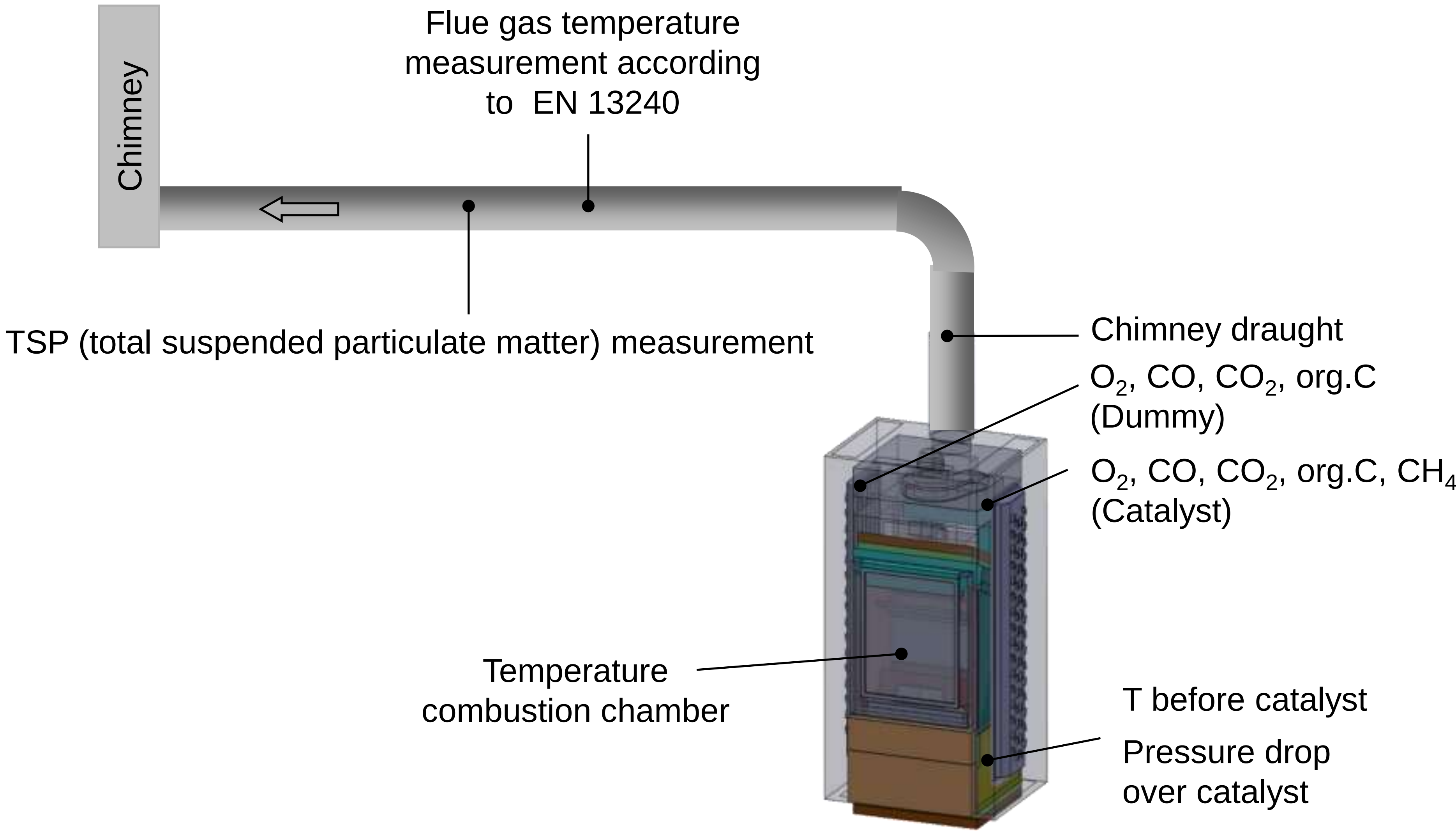


Methodology -
Description of the chimney stove applied – catalyst position II

- **The foam ceramic has been implemented at the outlet of the main combustion chamber of the stove.**



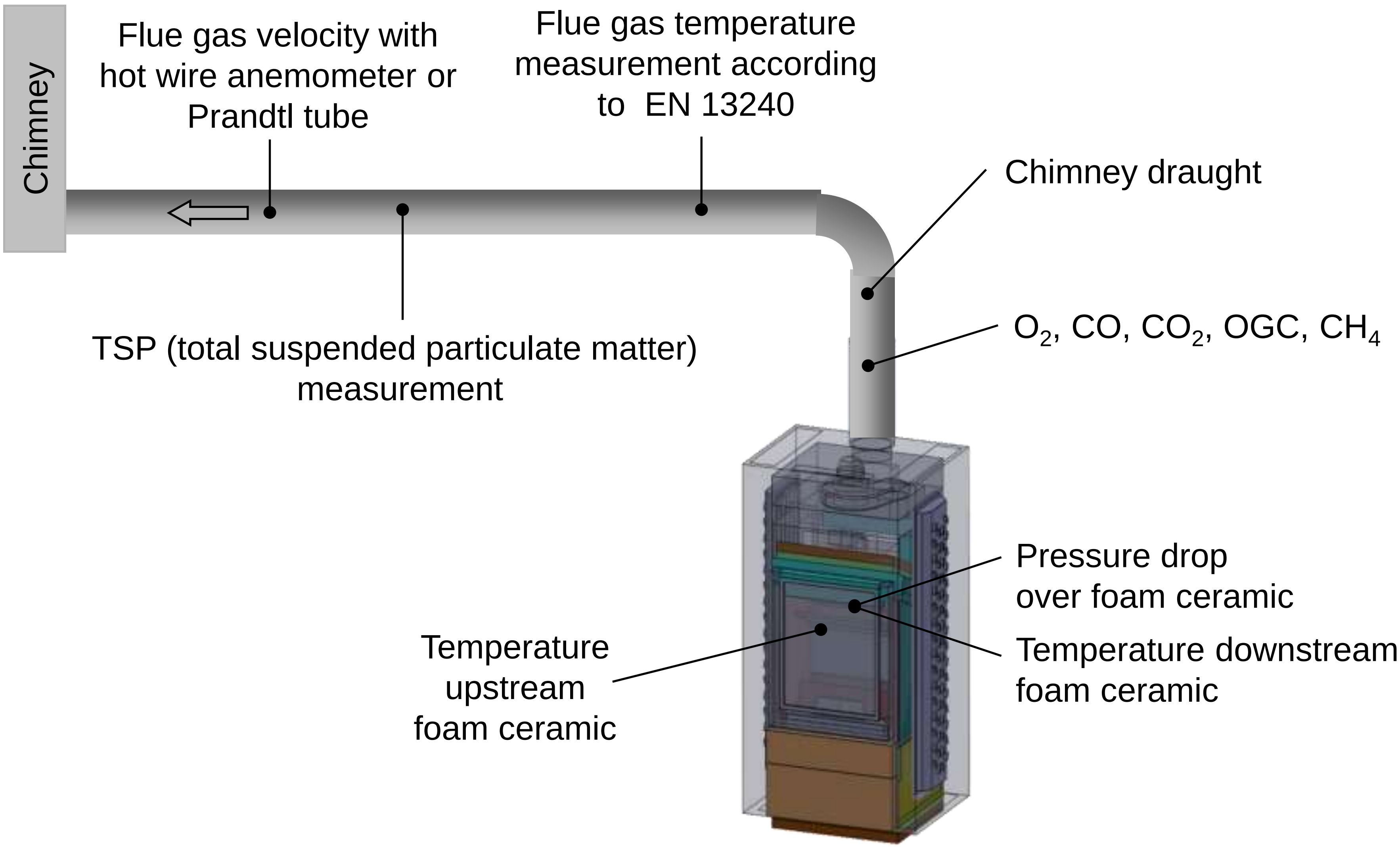
Methodology -
Test stand set-up – catalyst position I (I)



Methodology -
Test stand set-up – catalyst position I (II)

- **Continuous measurements**
  - **Flue gas composition: O_2, CO, OGC, CH_4 (only downstream catalyst) (only during dedicated measurement days)**
  - **Combustion chamber temperature (thermocouple Type K) and flue gas temperature according to Flue gas temperature according to EN 13240 (with suction pyrometer)**
  - **Temperature at catalyst inlet (thermocouple Type K)**
  - **Pressure drop over the catalyst**
  - **Chimney draught**
- **Discontinuous measurements and analyses**
  - **TSP emission measurements according to VDI 2066 (only during the dedicated measurement days)**
  - **Mass of fuel applied per batch**
  - **Analyses of selected fuel samples regarding moisture content and ash content**
  - **Mass of ash produced during a series of batches = during one test day**

Methodology -
Test stand set-up – catalyst position II (I)



Methodology - Test stand set-up – catalyst position II (II)

- **Continuous measurements**
  - Flue gas composition: O_2, CO, OGC, CH_4 (only during dedicated measurement days)
  - Flue gas temperature (thermocouple Type K) upstream foam ceramic and temperature downstream foam ceramic (thermocouple Type K)
  - Flue gas temperature according to EN 13240 (without suction pyrometer)
  - Flue gas velocity with hot wire anemometer (Schmidt Technology) or with Prandtl tube
  - Pressure drop over foam ceramic and chimney draught

- **Discontinuous measurements and analyses**
  - TSP emission measurements according to VDI 2066 (only during the dedicated measurement days)
  - Mass of fuel applied per batch
  - Analyses of selected fuel samples regarding moisture content and ash content
  - Mass of ash produced during a series of batches = during one test day

Methodology - Description and characterisation of the catalysts applied (I)

- **Metal based honeycomb catalysts have been installed at the outlet of the post combustion chamber – position I**

No	1	2	3
Name	EnviCat®2520	Tailor-made catalyst I	Tailor-made catalyst II
Supplier	Clariant AG (DE)		
Substrate	metal	metal	metal
Structure	honeycomb	honeycomb	honeycomb
CPSI [1)]	50	50	50
Dimension (HxWxL)	32 x 160 x 50 mm	30 x 160 x 50 mm	30 x 160 x 50 mm
Washcoat	Al_2O_3		
Active metal	Pt, Pb	Pt	Pt, Pd
Light-off temperature[2)]	200°C	not defined yet since the catalysts are prototypes	not defined yet since the catalysts are prototypes
Max. operation temp	650°C	650°C	650°C

Explanations: [1)] Cells per square inch (1 CPSI ~ 645 mm^2); [2)] Temperature that marks start of reactions

Methodology - Description and characterisation of the catalysts applied (II)

- **Foam ceramics have been installed at the outlet of the main combustion chamber – position II**

No	1	2	3
Name	Non-catalytic foam ceramic	Tailor-made catalyst I	Tailor-made catalyst II
Substrate	SSiC	SSiC	SSiC
Structure	Foam ceramic	Foam ceramic	Foam ceramic
PPI [1)]	10	10	10
Dimension (HxWxL)	380 x 50 x 50 mm	380 x 50 x 50 mm	380 x 50 x 50 mm
Active metal	No active catalyst	Pt [2)]	Pt [2)]

Explanations: [1)] Pores per inch; [2)] Pt content of tailor-made catalyst II higher than Pt content of tailor-made catalyst I

Methodology -
Test run methodology (I)

- **Prior to the test runs a leakage air test has been performed**
- **General operation conditions**
  - **Constant draught of 12 Pa**
  - **Test fuel: hardwood (beech) without bark, triangle shape**
- **Overall procedure**
  - **Stove operation over 10 working days (stove operation with catalytically coated foam ceramic is still ongoing)**
  - **Performance of 2 or 3 dedicated one-day measurement series with emission measurements**
- **Additional test runs**
  - **Performance of one dedicated test run with the stove without integrated foam ceramic in order to basically compare test runs results**

Methodology -
Test run methodology (II)

- According to the stove operation defined during the meeting in Copenhagen (04/2015), one operation day consists of 8 successive batches (5 full load + 3 partial load) starting from cold conditions (including the ignition batch)

- Refilling
  - Time for refilling: CO_2 content of the flue gas is ≤ 4 vol% and ≤ 25 % of the maximum CO_2 content of the respective batch (if CO_2 max is ≤ 12% ➔ refilling at 3 % CO_2)

- Mode of refilling as defined by the manufacturer
  - Number of logs: 2 for Batch 2 to 8
  - Mass of batch: 2.4 kg (full load) and 1.2 (partial load)
  - Dimensions of firewood pieces: 25 cm length

- Performance of gaseous and PM emission measurements
  - Gaseous emissons (CO, OGC, O_2, CH_4): continuous measurement from before ignition of batch 1 until the end of batch 8
  - PM emissions: over the whole batch (from closing the door until opening it again)

Methodology -
Test run methodology (III)

Measurement equipment applied

- CO, O_2, CO_2
  - Emerson NGA 2000
- CH_4 and OGC
  - GRAPHITE 52 M-D PORTABLE (ENVIRONNEMENT S.A.)
- TSP emissions
  - equipment according to VDI 2066-1

Methodology - Test run methodology (IV)

Data evaluation - conventional

- **Emissions**
  - **Time weighted average values, calculated as mg/Nm³ at 13% O_2 (based on time weighted average O_2 content over all considered batches)**
  - **mg/MJ derived from dividing the mg/Nm³ value by 1.5 (approximation)**
- **Efficiency**
  - **Calculation according to prEN 16510 / DIN EN 13240**
  - **Losses of unburnt material on the grate: 0.5 % (DIN EN 13240)**
  - **Thermal and chemical flue gas losses during cooling down phase are not considered**
- **Full load**
  - **Evaluation of all batches 1-5 (PM sampling: batches 1, 3, 5)**
- **Partial load**
  - **Evaluation of batches 1, 2, 6, 7, 8 (PM sampling: batches 1, 7)**

Methodology - Test run methodology (V)

Data evaluation – flue gas volume based

- **Emissions**
  - **mg/Nm³ derived from dividing the overall mg value by the flue gas volume at 13% O_2 (based on time weighted average O_2 content over the batch)**
  - **mg/MJ derived from dividing the overall mg value by the power input related to the NCV of the fuel mass converted during the batch (beech wood without remaining char coal and fuel ash)**

fuel composition		beech wood [1]	beech wood without remaining char coal [2]
parameter	unit		
moisture content	[wt.% w.b.]	15.00	15.80
carbon	[wt.% d.b.]	49.1	45.6
hydrogen	[wt.% d.b.]	6.1	6.6
oxygen	[wt.% d.b.]	44.4	47.7
ash content [3]	[wt.% d.b.]	0.4	0.00
gross calorific value (GCV)	[wt.% d.b.]	19.3	18.7
net calorific value (NCV)	[wt.% w.b.]	15.0	14.2

Explanations:[1] fuel composition according to wet chemical analyses; [2] fuel composition without remaining char coal (including fuel ash) at the end of batch; thus, this fuel composition is related to the fuel converted during the batch; composition of remaining char coal (including fuel ash): 92.5 wt.% C, 0.8 wt.% H, 1.5 wt.% O, 5.2 wt.% ash; [3] remaining char coal includes entire fuel ash; therefore, ash content of fuel converted during the batch (beech wood without remaining char coal) is equal to 0

Results of the test runs with a logwood stove and different catalysts

Results of the test runs performed

with metal based catalysts

General aspects

- General remarks regarding the data presented on the next slides
  - **O_2 contents in vol% are related to dry flue gas**
  - **Emissions in mg/Nm³ are related to dry flue gas and 13 vol% O_2**
  - **Emissions in mg/MJ are related to the net calorific value of the fuel**
  - **CO and OGC emission reduction**
    - CO and OGC measurement data are recorded in a 2-second interval from which 10 second mean values are calculated
    - for each 10-second data point the emission reduction is calculated from the averaged emissions downstream the catalyst and downstream the dummy
    - an average value of these emission reductions is calculated over the respective test run period and is then displayed in the tables/diagrams
  - **% CH_4 in OGC = (ppm CH_4 / ppm OGC) * 100**
  - **n.m. no measurement performed**

Fuel applied

Beech logs without bark		
Moisture content [1)]	wt% wet basis	10.1-15.7
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
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: 12.4 wt% w.b. (33 samples)
[2)] calculated according to Gaur

Results of test runs with a logwood stove and different catalysts

Results of the test runs performed with Catalyst 1 – EnviCat® – at catalyst position I

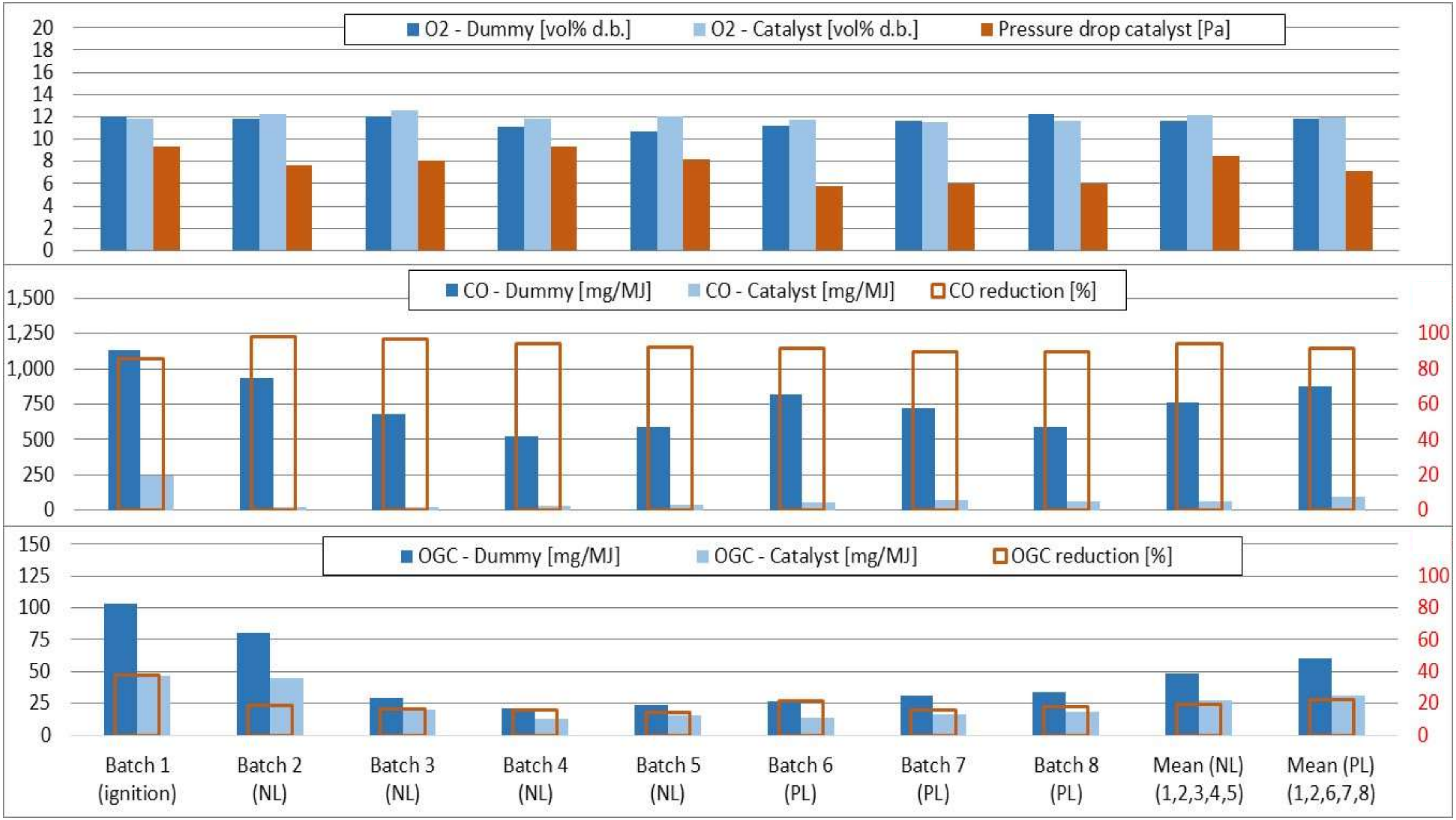
Catalyst 1 – EnviCat® – Overview

Day	Date	Comments
1	12/08/2015	Measurements – series 1
2	13/08/2015	Operation
3	14/08/2015	Operation
4	17/08/2015	Operation
5	18/08/2015	Operation
6	19/08/2015	Measurements – series 2
7	21/08/2015	Operation
8	24/08/2015	Operation
9	25/08/2015	Operation
10	26/08/2015	Measurements – series 3 Manual cleaning of the catalyst
11	27/08/2015	Measurements – series 4

Catalyst 1 – EnviCat® – Day 1: measurements – series 1 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		12.08 13:25	12.08 14:18	12.08 15:28	12.08 16:45	12.08 17:47	12.08 18:53	12.08 19:37	12.08 20:17		
Door opened		12.08 14:18	12.08 15:28	12.08 16:44	12.08 17:46	12.08 18:52	12.08 19:36	12.08 20:16	12.08 20:55		
Fuel input	kg w.b.	2,7	2,4	2,4	2,4	2,4	1,2	1,2	1,2	12,3	8,7
O_2 - Dummy	**vol% d.b.**	**12,1**	**11,9**	**12,0**	**11,1**	**10,7**	**11,2**	**11,6**	**12,3**	**11,6**	**11,9**
O_2 - Catalyst	**vol% d.b.**	**11,8**	**12,3**	**12,6**	**11,8**	**12,0**	**11,8**	**11,5**	**11,6**	**12,2**	**11,9**
CO - Dummy	mg/Nm³	1.698,4	1.406,7	1.021,9	789,2	882,1	1.224,8	1.075,8	885,2	1.146,6	1.316,4
CO - Catalyst	mg/Nm³	367,1	29,9	31,7	39,2	53,6	81,7	109,9	88,9	95,0	137,8
CO - Dummy	**mg/MJ**	**1.132,3**	**937,8**	**681,3**	**526,1**	**588,1**	**816,5**	**717,2**	**590,1**	**764,4**	**877,6**
CO - Catalyst	**mg/MJ**	**244,7**	**19,9**	**21,1**	**26,1**	**35,7**	**54,5**	**73,3**	**59,2**	**63,3**	**91,9**
CO reduction	**%**	**85,4**	**98,0**	**96,9**	**94,4**	**92,5**	**91,3**	**89,8**	**89,4**	**94,0**	**91,4**
OGC - Dummy	mg/Nm³	155,4	121,3	43,3	31,6	35,1	40,1	47,0	51,4	72,8	90,4
OGC - Catalyst	mg/Nm³	70,5	66,6	30,5	18,8	23,4	20,4	24,5	27,0	41,5	46,0
CH4 - Catalyst	mg/Nm³	56,8	56,2	21,8	12,0	18,8	16,5	19,9	23,3	32,6	37,8
OGC - Dummy	**mg/MJ**	**103,6**	**80,8**	**28,9**	**21,1**	**23,4**	**26,8**	**31,3**	**34,2**	**48,5**	**60,3**
OGC - Catalyst	**mg/MJ**	**47,0**	**44,4**	**20,3**	**12,5**	**15,6**	**13,6**	**16,3**	**18,0**	**27,7**	**30,7**
CH4 - Catalyst	mg/MJ	37,9	37,5	14,5	8,0	12,5	11,0	13,3	15,5	21,7	25,2
CH4 in OGC	%	80,6	84,4	71,5	63,9	80,1	80,9	81,1	86,4	78,5	82,1
OGC reduction	**%**	**38,0**	**18,7**	**16,4**	**15,7**	**14,2**	**21,8**	**16,0**	**18,1**	**19,3**	**22,3**
TSP	**mg/Nm³**	**40,4**	**n.m.**	**24,5**	**n.m.**	**27,0**	**n.m.**	**32,1**	**n.m.**	**28,8**	**36,8**
TSP	**mg/MJ**	**27,0**	**n.m.**	**16,3**	**n.m.**	**18,0**	**n.m.**	**21,4**	**n.m.**	**19,2**	**24,5**
T combustion chamber	°C	576,6	582,0	598,6	642,9	626,3	620,2	630,0	610,5	603,4	598,2
T Catalyst inlet	°C	349,8	453,2	505,6	543,4	548,7	525,1	527,7	520,2	483,6	465,4
T flue gas (EN13240)	°C	79,8	126,9	153,3	172,6	183,1	180,1	185,2	191,3	145,3	145,8
Chimney draught	Pa	12,3	12,5	12,5	12,6	12,6	12,6	12,6	12,6	12,5	12,5
Pressure drop catalyst	**Pa**	**9,3**	**7,6**	**8,0**	**9,3**	**8,2**	**5,7**	**6,0**	**6,0**	**8,5**	**7,2**
Efficiency (EN13240)	**%**	**95,2**	**91,6**	**87,4**	**86,7**	**85,4**	**86,1**	**85,9**	**85,3**	**88,7**	**88,9**

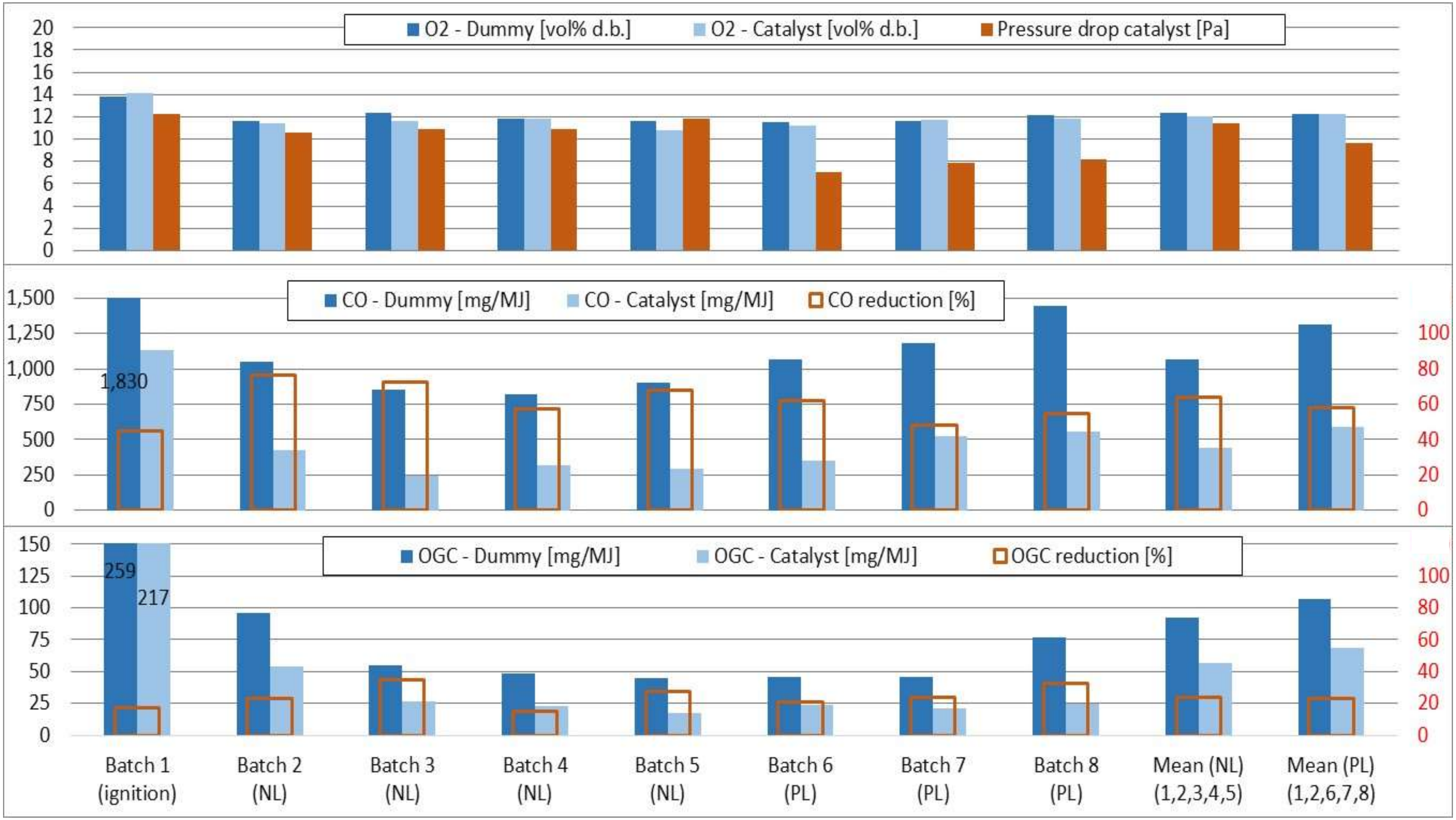
Catalyst 1 – EnviCat® –
Day 1: measurements – series 1 (II)



Catalyst 1 – EnviCat® –
Day 6: measurements – series 2 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		19/08 11:06	19/08 12:11	19/08 13:19	19/08 14:30	19/08 15:43	19/08 16:49	19/08 17:35	19/08 18:21		
Door opened		19/08 12:10	19/08 13:17	19/08 14:29	19/08 15:41	19/08 16:47	19/08 17:34	19/08 18:20	19/08 19:03		
Fuel input	kg w.b.	2.7	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.3	8.7
O_2 - Dummy	**vol% d.b.**	**13.8**	**11.6**	**12.3**	**11.8**	**11.7**	**11.6**	**11.6**	**12.1**	**12.3**	**12.3**
O_2 - Catalyst	**vol% d.b.**	**14.1**	**11.4**	**11.6**	**11.8**	**10.8**	**11.3**	**11.7**	**11.8**	**12.0**	**12.2**
CO - Dummy	mg/Nm³	2,745.7	1,572.8	1,281.0	1,233.7	1,347.2	1,604.4	1,775.3	2,170.1	1,599.9	1,971.7
CO - Catalyst	mg/Nm³	1,694.8	635.2	365.0	474.1	441.3	526.6	782.7	832.2	664.4	887.3
CO - Dummy	**mg/MJ**	**1,830.5**	**1,048.5**	**854.0**	**822.5**	**898.2**	**1,069.6**	**1,183.6**	**1,446.7**	**1,066.6**	**1,314.5**
CO - Catalyst	**mg/MJ**	**1,129.9**	**423.5**	**243.3**	**316.1**	**294.2**	**351.1**	**521.8**	**554.8**	**442.9**	**591.5**
CO reduction	**%**	**45.1**	**76.6**	**72.2**	**57.1**	**67.7**	**62.2**	**48.2**	**54.4**	**63.9**	**58.1**
OGC - Dummy	mg/Nm³	388.0	144.3	82.6	72.8	67.0	68.2	68.9	114.7	138.2	160.6
OGC - Catalyst	mg/Nm³	324.9	80.3	39.5	34.6	25.8	35.2	31.4	37.2	85.7	102.8
CH4 - Catalyst	mg/Nm³	145.8	41.7	25.4	20.0	15.2	32.2	22.8	24.6	44.5	55.7
OGC - Dummy	**mg/MJ**	**258.7**	**96.2**	**55.0**	**48.5**	**44.7**	**45.5**	**46.0**	**76.5**	**92.1**	**107.1**
OGC - Catalyst	**mg/MJ**	**216.6**	**53.5**	**26.3**	**23.1**	**17.2**	**23.4**	**20.9**	**24.8**	**57.1**	**68.5**
CH4 - Catalyst	mg/MJ	97.2	27.8	16.9	13.4	10.2	21.5	15.2	16.4	29.7	37.1
CH4 in OGC	%	44.9	52.0	64.3	57.9	59.0	91.6	72.7	66.1	52.0	54.2
OGC reduction	**%**	**17.0**	**22.9**	**34.4**	**15.2**	**27.6**	**21.0**	**24.1**	**32.9**	**23.5**	**22.9**
TSP	**mg/Nm³**	**93.1**	**n.m.**	**21.6**	**n.m.**	**24.1**	**n.m.**	**20.6**	**n.m.**	**36.6**	**50.0**
TSP	**mg/MJ**	**62.0**	**n.m.**	**14.4**	**n.m.**	**16.0**	**n.m.**	**13.7**	**n.m.**	**24.4**	**33.4**
T combustion chamber	°C	504.7	577.7	599.8	600.0	619.5	612.5	594.3	599.5	577.7	569.2
T Catalyst inlet	°C	293.5	451.9	504.4	515.7	539.0	499.9	495.7	489.8	461.4	434.3
T flue gas (EN13240)	°C	72.3	116.2	141.8	158.3	170.9	165.3	164.8	159.6	132.7	129.5
Chimney draught	Pa	12.2	12.7	12.7	12.7	12.7	12.7	12.7	12.6	12.6	12.6
Pressure drop catalyst	**Pa**	**12.3**	**10.6**	**10.9**	**10.9**	**11.9**	**7.0**	**7.9**	**8.2**	**11.4**	**9.6**
Efficiency (EN13240)	**%**	**93.9**	**92.5**	**89.2**	**87.4**	**87.5**	**87.5**	**86.8**	**87.2**	**89.4**	**89.4**

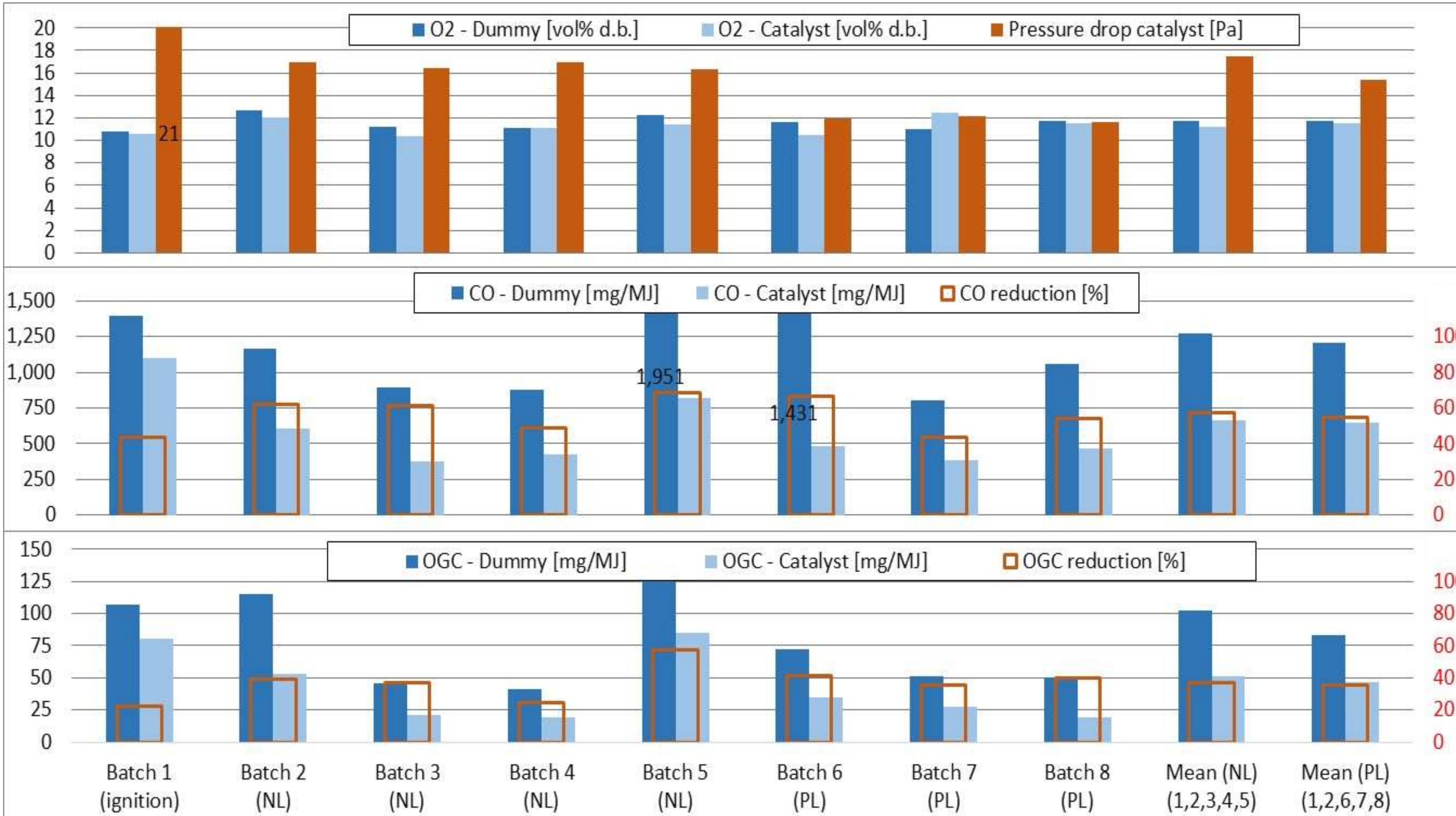
Catalyst 1 – EnviCat® –
Day 6: measurements – series 2 (II)



Catalyst 1 – EnviCat® – Day 10: measurements – series 3 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		26/08 08:20	26/08 09:15	26/08 10:28	26/08 11:33	26/08 12:41	26/08 13:58	26/08 14:43	26/08 15:24		
Door opened		26/08 09:14	26/08 10:26	26/08 11:32	26/08 12:40	26/08 13:57	26/08 14:42	26/08 15:23	26/08 16:11		
Fuel input	kg w.b.	2.7	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.3	8.7
O_2 - Dummy	**vol% d.b.**	**10.8**	**12.6**	**11.2**	**11.1**	**12.3**	**11.6**	**11.0**	**11.8**	**11.8**	**11.8**
O_2 - Catalyst	**vol% d.b.**	**10.6**	**12.1**	**10.4**	**11.1**	**11.4**	**10.5**	**12.4**	**11.5**	**11.3**	**11.5**
CO - Dummy	mg/Nm³	2,092.8	1,751.1	1,345.1	1,318.1	2,926.9	2,146.5	1,204.0	1,585.2	1,914.3	1,803.4
CO - Catalyst	mg/Nm³	1,653.6	913.8	566.0	636.4	1,224.1	716.7	570.8	700.9	996.1	972.2
CO - Dummy	**mg/MJ**	**1,395.2**	**1,167.4**	**896.7**	**878.7**	**1,951.3**	**1,431.0**	**802.7**	**1,056.8**	**1,276.2**	**1,202.3**
CO - Catalyst	**mg/MJ**	**1,102.4**	**609.2**	**377.3**	**424.2**	**816.0**	**477.8**	**380.5**	**467.3**	**664.1**	**648.1**
CO reduction	**%**	**43.5**	**61.9**	**61.1**	**48.9**	**68.8**	**66.6**	**43.3**	**54.0**	**57.6**	**54.5**
OGC - Dummy	mg/Nm³	160.1	172.2	68.7	61.3	304.6	107.7	77.2	75.5	153.6	125.2
OGC - Catalyst	mg/Nm³	120.2	79.6	32.1	29.3	127.8	52.1	40.8	28.5	77.2	69.3
CH4 - Catalyst	mg/Nm³	53.1	53.4	16.4	14.9	96.5	44.6	34.9	21.1	47.3	43.4
OGC - Dummy	**mg/MJ**	**106.7**	**114.8**	**45.8**	**40.9**	**203.1**	**71.8**	**51.4**	**50.3**	**102.4**	**83.4**
OGC - Catalyst	**mg/MJ**	**80.1**	**53.1**	**21.4**	**19.6**	**85.2**	**34.7**	**27.2**	**19.0**	**51.5**	**46.2**
CH4 - Catalyst	mg/MJ	35.4	35.6	10.9	10.0	64.3	29.7	23.3	14.1	31.5	28.9
CH4 in OGC	%	44.2	67.0	51.2	50.9	75.5	85.7	85.5	74.1	61.2	62.6
OGC reduction	**%**	**22.4**	**39.0**	**37.1**	**24.7**	**57.1**	**41.2**	**35.6**	**39.8**	**37.0**	**35.3**
TSP	**mg/Nm³**	**44.7**	**n.m.**	**15.5**	**n.m.**	**45.5**	**n.m.**	**20.5**	**n.m.**	**33.7**	**34.8**
TSP	**mg/MJ**	**29.8**	**n.m.**	**10.4**	**n.m.**	**30.3**	**n.m.**	**13.7**	**n.m.**	**22.5**	**23.2**
T combustion chamber	°C	587.1	578.1	627.9	633.6	573.4	600.4	594.5	609.7	595.7	588.8
T Catalyst inlet	°C	351.1	458.5	519.8	535.4	518.8	505.4	484.2	495.0	480.7	453.6
T flue gas (EN13240)	°C	77.4	117.0	138.8	153.9	163.2	161.2	162.5	164.2	132.8	132.1
Chimney draught	Pa	12.1	12.3	12.2	12.2	12.3	12.4	12.4	12.3	12.3	12.3
Pressure drop catalyst	**Pa**	**21.4**	**17.0**	**16.4**	**17.0**	**16.4**	**12.0**	**12.1**	**11.6**	**17.5**	**15.4**
Efficiency (EN13240)	**%**	**95.0**	**91.8**	**90.4**	**88.5**	**87.1**	**88.5**	**86.2**	**87.2**	**89.9**	**89.7**

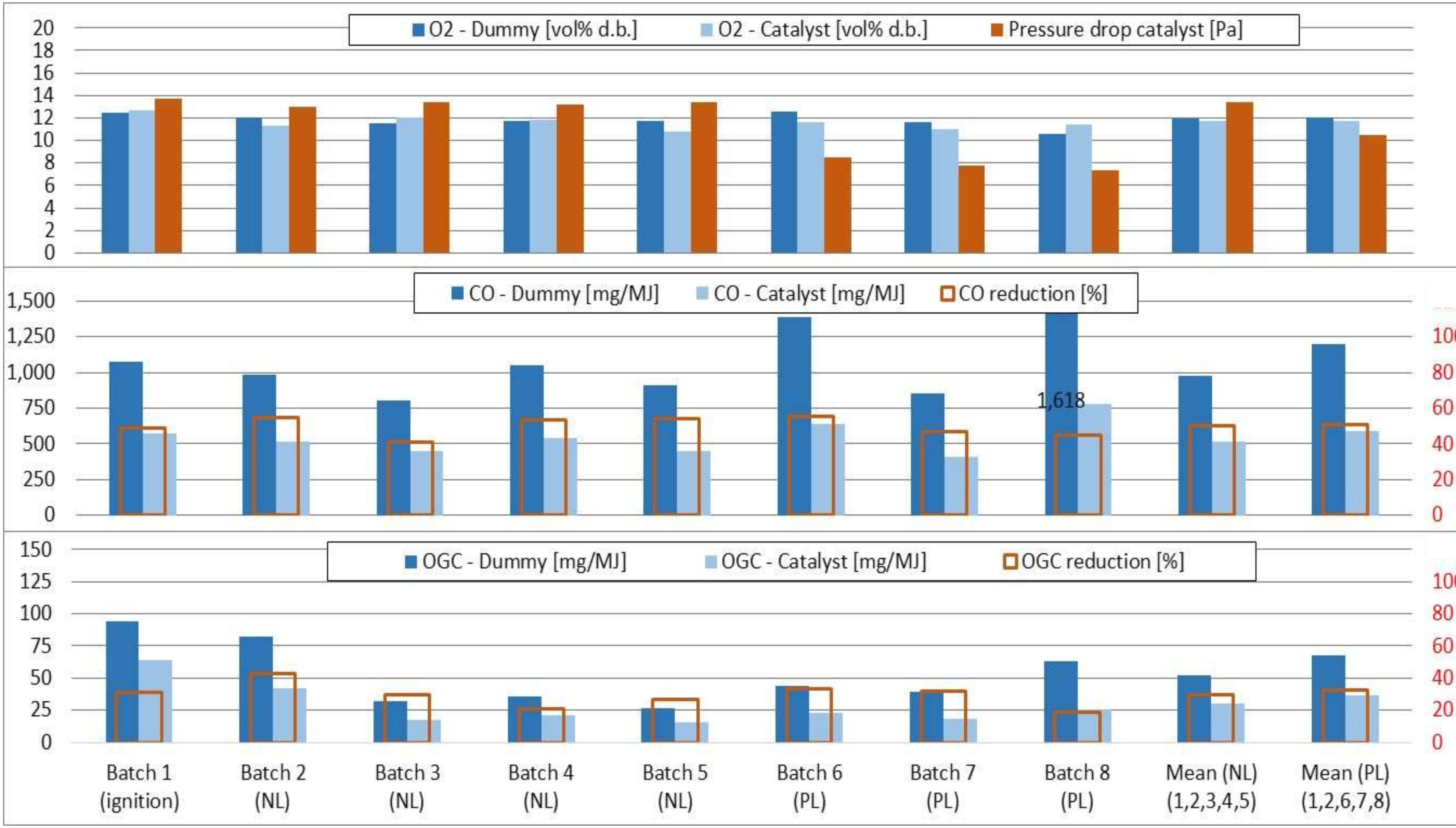
Catalyst 1 – EnviCat® –
Day 10: measurements – series 3 (II)



Catalyst 1 – EnviCat® – Day 11: measurements – series 4 (I)

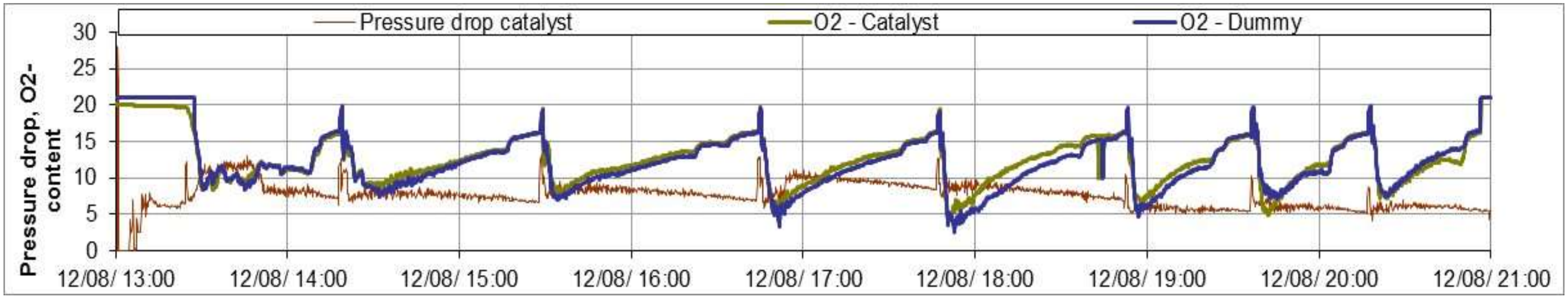
		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		27/08 09:16	27/08 10:12	27/08 11:19	27/08 12:29	27/08 13:42	27/08 14:49	27/08 15:40	27/08 16:21		
Door opened		27/08 10:10	27/08 11:18	27/08 12:27	27/08 13:41	27/08 14:48	27/08 15:39	27/08 16:19	27/08 17:05		
Fuel input	kg w.b.	2.8	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.4	8.8
O_2 - Dummy	**vol% d.b.**	**12.5**	**12.0**	**11.5**	**11.7**	**11.7**	**12.6**	**11.6**	**10.6**	**12.0**	**12.0**
O_2 - Catalyst	**vol% d.b.**	**12.7**	**11.3**	**12.0**	**11.8**	**10.8**	**11.7**	**11.0**	**11.4**	**11.8**	**11.7**
CO - Dummy	mg/Nm³	1,615.0	1,472.7	1,198.3	1,580.8	1,370.0	2,080.6	1,276.4	2,427.6	1,468.3	1,802.1
CO - Catalyst	mg/Nm³	856.0	769.4	676.3	803.4	676.4	952.5	615.3	1,171.9	767.4	884.5
CO - Dummy	**mg/MJ**	**1,076.7**	**981.8**	**798.9**	**1,053.8**	**913.3**	**1,387.1**	**850.9**	**1,618.4**	**978.9**	**1,201.4**
CO - Catalyst	**mg/MJ**	**570.7**	**513.0**	**450.9**	**535.6**	**450.9**	**635.0**	**410.2**	**781.2**	**511.6**	**589.7**
CO reduction	**%**	**48.5**	**54.6**	**40.8**	**53.6**	**54.1**	**55.4**	**46.6**	**45.0**	**50.3**	**50.5**
OGC - Dummy	mg/Nm³	141.7	123.1	48.2	53.3	39.2	66.3	58.5	94.8	77.6	101.7
OGC - Catalyst	mg/Nm³	96.0	63.4	26.1	31.0	23.9	34.3	27.4	38.5	45.5	54.4
CH4 - Catalyst	mg/Nm³	44.1	31.7	15.4	17.4	15.9	27.8	18.2	28.3	24.6	31.8
OGC - Dummy	**mg/MJ**	**94.5**	**82.0**	**32.1**	**35.5**	**26.1**	**44.2**	**39.0**	**63.2**	**51.7**	**67.8**
OGC - Catalyst	**mg/MJ**	**64.0**	**42.2**	**17.4**	**20.7**	**16.0**	**22.8**	**18.3**	**25.6**	**30.3**	**36.2**
CH4 - Catalyst	mg/MJ	29.4	21.2	10.2	11.6	10.6	18.5	12.1	18.9	16.4	21.2
CH4 in OGC	%	45.9	50.1	59.0	56.1	66.6	81.1	66.3	73.5	54.0	58.6
OGC reduction	**%**	**31.3**	**43.0**	**29.5**	**20.7**	**26.8**	**33.6**	**32.0**	**19.0**	**29.9**	**32.6**
TSP	**mg/Nm³**	**32.3**	**n.m.**	**17.5**	**n.m.**	**26.3**	**n.m.**	**17.1**	**n.m.**	**25.4**	**25.5**
TSP	**mg/MJ**	**21.6**	**n.m.**	**11.7**	**n.m.**	**17.6**	**n.m.**	**11.4**	**n.m.**	**16.9**	**17.0**
T combustion chamber	°C	563.4	593.3	623.8	619.6	632.7	583.4	605.7	606.7	604.9	586.0
T Catalyst inlet	°C	349.5	486.2	541.4	550.3	563.3	517.5	503.3	502.9	502.9	467.4
T flue gas (EN13240)	°C	77.9	121.7	148.9	166.7	176.1	175.0	172.8	175.3	141.0	140.2
Chimney draught	Pa	12.2	12.3	12.8	13.0	13.3	14.7	13.1	12.3	12.7	12.9
Pressure drop catalyst	**Pa**	**13.8**	**13.0**	**13.4**	**13.2**	**13.4**	**8.5**	**7.8**	**7.3**	**13.4**	**10.5**
Efficiency (EN13240)	**%**	**94.5**	**91.9**	**87.6**	**86.2**	**86.7**	**85.5**	**86.7**	**85.7**	**88.6**	**88.6**

Catalyst 1 – EnviCat® – Day 11: measurements – series 4 (II)

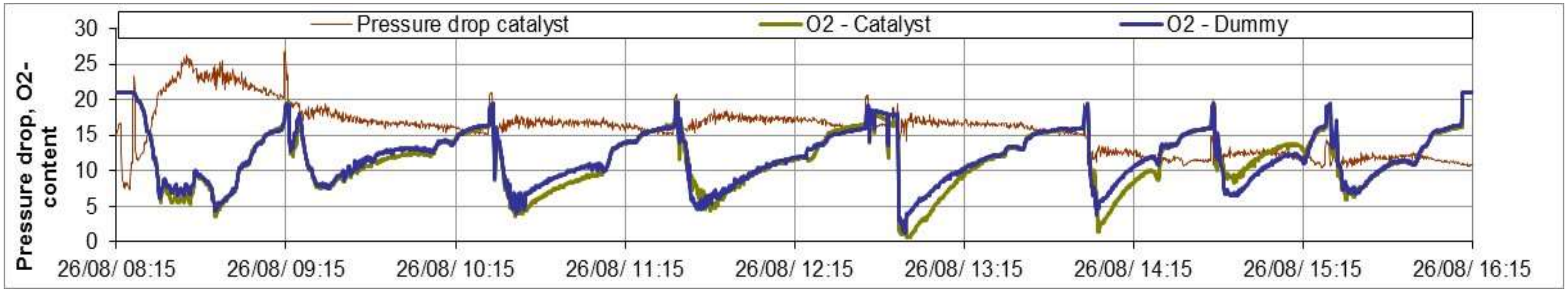


Catalyst 1 – EnviCat® – comparisons of day 1, 10 and 11 – pressure drop and O_2 trends

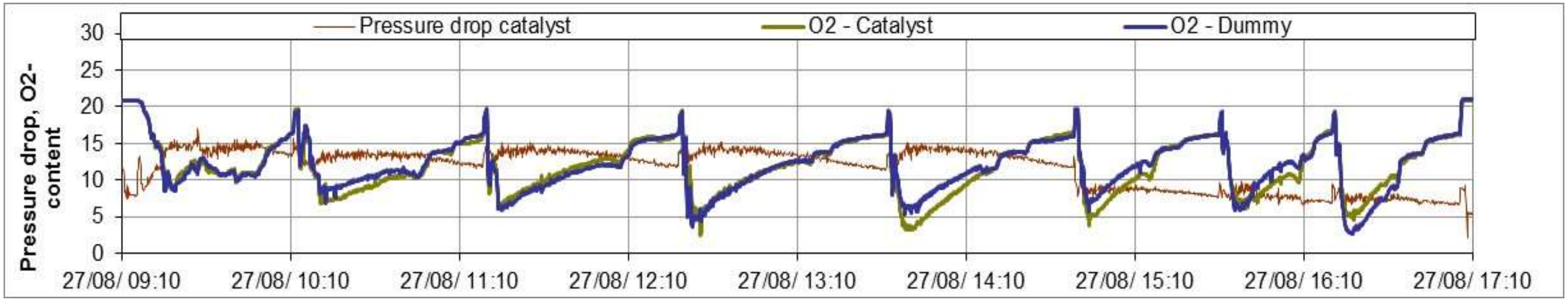
1



10

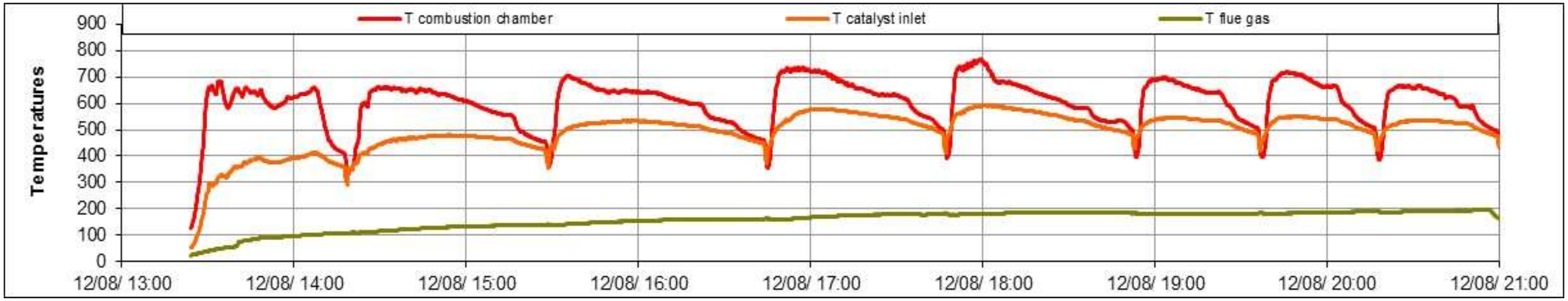


11

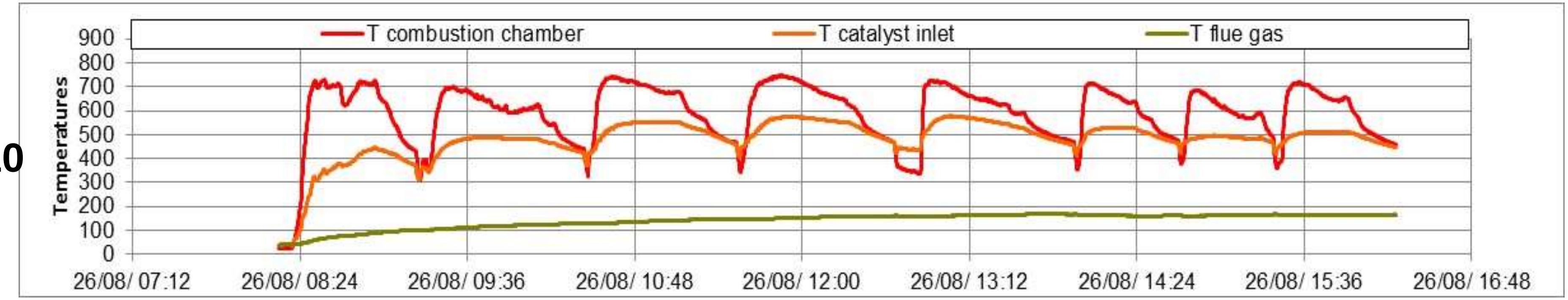


Catalyst 1 – EnviCat® – comparisons of day 1, 10 and 11 – temperatures

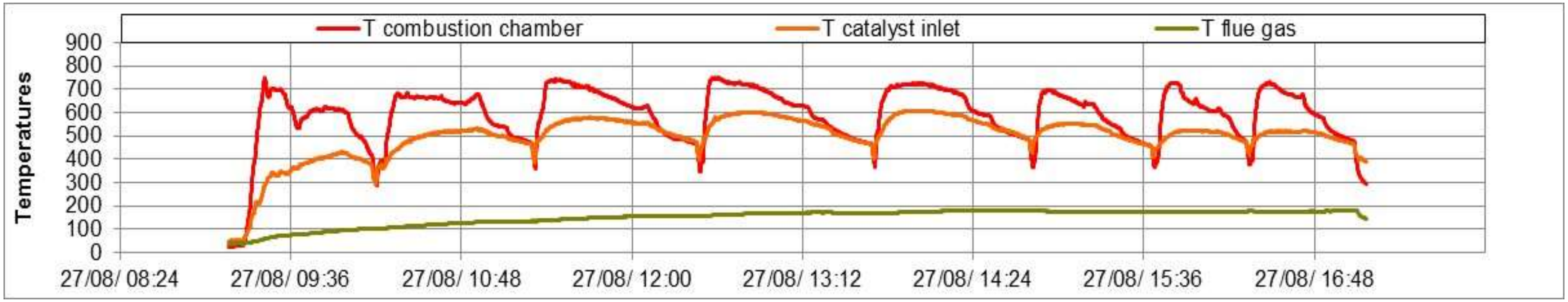
1



10

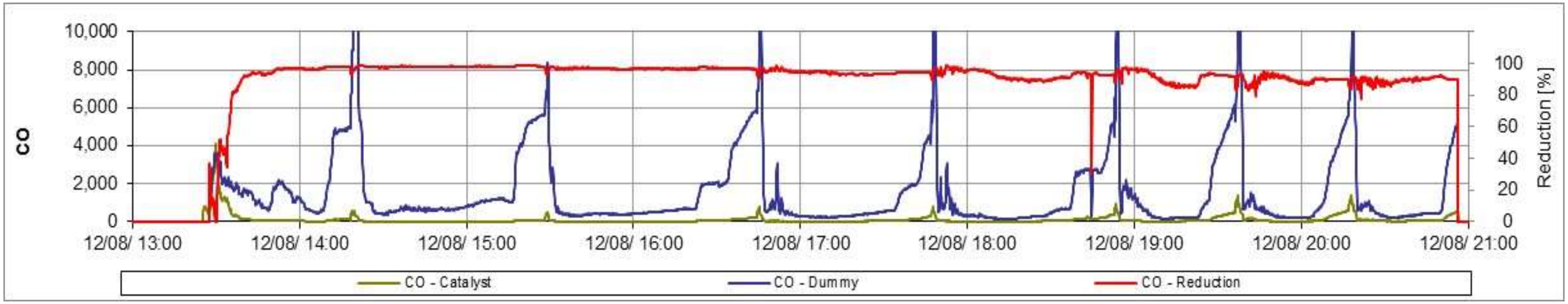


11

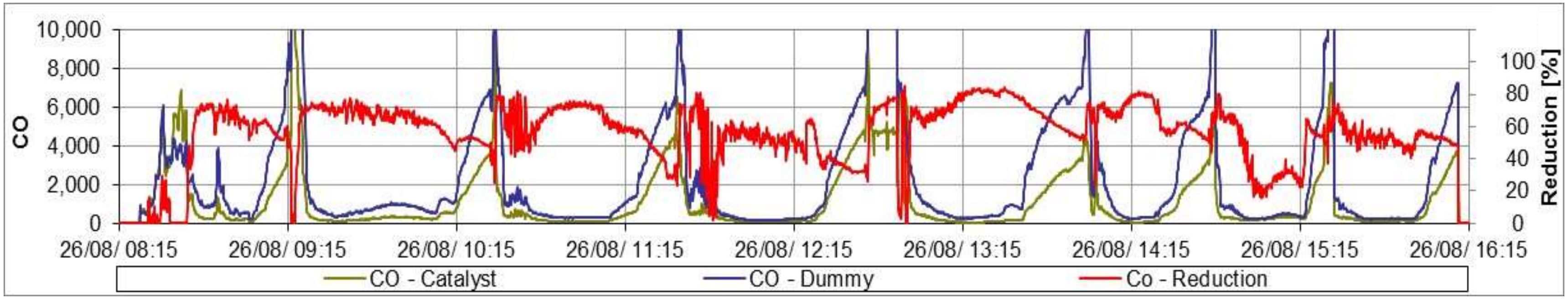


Catalyst 1 – EnviCat® – comparisons of day 1, 10 and 11 – CO emission and CO-reduction trends

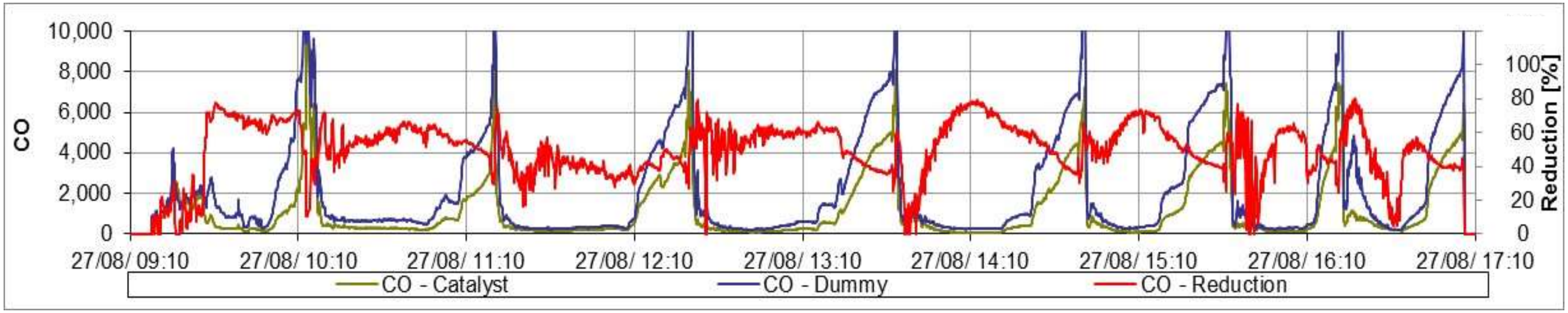
1



10

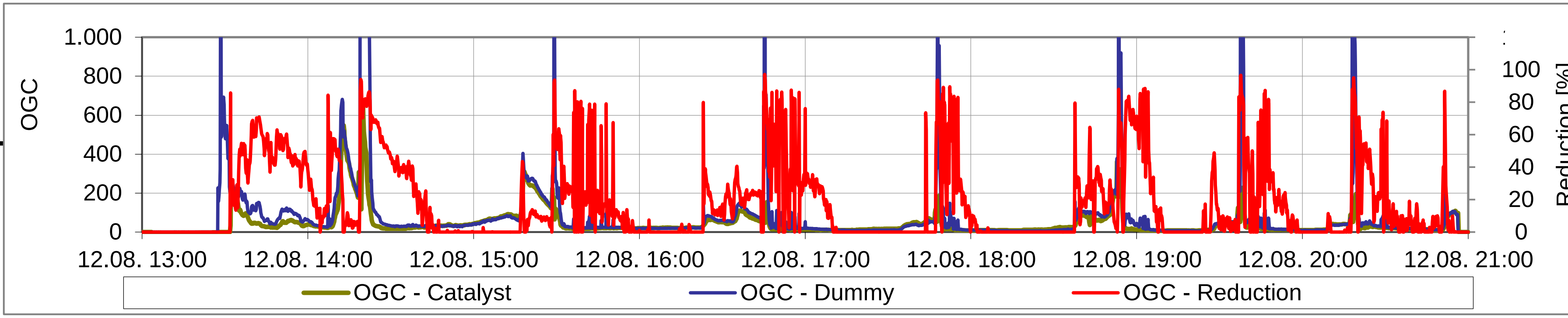


11

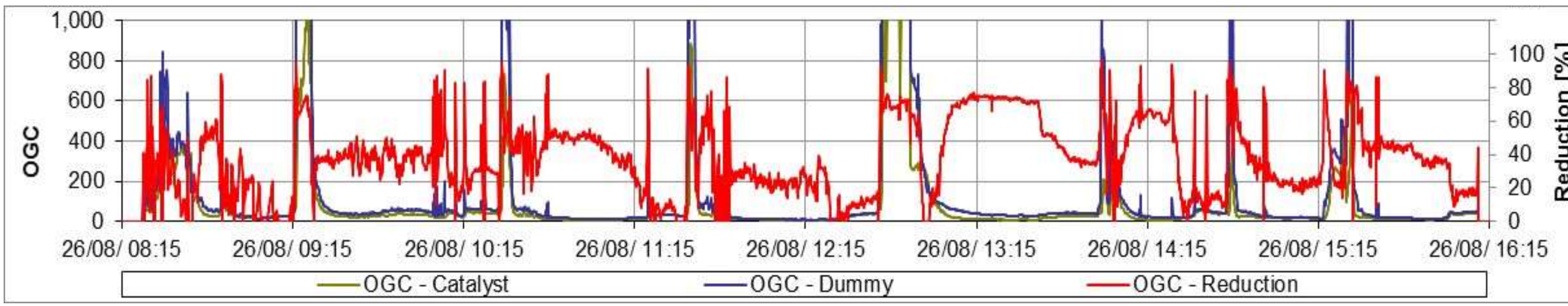


Catalyst 1 – EnviCat® – comparisons of day 1, 10 and 11 – OGC emission and OGC-reduction trends

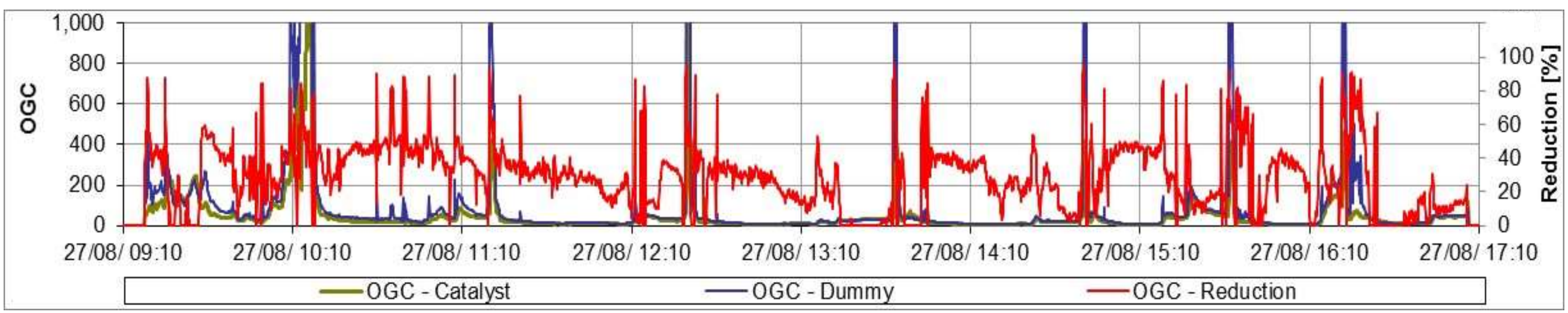
1



10

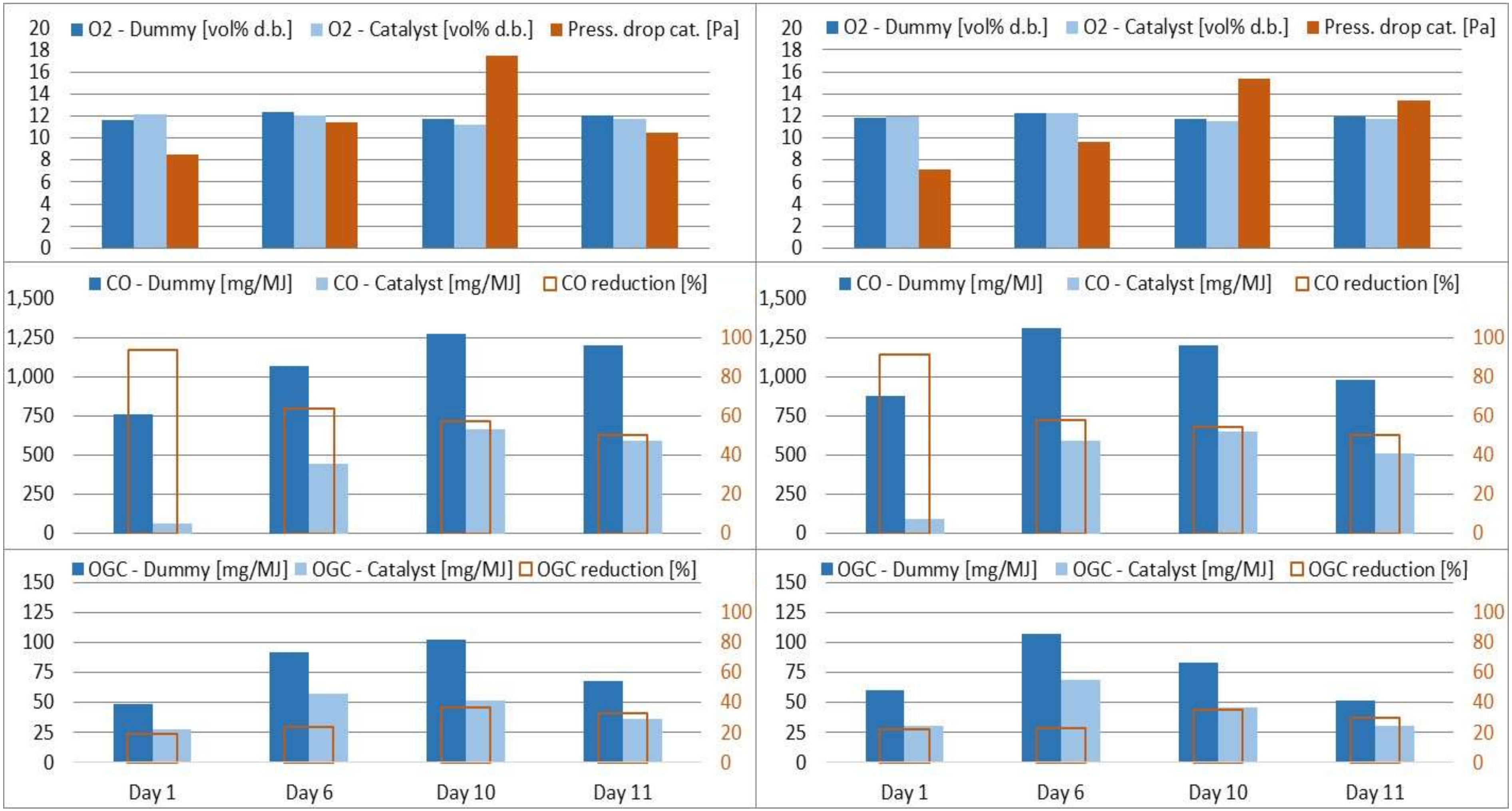


11



Catalyst 1 – EnviCat® – comparisons of mean values

Nominal load | **Partial load**

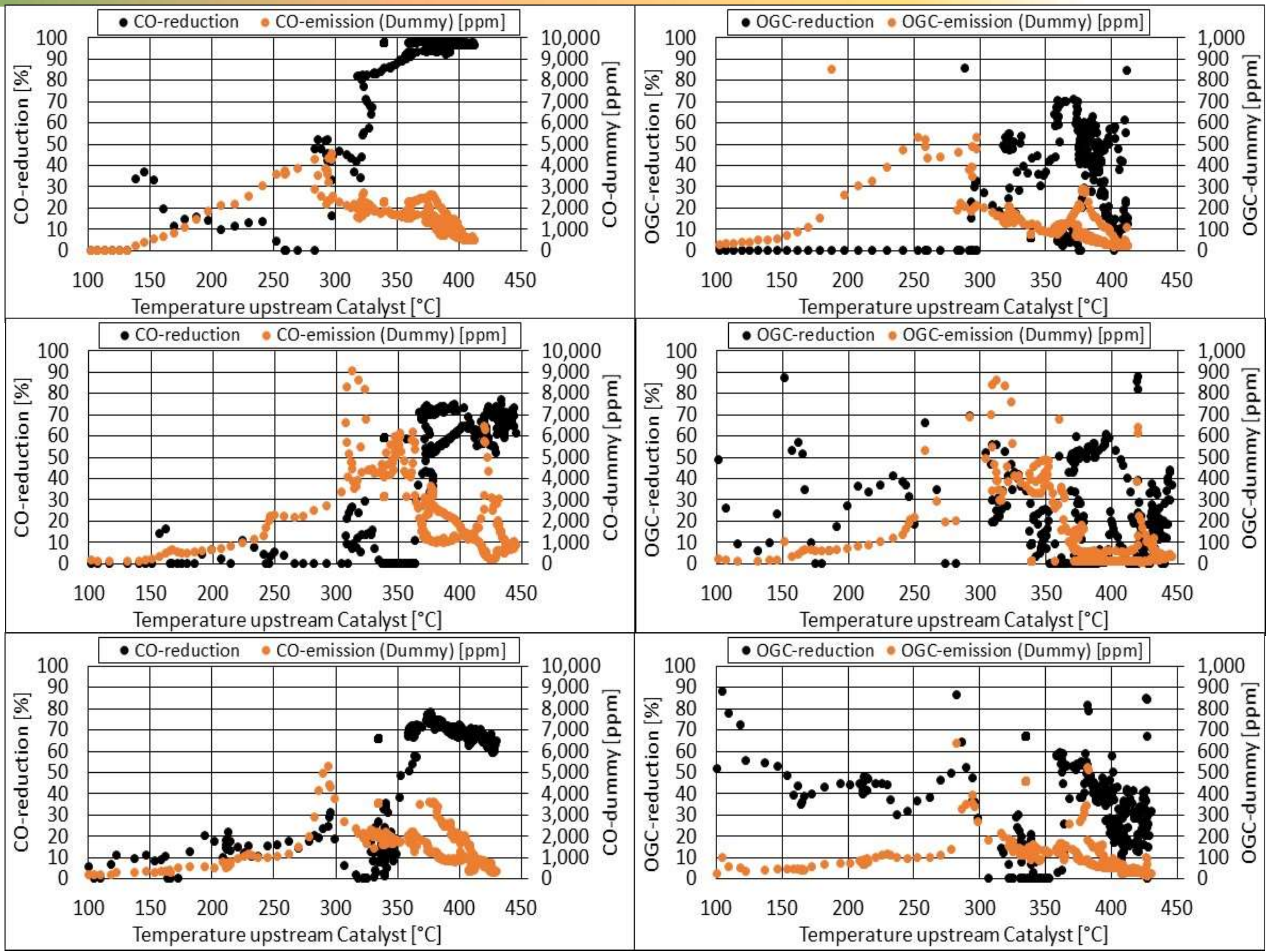


Catalyst 1 – EnviCat® – light-off behaviour day 1, 10 and 11 during the ignition batch

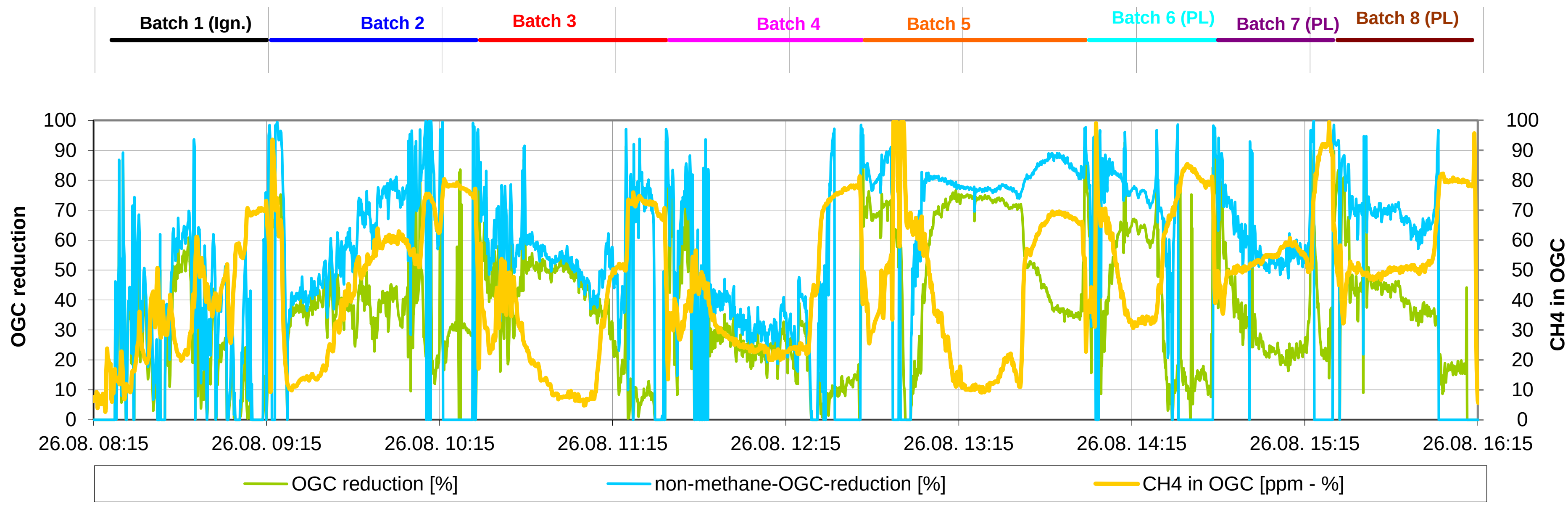
1

10

11



Catalyst 1 – EnviCat® – Influence of CH_4 on OGC reduction



		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		26.08 08:20:45	26.08 09:15:56	26.08 10:28:11	26.08 11:33:39	26.08 12:41:08	26.08 13:58:39	26.08 14:43:14	26.08 15:24:31	26.08 08:20:45	26.08 08:20:45
Door opened		26.08 09:14:21	26.08 10:26:44	26.08 11:32:23	26.08 12:40:05	26.08 13:57:21	26.08 14:42:18	26.08 15:23:00	26.08 16:11:01	26.08 13:57:21	26.08 10:26:44
OGC reduction	[%]	22.4	39.0	37.1	24.7	57.1	41.2	35.6	39.8	37.0	35.3
non-methane-OGC-reduction	[%]	32.0	64.3	55.7	39.1	78.6	74.3	62.5	71.3	55.5	58.8

Explanations: Results of test run at day 1; OGC reduction (green), non-methane OGC reduction (blue); % CH_4 in OGC = (ppm CH_4 / ppm OGC) * 100

Catalyst 1 – EnviCat® – Pictures of catalyst before and after cleaning

Catalyst before the test runs (view at outlet)

Catalyst after 2 weeks of operation (view at inlet)

Catalyst after manual cleaning after 2 weeks of operation (view at inlet)

- **Cleaning:**
  - Step I: scrape off depositions for sampling

Picture of depositions

  - Step 2: cleaning with a soft brush
  - Step 3: purging every cell of the catalyst and the dummy with compressed air

Catalyst 1 – EnviCat® – Summary (I)

- **The EnviCat® Long life Plus was operated for 10 days (80 batches) before cleaning it.**

- **With the exception of the ignition batch the flue gas temperatures at catalyst inlet were well above the light-off temperature of 200°C (light-off temperature defined by the manufacturer).**
  - **In average they amounted between 452 and 563°C (mean values over single batches excluding the ignition batches)**
  - **Also during re-charging they did not drop below 250°C**
  - **The maximum operation temperature of 650°C has not been exceeded (maximum temperature: 608°C)**

- **The stove could be operated at typical air supply conditions leading to average O_2 contents in the flue gas over a whole batch of between 10.6 and 12.6 vol% (dry flue gas, excluding the ignition batches).**

Catalyst 1 – EnviCat® – Summary (II)

- At the 1st day of operation for CO very high but for OGC only moderate emission reduction efficiencies could be determined
  - CO (mean value for full load operation): 764 ➔ 63 mg/MJ = 94.0%
  - CO (mean value for partial load operation): 878 ➔ 92 mg/MJ = 91.4%
  - OGC (mean value for full load operation): 48.5 ➔ 27.7 mg/MJ = 19.3%
  - OGC (mean value for partial load operation): 60.3 ➔ 30.7 mg/MJ = 22.3%

- The pressure drop over the catalyst amounted to in average
  - 8.5 Pa (full load)
  - 7.2 Pa (partial load)

- During full load operation particulate emissions (TSP) amounted to in average 19.3 mg/MJ which is at about the same level as measured during pre-tests without catalyst and dummy (24.4 mg/MJ)

Catalyst 1 – EnviCat® – Summary (III)

- During the first week of operation the CO emission reduction efficiency dropped to in average 63.9% (full load) and 58.1% (partial load). Within the second week of operation the CO emission reduction efficiency further dropped to in average 57.6% (full load) and 54.5% (partial load).
- The OGC emission reduction efficiency increased to in average 23.5% (full load) and 22.9% (partial load) after one week and to 37.0% (full load) and 35.3% (partial load) after two weeks of operation.
- The pressure drop over the catalyst increased to in average 11.4 Pa (full load) and 9.6 Pa (partial load) after one week and to in average 17.5 Pa (full load) and 15.4 Pa (partial load) after two weeks of operation.
- During full load operation particulate emissions (TSP) remained at about the same level (24.4 mg/MJ after one week and 22.5 mg/MJ after 2 weeks)

Catalyst 1 – EnviCat® – Summary (IV)

- **An inspection of the catalyst after 2 weeks of operation revealed significant and partly very hard to remove fly ash deposits blocking a part of the catalyst inlet surface**
  ➔ reason for the increasing pressure losses.

- **After manual cleaning the pressure drop over the catalyst could be reduced again to 13.4 Pa (full load) and 10.5 Pa (partial load). These values are still significantly higher than the initial values (8.5 respectively 7.2 Pa), thus, not all deposits could be successfully removed.**

- **The cleaning showed no effect on the emission reduction efficiencies.**
  - **CO emission reduction remained on a rather low level of in average 50% (at full and partial load)**
  - **OGC emission reduction was with 29.9% (full load) and 32.6% (partial load) still about 50% higher than at the beginning of the testing campaign.**

Catalyst 1 – EnviCat® – Summary (V)

- **OGC-emission reduction:**
  - **The share of CH_4 on the OGC emissions increases downstream the catalyst up to 90% as it is well known that CH_4 is hardly converted by the catalyst. Therefore, the evaluation of the methane free OGC reduction showed a significantly higher emission reduction (30 to 80% higher) under the consideration that CH_4 is not converted by the catalyst.**

- **Evaluating the flue gas temperature upstream the catalyst and the CO emission reductions achieved shows:**
  - **Day1: light-off temperature: about 280°C**
  - **Day 10: light-off temperature: about 310°C**
  - **Day 11: light-off temperature: about 320°C (after cleaning)**

→ obviously the light-off temperature regarding CO emission reduction increases with operation time starting at a value which is higher compared to the data provided by the manufacturer

Catalyst 1 – EnviCat® – Summary (VI)

- Regarding OGC-emissions the light-off temperatures seem to be slightly higher and also increase with operation time.
- The manual cleaning showed no effect on the light-off temperatures (temperature that marks start of reactions).

Results of the test runs with a logwood stove and different catalysts

Results of the test runs performed with Catalyst 2 – Tailor-made catalyst I – at catalyst position I

Catalyst 2 – Tailor-made catalyst I – Overview

Day	Date	Comments
1	31/08/2015	Measurements – series 1
2	01/09/2015	Operation
3	02/09/2015	Operation
4	03/09/2015	Operation
5	04/09/2015	Operation
6	07/09/2015	Measurements – series 2
7	08/09/2015	Operation
8	09/09/2015	Operation
9	10/09/2015	Operation
10	11/09/2015	Operation
11	14/09/2015	Measurements – series 3 Manual cleaning of the catalyst
12	17/09/2015	Measurements – series 4

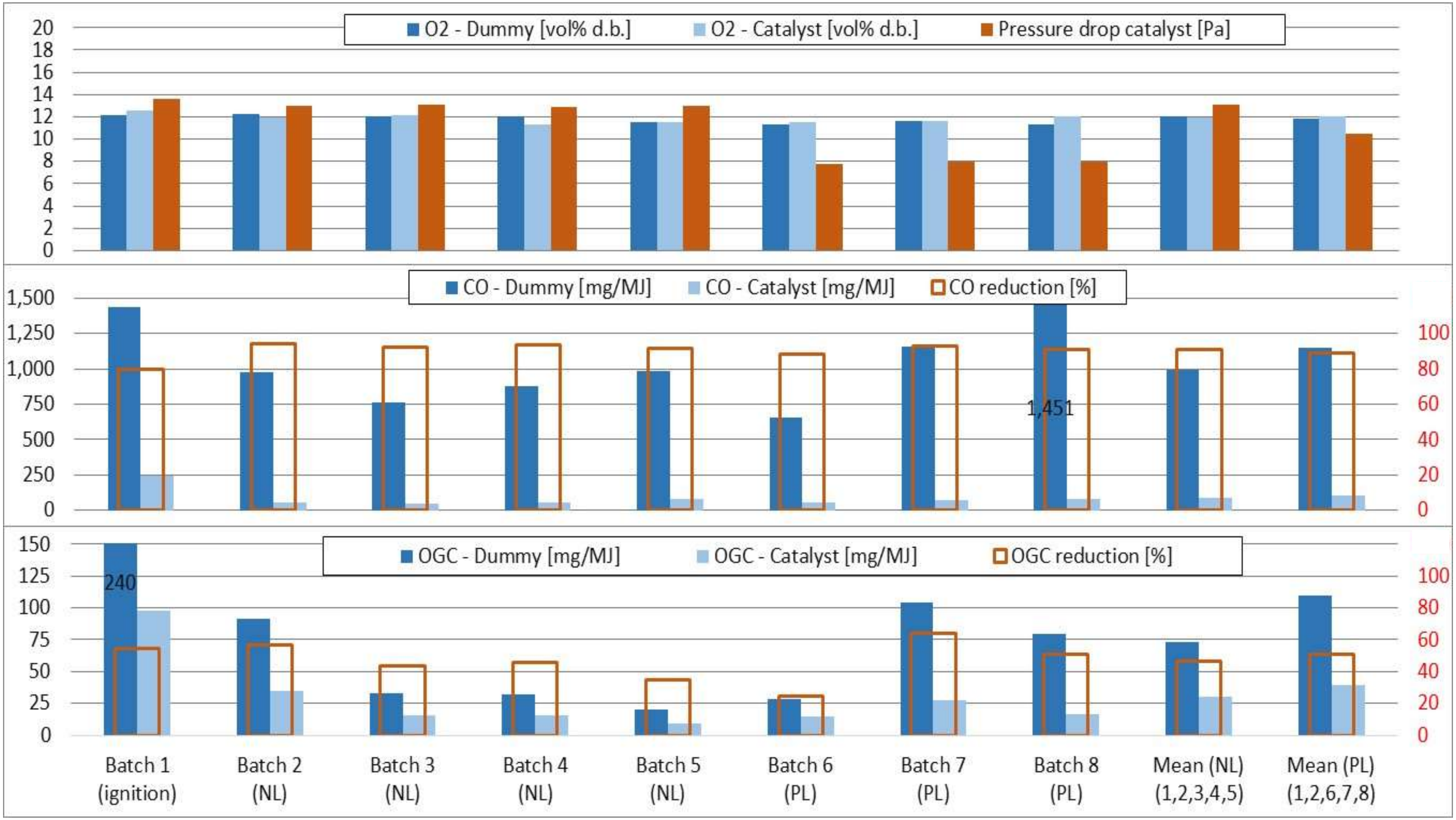
No	2
Name	Tailor-made catalyst I
Substrate	metal
Structure	honeycomb
CPSI[1)]	50
Dimension (HxWxL)	30 x 160 x 50 mm
Washcoat	H1010 (CeO_2)
Active metal	Pt
Light-off temperature[2)]	not defined yet since the catalysts are prototypes
Max. operation temp	650°C

Explanations: [1)] Cells per square inch (1 CPSI ~ 645 mm²); [2)] Temperature that marks start of reactions

Catalyst 2 – Tailor-made catalyst I – Day 1: measurements – series 1 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		31/08 10:41	31/08 11:34	31/08 12:41	31/08 13:54	31/08 15:05	31/08 16:20	31/08 17:03	31/08 17:45		
Door opened		31/08 11:33	31/08 12:41	31/08 13:53	31/08 15:04	31/08 16:19	31/08 17:02	31/08 17:44	31/08 18:34		
Fuel input	kg w.b.	2.7	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.3	8.7
O_2 - Dummy	**vol% d.b.**	**12.2**	**12.3**	**12.1**	**12.1**	**11.6**	**11.3**	**11.7**	**11.3**	**12.1**	**11.9**
O_2 - Catalyst	**vol% d.b.**	**12.5**	**12.0**	**12.2**	**11.3**	**11.6**	**11.5**	**11.7**	**12.0**	**11.9**	**12.1**
CO - Dummy	mg/Nm³	2,153.6	1,458.1	1,138.0	1,312.3	1,472.1	988.0	1,734.0	2,177.0	1,489.2	1,728.7
CO - Catalyst	mg/Nm³	359.9	83.5	71.4	75.6	112.0	76.9	108.4	115.5	127.8	149.3
CO - Dummy	**mg/MJ**	**1,435.7**	**972.0**	**758.7**	**874.9**	**981.4**	**658.7**	**1,156.0**	**1,451.3**	**992.8**	**1,152.4**
CO - Catalyst	**mg/MJ**	**239.9**	**55.6**	**47.6**	**50.4**	**74.6**	**51.3**	**72.3**	**77.0**	**85.2**	**99.5**
CO reduction	**%**	**79.5**	**94.0**	**92.4**	**93.8**	**91.7**	**88.1**	**92.8**	**90.8**	**90.9**	**89.2**
OGC - Dummy	mg/Nm³	360.1	136.8	49.5	48.4	29.9	42.8	156.6	118.6	109.7	164.8
OGC - Catalyst	mg/Nm³	147.1	51.7	22.8	23.6	14.0	21.9	40.8	24.7	44.9	58.6
CH4 - Catalyst	mg/Nm³	68.0	39.5	14.9	19.8	10.8	17.9	37.9	23.3	28.3	39.1
OGC - Dummy	**mg/MJ**	**240.1**	**91.2**	**33.0**	**32.2**	**20.0**	**28.5**	**104.4**	**79.1**	**73.1**	**109.9**
OGC - Catalyst	**mg/MJ**	**98.1**	**34.5**	**15.2**	**15.7**	**9.3**	**14.6**	**27.2**	**16.4**	**29.9**	**39.1**
CH4 - Catalyst	mg/MJ	45.3	26.3	9.9	13.2	7.2	11.9	25.2	15.5	18.8	26.1
CH4 in OGC	%	46.2	76.3	65.4	84.0	77.7	81.5	92.7	94.5	63.0	66.7
OGC reduction	%	54.3	56.9	43.9	45.8	34.9	24.7	64.2	50.9	46.3	50.6
TSP	**mg/Nm³**	**220.4**	**n.m.**	**16.5**	**n.m.**	**27.5**	**n.m.**	**28.1**	**n.m.**	**54.7**	**121.4**
TSP	**mg/MJ**	**146.9**	**n.m.**	**11.0**	**n.m.**	**18.3**	**n.m.**	**18.7**	**n.m.**	**36.5**	**81.0**
T combustion chamber	°C	562.0	591.4	614.9	630.1	620.0	626.5	629.8	610.4	604.5	599.3
T Catalyst inlet	°C	315.1	465.6	514.4	536.6	550.7	510.5	518.7	519.6	485.3	460.4
T flue gas (EN13240)	°C	71.0	120.6	146.9	162.7	175.0	170.4	171.8	177.5	139.2	138.1
Chimney draught	Pa	12.4	12.4	12.4	12.4	12.3	12.4	12.3	12.4	12.4	12.4
Pressure drop catalyst	**Pa**	**13.6**	**12.9**	**13.1**	**12.9**	**13.0**	**7.8**	**8.0**	**7.9**	**13.1**	**10.4**
Efficiency (EN13240)	**%**	**95.5**	**92.1**	**88.3**	**87.9**	**86.5**	**86.9**	**86.6**	**85.6**	**89.2**	**89.2**

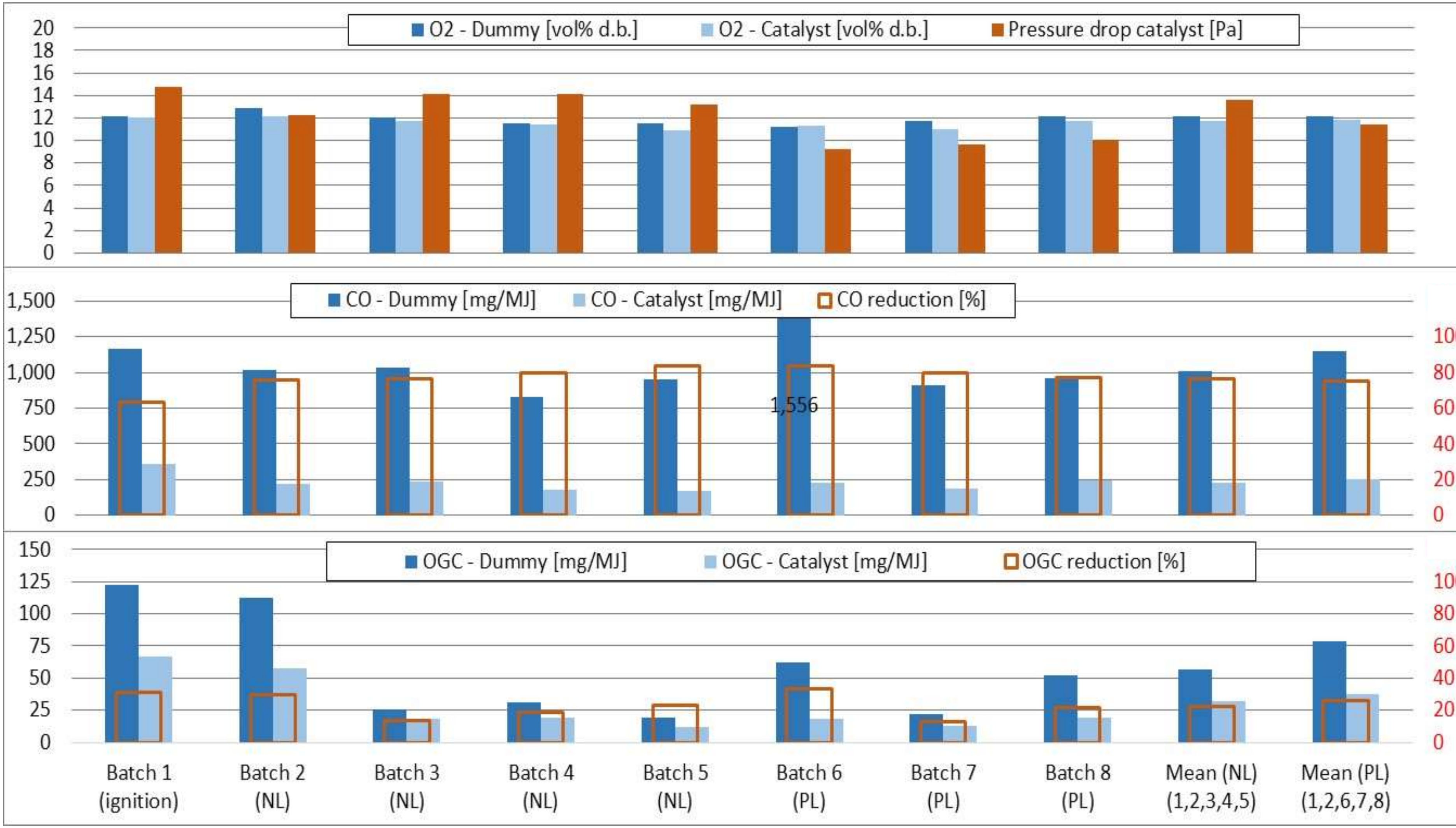
Catalyst 2 – Tailor-made catalyst I – Day 1: measurements – series 1 (II)



Catalyst 2 – Tailor-made catalyst I – Day 6: measurements – series 2 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		07/09 10:56	07/09 11:45	07/09 12:55	07/09 14:06	07/09 15:11	07/09 16:19	07/09 17:04	07/09 17:43		
Door opened		07/09 11:44	07/09 12:54	07/09 14:04	07/09 15:10	07/09 16:17	07/09 17:03	07/09 17:42	07/09 18:22		
Fuel input	kg w.b.	2.7	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.3	8.7
O_2 - Dummy	**vol% d.b.**	**12.1**	**12.9**	**12.1**	**11.5**	**11.5**	**11.2**	**11.7**	**12.1**	**12.1**	**12.2**
O_2 - Catalyst	**vol% d.b.**	**12.0**	**12.2**	**11.7**	**11.5**	**10.9**	**11.3**	**11.0**	**11.7**	**11.7**	**11.8**
CO - Dummy	mg/Nm³	1,746.9	1,520.4	1,553.2	1,243.5	1,423.4	2,334.6	1,366.1	1,440.4	1,510.1	1,718.4
CO - Catalyst	mg/Nm³	537.2	331.8	349.8	265.7	252.2	346.2	283.2	359.0	343.0	378.1
CO - Dummy	**mg/MJ**	**1,164.6**	**1,013.6**	**1,035.5**	**829.0**	**948.9**	**1,556.4**	**910.8**	**960.2**	**1,006.7**	**1,145.6**
CO - Catalyst	**mg/MJ**	**358.1**	**221.2**	**233.2**	**177.1**	**168.1**	**230.8**	**188.8**	**239.3**	**228.6**	**252.1**
CO reduction	**%**	**62.9**	**75.7**	**76.7**	**79.4**	**83.7**	**83.5**	**79.9**	**77.1**	**76.3**	**75.4**
OGC - Dummy	mg/Nm³	183.6	168.7	39.0	47.2	28.2	92.9	32.7	78.2	85.7	118.2
OGC - Catalyst	mg/Nm³	100.2	85.8	27.3	29.2	18.0	27.8	18.6	29.4	48.4	56.7
CH4 - Catalyst	mg/Nm³	57.0	54.6	19.8	18.9	12.9	20.9	13.1	18.0	31.0	35.6
OGC - Dummy	**mg/MJ**	**122.4**	**112.4**	**26.0**	**31.5**	**18.8**	**61.9**	**21.8**	**52.1**	**57.1**	**78.8**
OGC - Catalyst	**mg/MJ**	**66.8**	**57.2**	**18.2**	**19.4**	**12.0**	**18.5**	**12.4**	**19.6**	**32.3**	**37.8**
CH4 - Catalyst	mg/MJ	38.0	36.4	13.2	12.6	8.6	13.9	8.7	12.0	20.6	23.7
CH4 in OGC	%	56.9	63.6	72.7	64.9	71.7	75.3	70.2	61.3	63.9	62.8
OGC reduction	%	31.0	29.8	13.4	18.9	23.0	33.0	13.1	21.6	22.6	26.3
TSP	**mg/Nm³**	**37.1**	**n.m.**	**28.3**	**n.m.**	**37.0**	**n.m.**	**17.9**	**n.m.**	**34.0**	**28.2**
TSP	**mg/MJ**	**24.7**	**n.m.**	**18.9**	**n.m.**	**24.6**	**n.m.**	**11.9**	**n.m.**	**22.7**	**18.8**
T combustion chamber	°C	603.0	561.8	606.2	633.9	630.8	627.3	636.2	632.3	604.0	603.7
T Catalyst inlet	°C	321.8	431.8	508.0	536.2	549.9	519.1	521.8	524.5	476.7	455.1
T flue gas (EN13240)	°C	61.5	102.8	145.4	163.0	170.2	168.3	170.1	176.5	132.2	129.7
Chimney draught	Pa	12.3	12.3	12.5	12.6	12.4	12.5	12.5	12.4	12.4	12.4
Pressure drop catalyst	**Pa**	**14.8**	**12.3**	**14.1**	**14.1**	**13.2**	**9.2**	**9.6**	**10.0**	**13.6**	**11.4**
Efficiency (EN13240)	**%**	**96.3**	**93.2**	**88.7**	**87.5**	**87.6**	**87.2**	**87.4**	**86.0**	**89.9**	**90.1**

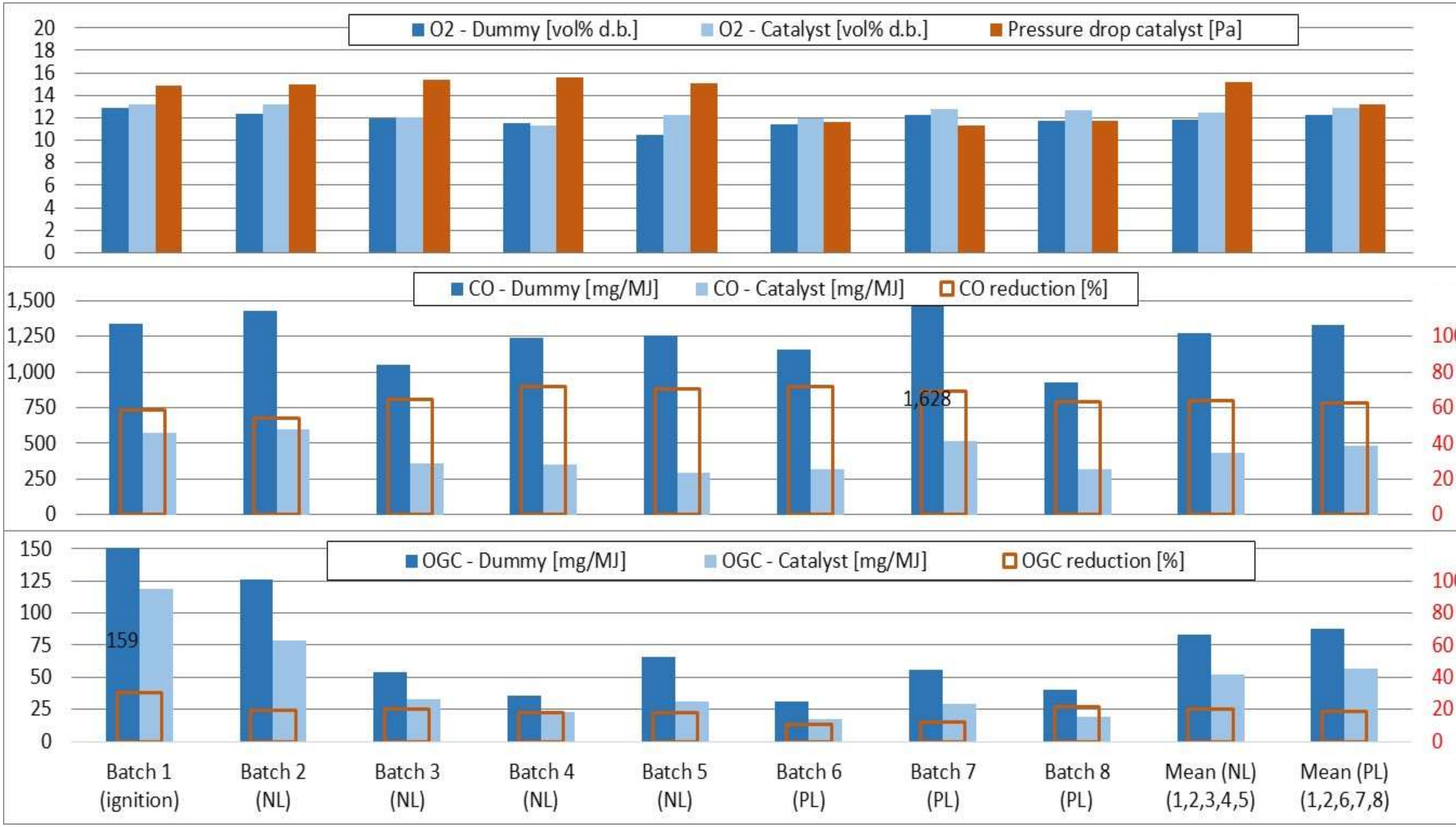
Catalyst 2 – Tailor-made catalyst I – Day 6: measurements – series 2 (II)



Catalyst 2 – Tailor-made catalyst I – Day 11: measurements – series 3 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		14/09 10:51	14/09 11:49	14/09 13:05	14/09 14:17	14/09 15:31	14/09 16:38	14/09 17:25	14/09 18:18		
Door opened		14/09 11:48	14/09 13:04	14/09 14:16	14/09 15:30	14/09 16:37	14/09 17:24	14/09 18:17	14/09 18:59		
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6
O_2 - Dummy	**vol% d.b.**	**12.9**	**12.4**	**11.9**	**11.5**	**10.5**	**11.4**	**12.3**	**11.7**	**11.9**	**12.2**
O_2 - Catalyst	**vol% d.b.**	**13.2**	**13.2**	**12.0**	**11.3**	**12.3**	**12.0**	**12.7**	**12.6**	**12.4**	**12.8**
CO - Dummy	mg/Nm³	2,003.8	2,143.5	1,573.4	1,863.8	1,884.1	1,731.9	2,441.6	1,384.4	1,903.8	1,995.5
CO - Catalyst	mg/Nm³	857.1	895.7	536.8	523.3	440.1	479.8	771.6	473.5	643.5	728.7
CO - Dummy	**mg/MJ**	**1,335.9**	**1,429.0**	**1,048.9**	**1,242.5**	**1,256.1**	**1,154.6**	**1,627.7**	**922.9**	**1,269.2**	**1,330.3**
CO - Catalyst	**mg/MJ**	**571.4**	**597.2**	**357.9**	**348.9**	**293.4**	**319.9**	**514.4**	**315.7**	**429.0**	**485.8**
CO reduction	**%**	**58.9**	**54.1**	**64.7**	**71.8**	**70.4**	**71.7**	**69.1**	**62.9**	**63.9**	**62.3**
OGC - Dummy	mg/Nm³	238.3	189.4	81.6	53.6	98.8	46.8	83.1	60.8	124.4	131.7
OGC - Catalyst	mg/Nm³	178.2	118.0	49.5	33.8	46.4	25.9	44.1	29.1	78.3	84.9
CH4 - Catalyst	mg/Nm³	106.3	85.0	41.2	25.3	36.6	19.7	30.3	17.1	56.0	57.2
OGC - Dummy	**mg/MJ**	**158.9**	**126.3**	**54.4**	**35.7**	**65.9**	**31.2**	**55.4**	**40.5**	**82.9**	**87.8**
OGC - Catalyst	**mg/MJ**	**118.8**	**78.7**	**33.0**	**22.6**	**30.9**	**17.2**	**29.4**	**19.4**	**52.2**	**56.6**
CH4 - Catalyst	mg/MJ	70.8	56.7	27.5	16.9	24.4	13.1	20.2	11.4	37.3	38.1
CH4 in OGC	%	59.6	72.0	83.4	74.9	79.0	76.2	68.7	58.8	71.5	67.3
OGC reduction	%	30.0	19.1	20.2	17.8	17.9	10.5	12.4	21.6	20.4	18.8
TSP	**mg/Nm³**	**44.1**	**n.m.**	**33.6**	**n.m.**	**24.3**	**n.m.**	**21.3**	**n.m.**	**33.4**	**33.7**
TSP	**mg/MJ**	**29.4**	**n.m.**	**22.4**	**n.m.**	**16.2**	**n.m.**	**14.2**	**n.m.**	**22.3**	**22.4**
T combustion chamber	°C	527.4	562.3	601.1	616.6	617.8	615.3	590.3	617.4	584.9	576.2
T Catalyst inlet	°C	280.1	415.6	488.4	528.7	515.7	501.5	490.8	489.4	451.0	427.1
T flue gas (EN13240)	°C	63.4	110.9	140.5	159.4	167.5	166.6	168.6	172.5	130.4	130.9
Chimney draught	Pa	13.4	12.0	12.1	12.1	12.1	12.1	12.1	12.0	12.3	12.3
Pressure drop catalyst	**Pa**	**14.9**	**15.0**	**15.4**	**15.6**	**15.1**	**11.7**	**11.3**	**11.7**	**15.2**	**13.2**
Efficiency (EN13240)	**%**	**95.6**	**91.4**	**88.6**	**87.8**	**85.9**	**86.4**	**84.9**	**84.8**	**89.1**	**88.5**

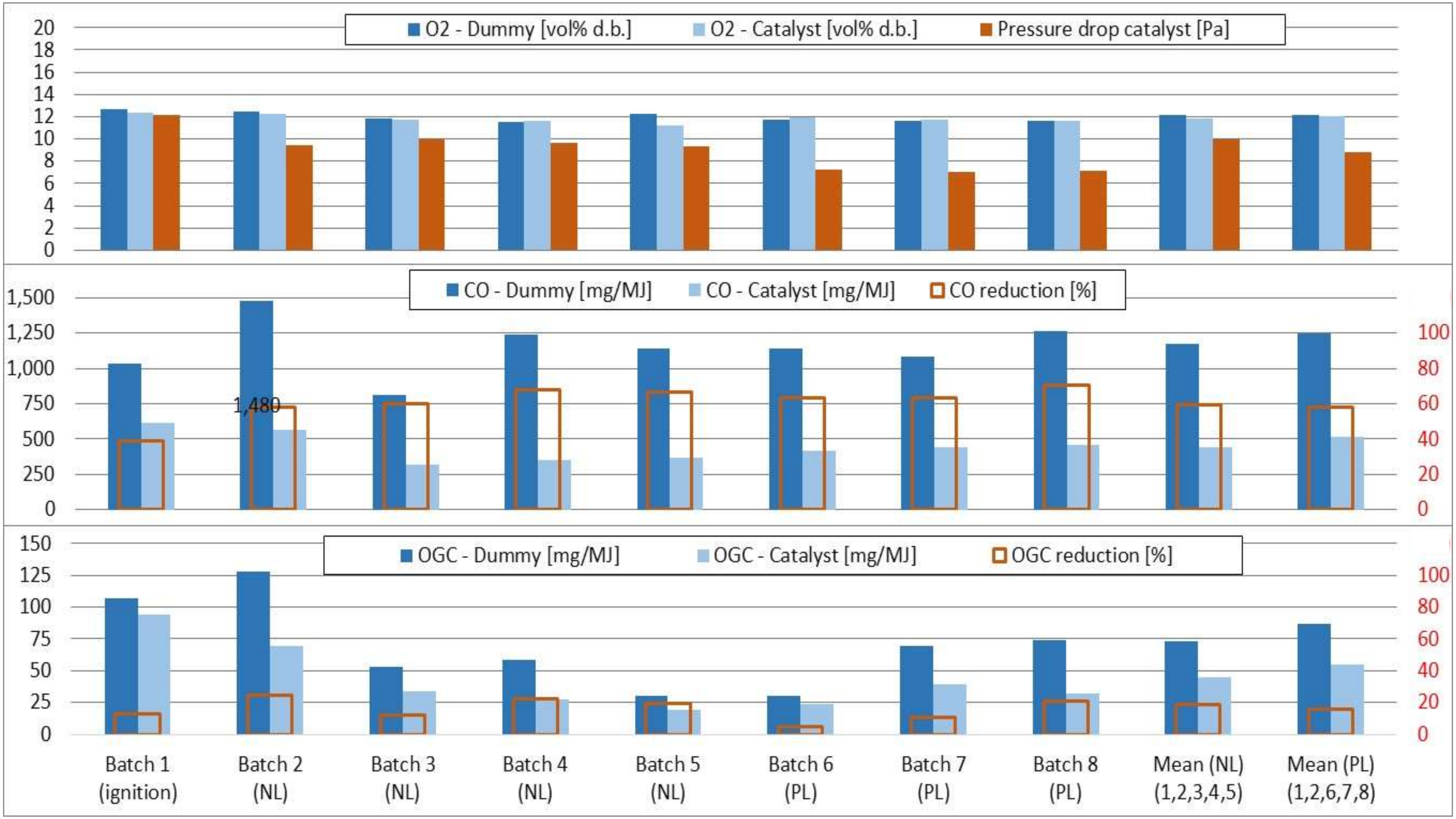
Catalyst 2 – Tailor-made catalyst I – Day 11: measurements – series 3 (II)



Catalyst 2 – Tailor-made catalyst I – Day 12: measurements – series 4 (I)

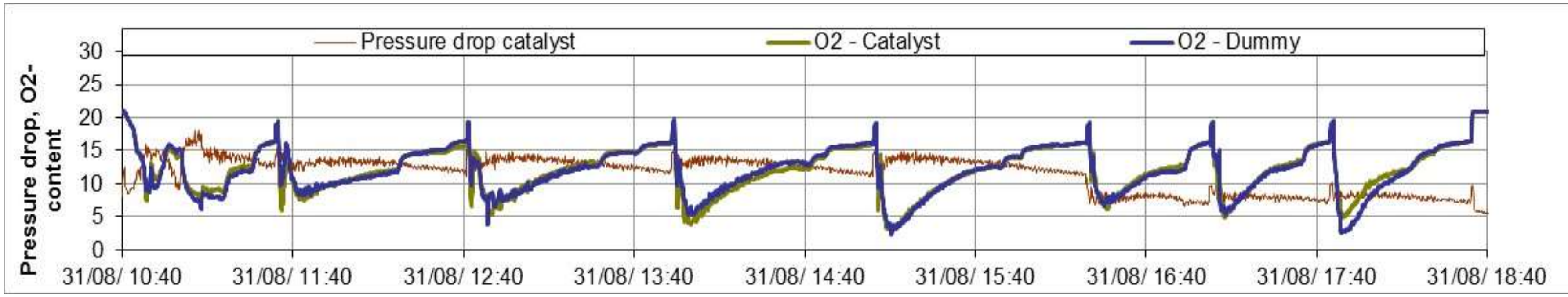
		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		17/09 10:00	17/09 10:47	17/09 12:02	17/09 13:07	17/09 14:17	17/09 15:30	17/09 16:13	17/09 16:52		
Door opened		17/09 10:46	17/09 12:00	17/09 13:06	17/09 14:16	17/09 15:28	17/09 16:12	17/09 16:51	17/09 17:32		
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6
O_2 - Dummy	**vol% d.b.**	**12.7**	**12.4**	**11.8**	**11.5**	**12.3**	**11.7**	**11.6**	**11.6**	**12.2**	**12.2**
O_2 - Catalyst	**vol% d.b.**	**12.4**	**12.2**	**11.7**	**11.6**	**11.2**	**11.9**	**11.8**	**11.6**	**11.9**	**12.1**
CO - Dummy	mg/Nm³	1,544.0	2,220.7	1,213.1	1,857.5	1,707.6	1,709.8	1,618.4	1,900.3	1,754.0	1,872.5
CO - Catalyst	mg/Nm³	922.4	852.0	477.7	528.6	555.2	618.0	658.9	689.1	660.2	774.1
CO - Dummy	**mg/MJ**	**1,029.3**	**1,480.5**	**808.7**	**1,238.4**	**1,138.4**	**1,139.9**	**1,078.9**	**1,266.9**	**1,169.4**	**1,248.3**
CO - Catalyst	**mg/MJ**	**615.0**	**568.0**	**318.4**	**352.4**	**370.1**	**412.0**	**439.3**	**459.4**	**440.1**	**516.1**
CO reduction	**%**	**39.0**	**57.7**	**60.2**	**68.0**	**66.3**	**63.0**	**63.2**	**70.6**	**59.5**	**58.1**
OGC - Dummy	mg/Nm³	161.0	191.7	79.0	87.8	44.6	45.4	104.6	110.6	109.5	130.8
OGC - Catalyst	mg/Nm³	140.9	104.3	50.2	41.5	28.9	35.6	58.4	47.4	67.8	81.9
CH4 - Catalyst	mg/Nm³	42.8	61.5	36.7	25.6	20.2	26.3	36.2	34.9	37.4	43.6
OGC - Dummy	**mg/MJ**	**107.4**	**127.8**	**52.6**	**58.5**	**29.8**	**30.2**	**69.8**	**73.7**	**73.0**	**87.2**
OGC - Catalyst	**mg/MJ**	**93.9**	**69.5**	**33.5**	**27.7**	**19.3**	**23.7**	**38.9**	**31.6**	**45.2**	**54.6**
CH4 - Catalyst	mg/MJ	28.5	41.0	24.5	17.1	13.5	17.5	24.2	23.3	24.9	29.1
CH4 in OGC	%	30.4	58.9	73.1	61.7	69.7	73.8	62.1	73.5	55.2	53.2
OGC reduction	%	13.2	24.6	12.2	22.4	19.7	4.7	11.0	20.6	18.8	15.9
TSP	**mg/Nm³**	**82.8**	**n.m.**	**22.7**	**n.m.**	**13.0**	**n.m.**	**35.1**	**n.m.**	**29.6**	**61.0**
TSP	**mg/MJ**	**55.2**	**n.m.**	**15.1**	**n.m.**	**8.7**	**n.m.**	**23.4**	**n.m.**	**19.8**	**40.7**
T combustion chamber	°C	592.5	562.0	616.1	614.8	602.6	626.0	619.9	621.6	594.8	596.1
T Catalyst inlet	°C	278.0	433.1	496.0	518.1	523.0	500.2	501.3	510.2	460.8	438.7
T flue gas (EN13240)	°C	62.0	112.7	139.8	156.9	165.8	165.9	167.1	172.0	131.9	131.0
Chimney draught	Pa	11.8	11.7	11.7	11.8	12.0	11.9	12.2	12.0	11.8	11.9
Pressure drop catalyst	**Pa**	**12.1**	**9.4**	**10.0**	**9.6**	**9.3**	**7.3**	**7.1**	**7.1**	**10.0**	**8.8**
Efficiency (EN13240)	**%**	**96.0**	**92.2**	**89.3**	**87.8**	**87.5**	**86.6**	**86.7**	**86.5**	**89.7**	**89.5**

Catalyst 2 – Tailor-made catalyst I – Day 12: measurements – series 4 (II)

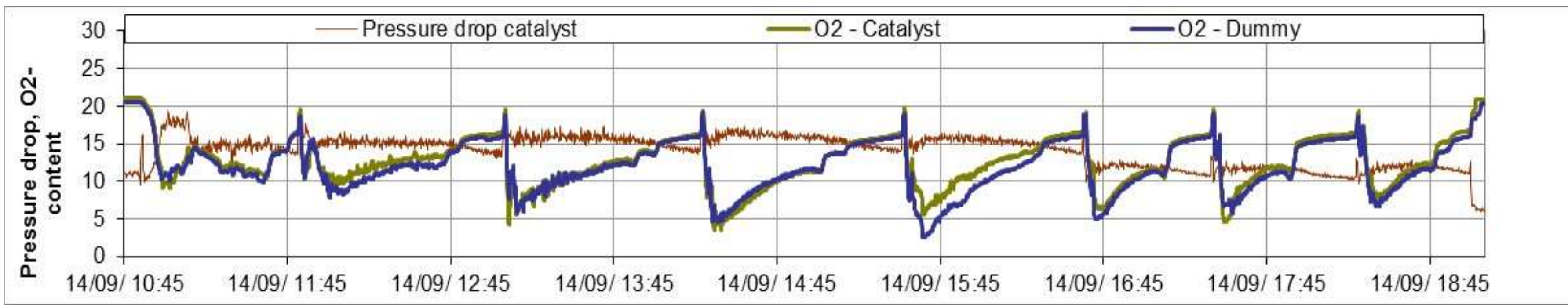


Catalyst 2 – Tailor-made catalyst I – comparisons of day 1, 11 and 12 – pressure drop and O_2 trends

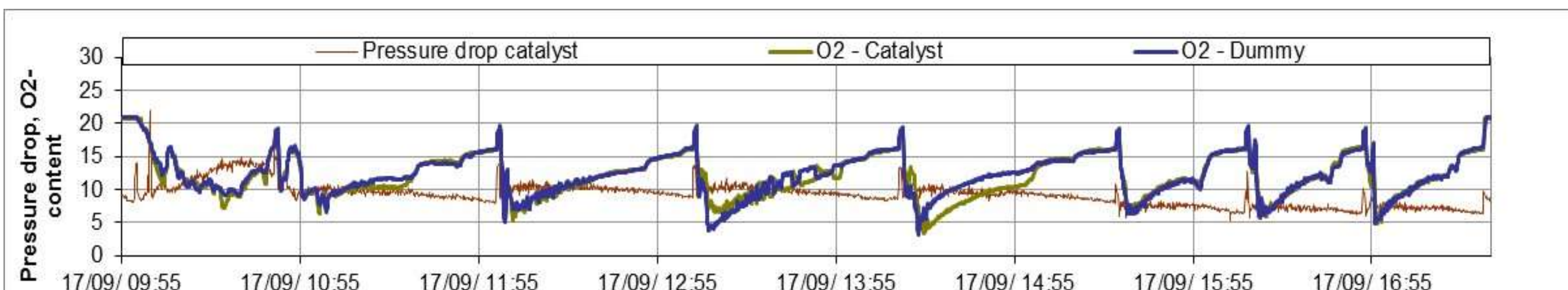
1



11

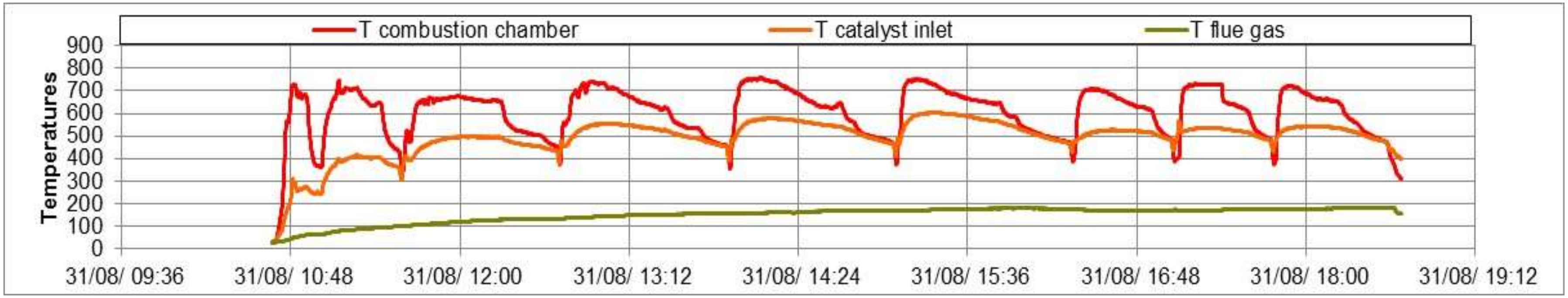


12

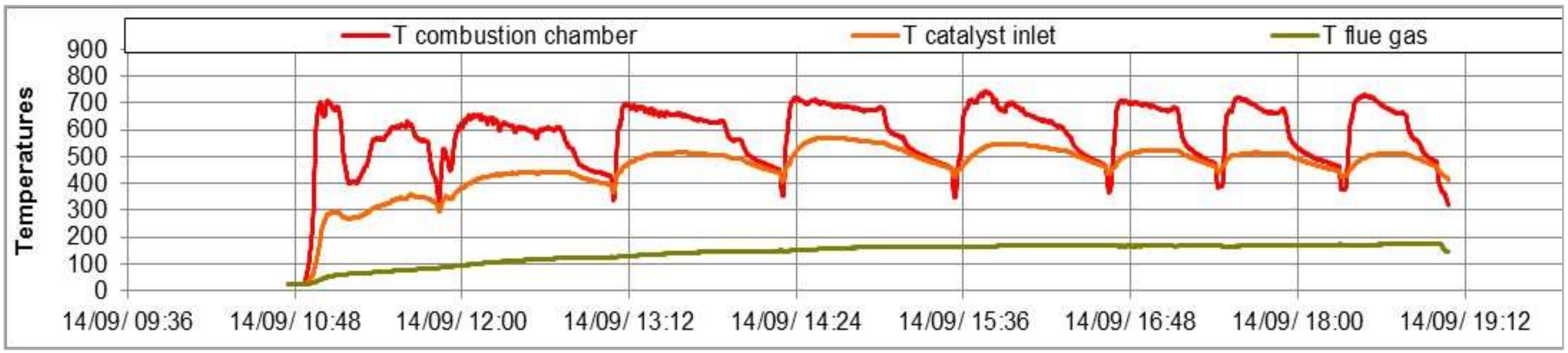


Catalyst 2 – Tailor-made catalyst I – comparisons of day 1, 11 and 12 – Temperatures

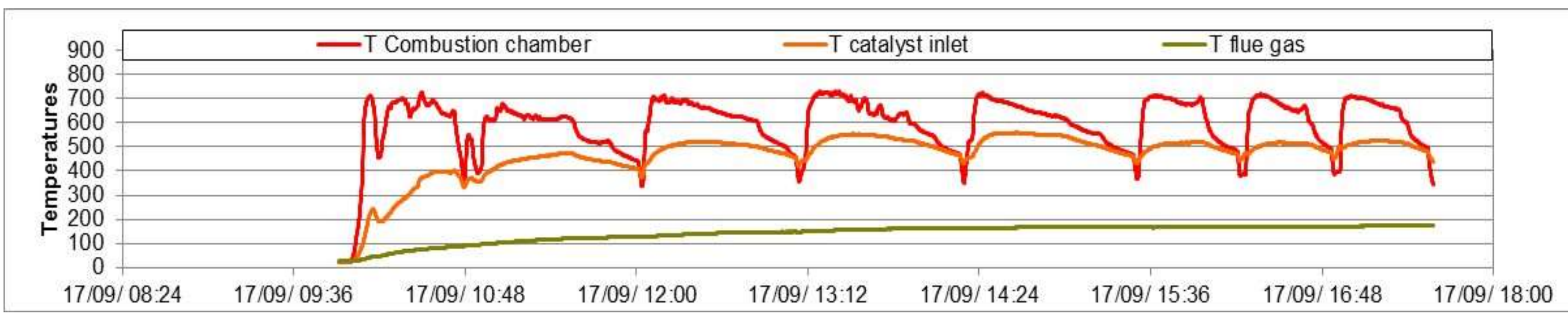
1



11

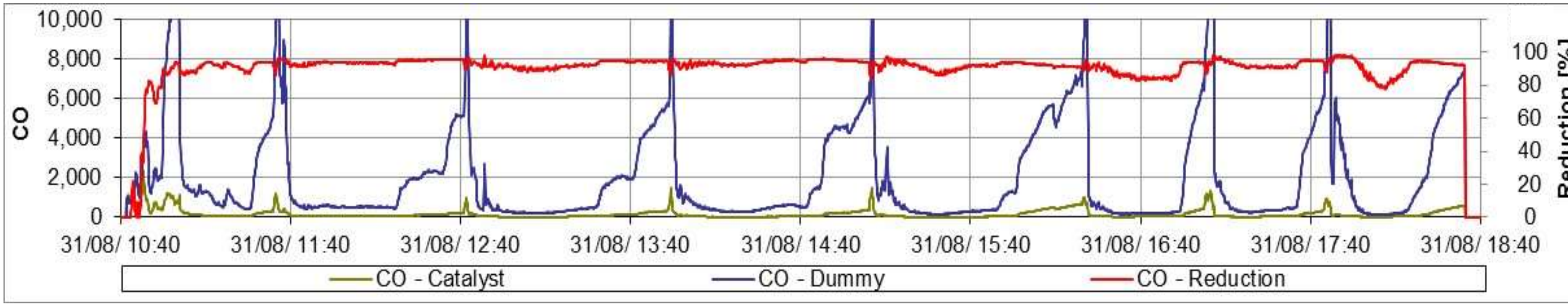


12

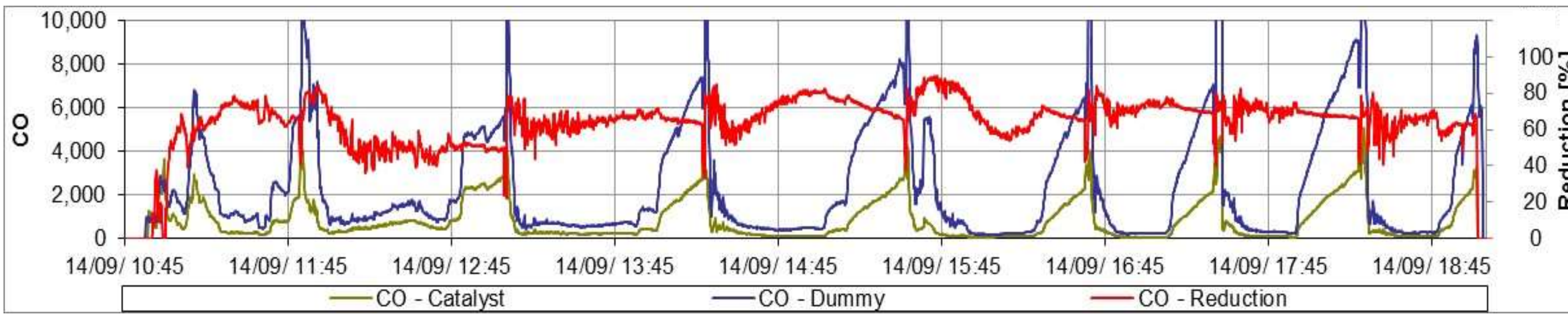


Catalyst 2 – Tailor-made catalyst I – comparisons of day 1, 11 and 12 – CO emission and CO-reduction trends

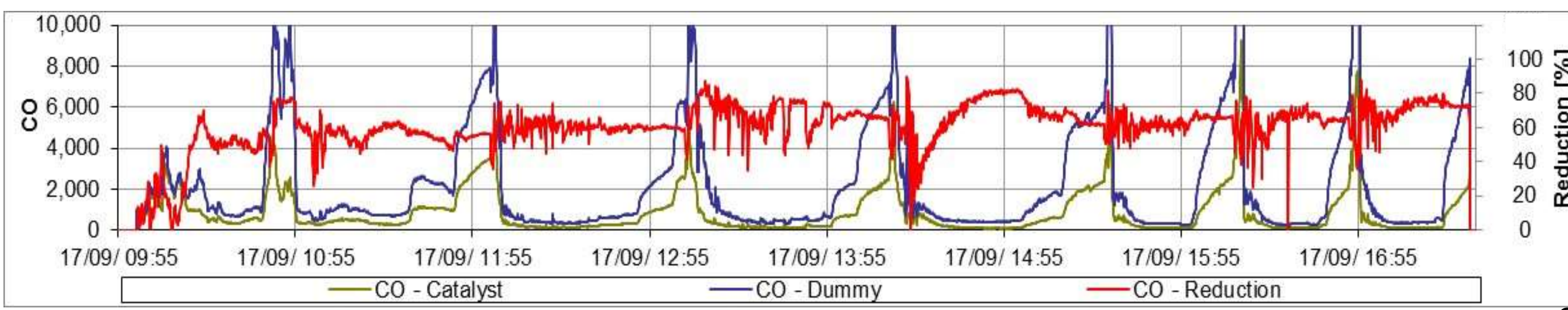
1



11

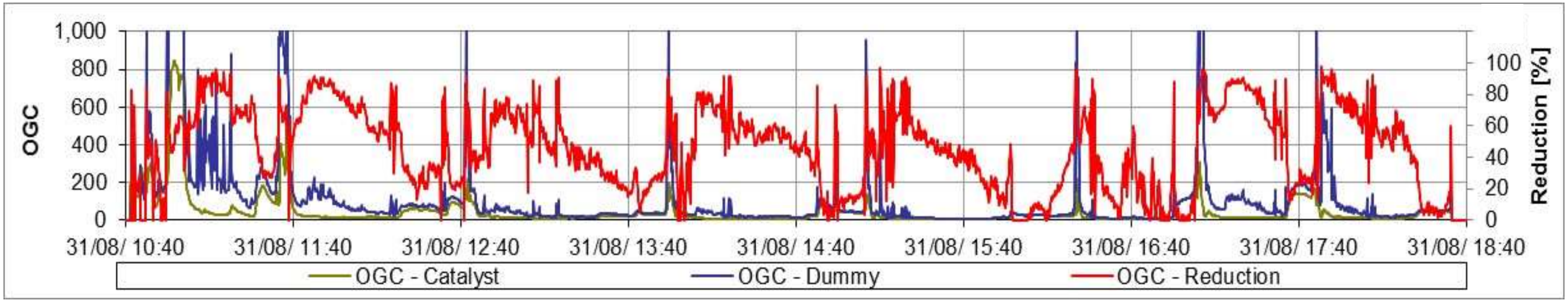


12

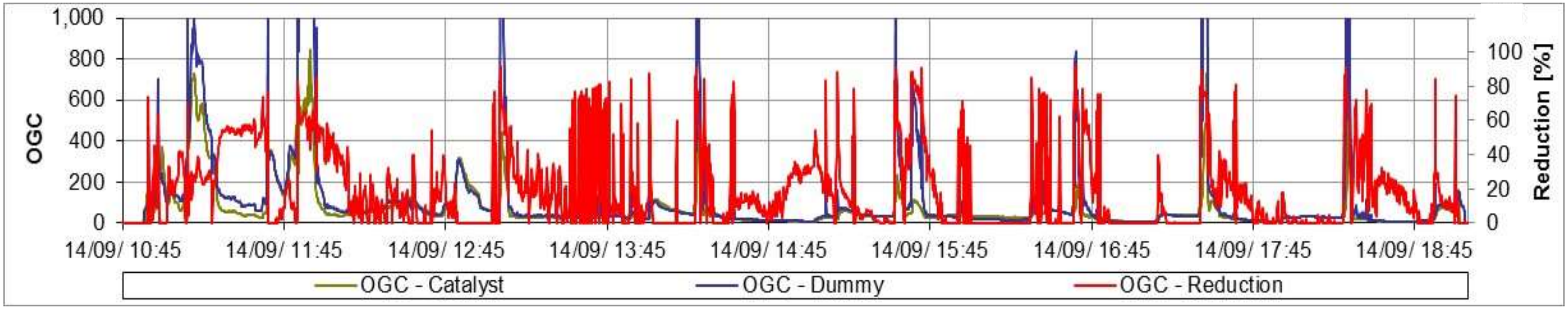


Catalyst 2 – Tailor-made catalyst I – comparisons of day 1, 11 and 12 – OGC emission and OGC-reduction trends

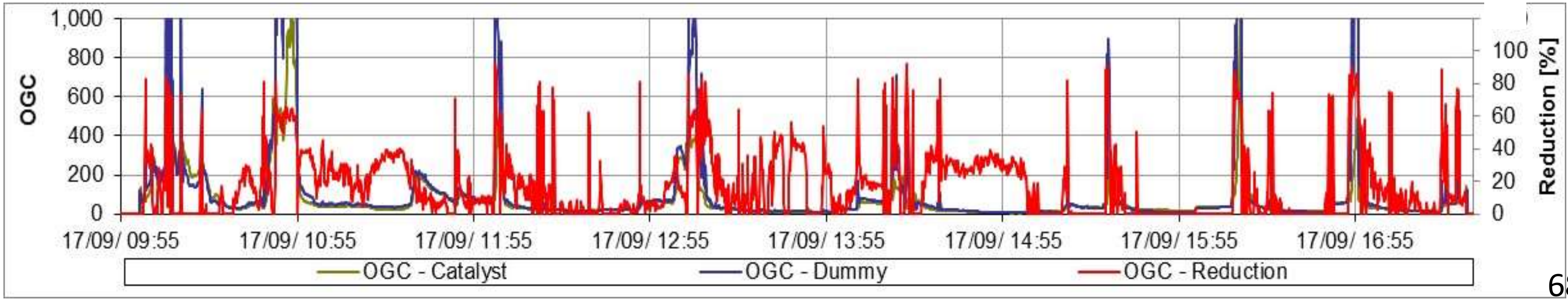
1



11



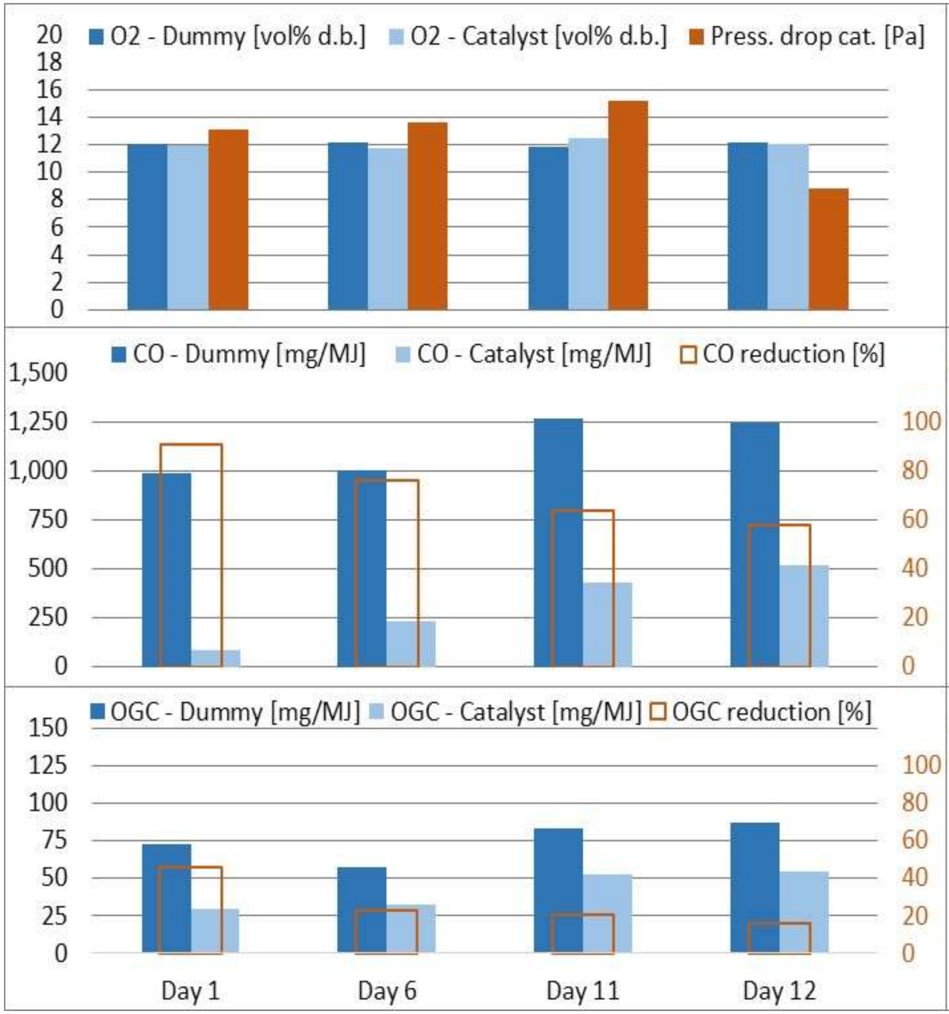
12

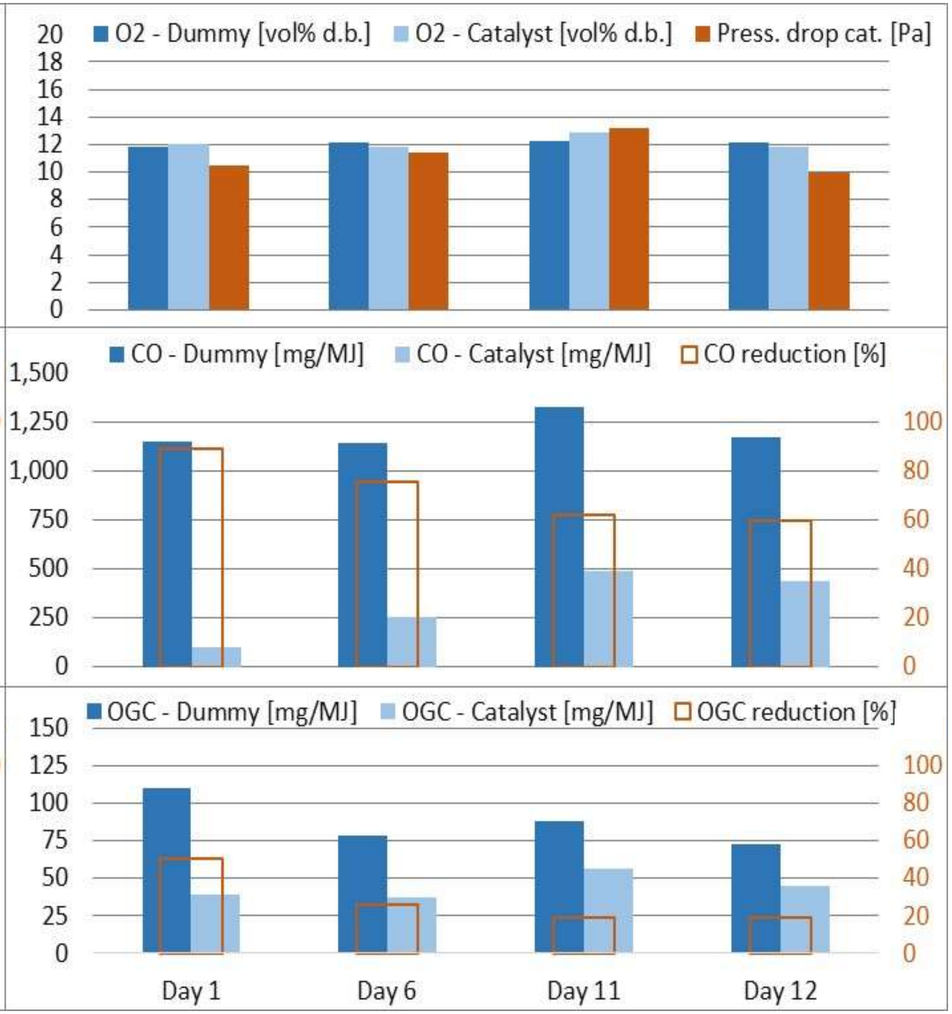


Catalyst 2 – Tailor-made catalyst I – comparisons of mean values

Nominal load

Partial load



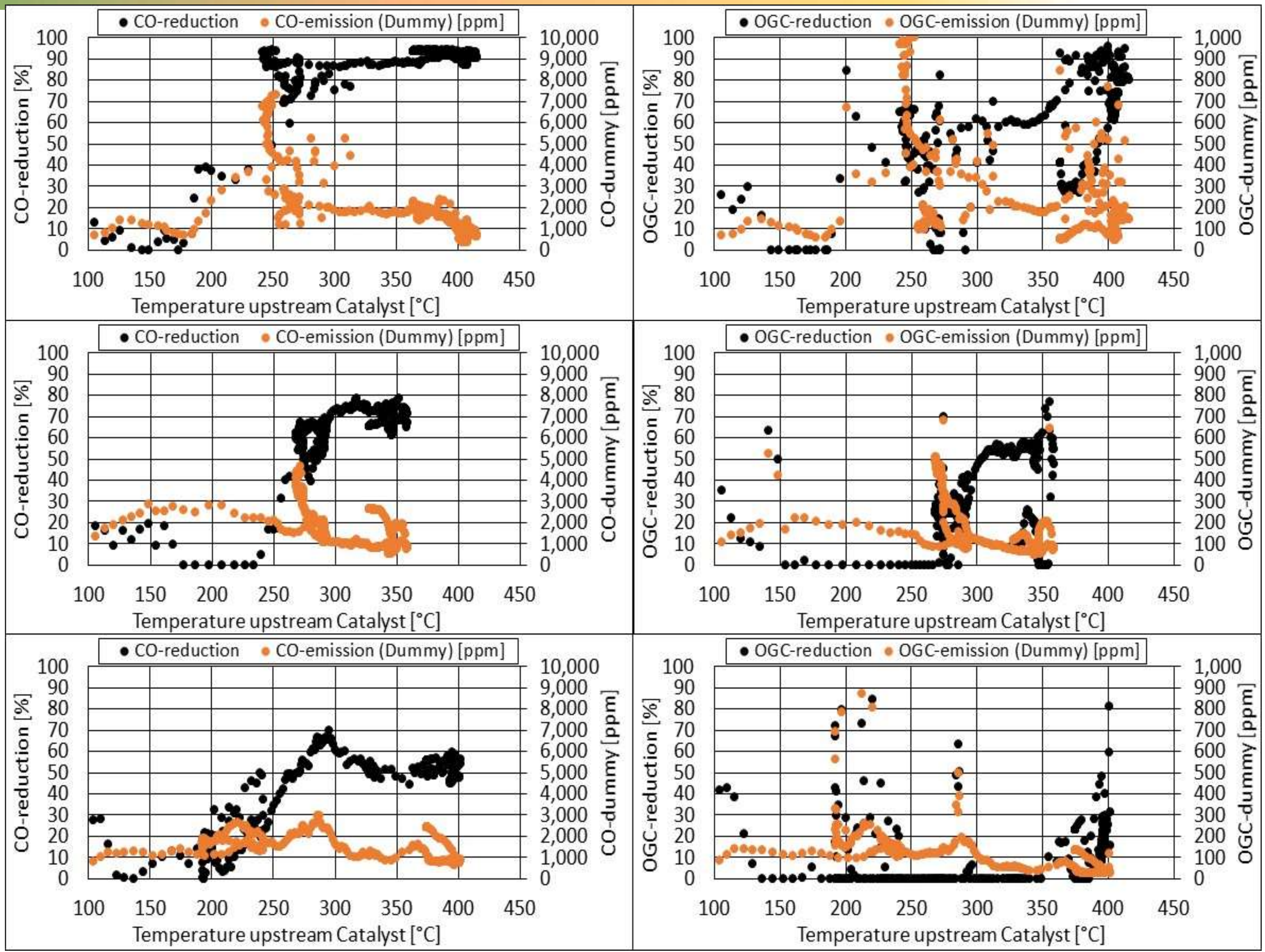


Catalyst 2 – Tailor-made catalyst I – light-off behaviour day 1, 11 and 12 during the ignition batch

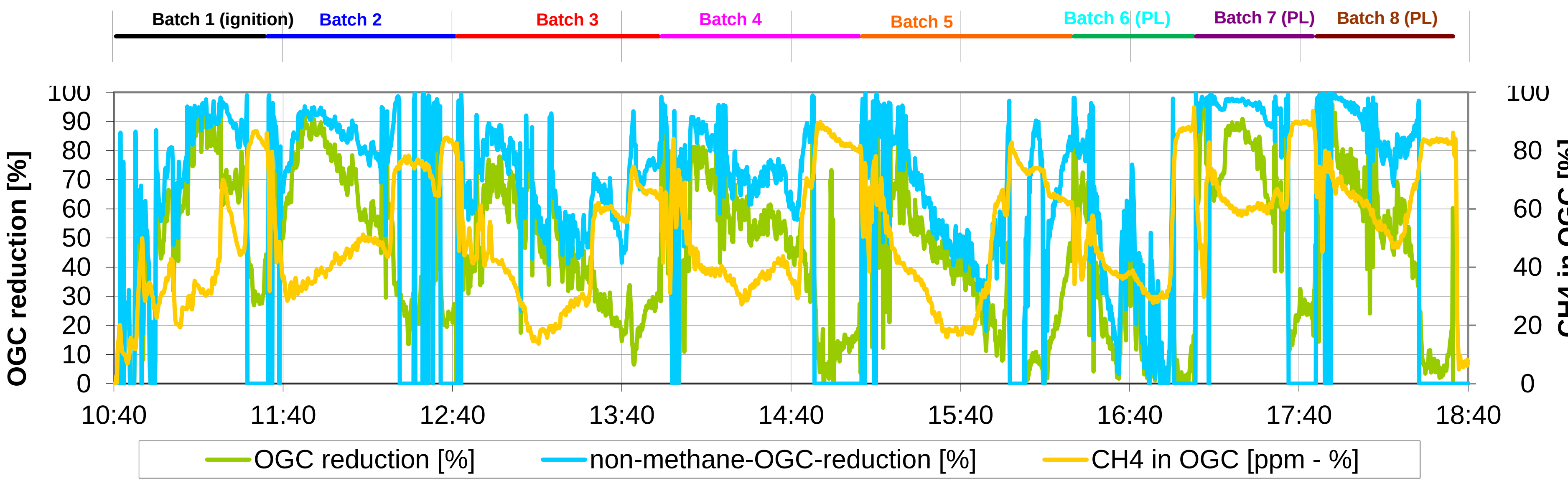
1

11

12



Catalyst 2 – Tailor-made catalyst I – Influence of CH_4 on OGC reduction



		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		31.08 10:41:07	31.08 11:34:44	31.08 12:41:50	31.08 13:54:09	31.08 15:05:00	31.08 16:20:00	31.08 17:03:13	31.08 17:45:52	31.08 10:41:07	31.08 10:41:07
Door opened		31.08 11:33:48	31.08 12:41:07	31.08 13:53:06	31.08 15:04:05	31.08 16:19:08	31.08 17:02:20	31.08 17:44:27	31.08 18:34:07	31.08 16:19:08	31.08 12:41:07
OGC reduction	[%]	54.3	56.9	43.9	45.8	34.9	24.7	64.2	50.9	46.3	50.6
non-methane-OGC-reduction	[%]	66.1	85.9	66.9	75.2	62.1	41.3	94.5	88.3	70.6	75.2

Explanations: Results of test run at day 1; OGC reduction (green), non-methane OGC reduction (blue); % CH_4 in OGC = ($ppm\ CH_4$ / ppm OGC) * 100

Catalyst 2 – Tailor-made catalyst I – Pictures of catalyst before and after cleaning

Catalyst before the test runs (view at outlet)

Catalyst after 2 weeks of operation (view at inlet)

Catalyst after manual cleaning after 2 weeks of operation (view at inlet)

- **Cleaning:**
  - **Step I: scrape off depositions for sampling**

  - **Step 2: cleaning with a soft brush**
  - **Step 3: purging every cell of the catalyst and the dummy with compressed air**

Catalyst 2 – Tailor-made catalyst I – Summary (I)

- The catalyst was operated for 11 days (88 batches) before cleaning it
- With the exception of the ignition batch the flue gas temperatures at catalyst inlet were well above the light-off temperature of approx. 240°C (light-off temperature defined based on measurements).
  - In average they where between 416 and 551°C (mean values over single batches excluding the ignition batches)
  - Also during re-charging they did not drop below 250°C
  - The maximum operation temperature of 650°C has not been exceeded (maximum temperature: 604°C)
- The stove could be operated at typical air supply conditions leading to average O_2 contents in the flue gas over a whole batch of between 10.5 and 12.9 vol% (dry flue gas, excluding the ignition batches).

Catalyst 2 – Tailor-made catalyst I – Summary (II)

- At the 1st day of operation for CO very high and for OGC high emission reduction efficiencies could be determined
  - CO (mean value for full load operation): 993 → 85 mg/MJ = 90.9%
  - CO (mean value for partial load operation): 1,152 → 100 mg/MJ = 89.2%
  - OGC (mean value for full load operation): 73.1 → 29.9 mg/MJ = 46.3%
  - OGC (mean value for partial load operation): 109.9 → 39.1 mg/MJ = 50.6%
- The pressure drop over the catalyst amounted to in average
  - 13.1 Pa (full load)
  - 10.4 Pa (partial load)

  which is in the expected range (due to the smaller surface compared with the Clariant catalyst)
- During full load operation particulate emissions (TSP) amounted to in average 36.5 mg/MJ. The high value was mainly due to very high emissions during Batch 1 (146.9 mg/MJ). The other batches showed emissions which are at about the same level as measured during pre-tests without catalyst and dummy (24.4 mg/MJ)

Catalyst 2 – Tailor-made catalyst I – Summary (II)

- During the first week of operation the CO emission reduction efficiency dropped to in average 76.3% (full load) and 75.4% (partial load). Within the second week of operation the CO emission reduction efficiency further dropped to in average 63.9% (full load) and 62.3% (partial load).
- The OGC emission reduction efficiency dropped to in average 22.6% (full load) and 26.3% (partial load) after one week and to 20.4% (full load) and 18.8% (partial load) after two weeks of operation.
- The pressure drop over the catalyst increased to in average 13.6 Pa (full load) and 11.4 Pa (partial load) after one week and to in average 15.2 Pa (full load) and 13.2 Pa (partial load) after two weeks of operation.
- During full load operation particulate emissions (TSP) remained at about the same level (22.7 mg/MJ after one week and 22.3 mg/MJ after 2 weeks)

Catalyst 2 – Tailor-made catalyst I – Summary (IV)

- An inspection of the catalyst after 2 weeks of operation revealed significant fly ash deposits blocking a part of the catalyst inlet surface → reason for the increasing pressure losses.
- After manual cleaning the pressure drop over the catalyst could be reduced again to 10.0 Pa (full load) and 8.8 Pa (partial load). These values are very close to the initial values.
- The cleaning showed no effect on the emission reduction efficiencies:
  - **CO emission reduction remained on a rather low level of in average close to 60% (at full and partial load)**
  - **OGC emission reduction remained on a rather low level of in average 19% resp. 16% (full and partial load)**

Catalyst 2 – Tailor-made catalyst I – Summary (V)

- **OGC-emission reduction:**
  - **The share of CH_4 on the OGC emissions increases downstream the catalyst up to 90% as it is well known that CH_4 is hardly converted by the catalyst. Therefore, the evaluation of the methane free OGC reduction showed a significantly higher emission reduction (20 to 80% higher) under the consideration that CH_4 is not converted by the catalyst.**
- **Evaluating the flue gas temperature upstream the catalyst and the CO emission reductions achieved shows:**
  - **Day1: light-off temperature: about 240°C**
  - **Day 10: light-off temperature: about 260°C**
  - **Day 11: light-off temperature: about 250°C (after cleaning)**

→ it seems that the light-off temperature does not significantly depend on the operation time

Catalyst 2 – Tailor-made catalyst I – Summary (VI)

- Regarding OGC-emissions the light-off temperatures seem to be about 30°C to 50°C higher and seem to increase with operation time.
- Consequently, also the manual cleaning showed no effect on the light-off temperatures.

Results of the test runs with a logwood stove and different catalysts

Results of the test runs performed with Catalyst 3 – Tailor-made catalyst II – at catalyst position I

Catalyst 3 – Tailor-made catalyst II – Overview

Day	Date	Comments
1	21/09/2015	Measurements – series 1
2	22/09/2015	Operation
3	23/09/2015	Operation
4	24/09/2015	Operation
5	25/09/2015	Operation
6	29/09/2015	Measurements – series 2
7	30/09/2015	Operation
8	01/10/2015	Operation
9	02/10/2015	Operation
10	07/10/2015	Operation
11	08/10/2015	Measurements – series 3 Manual cleaning of the catalyst
12	13/10/2015	Measurements – series 4

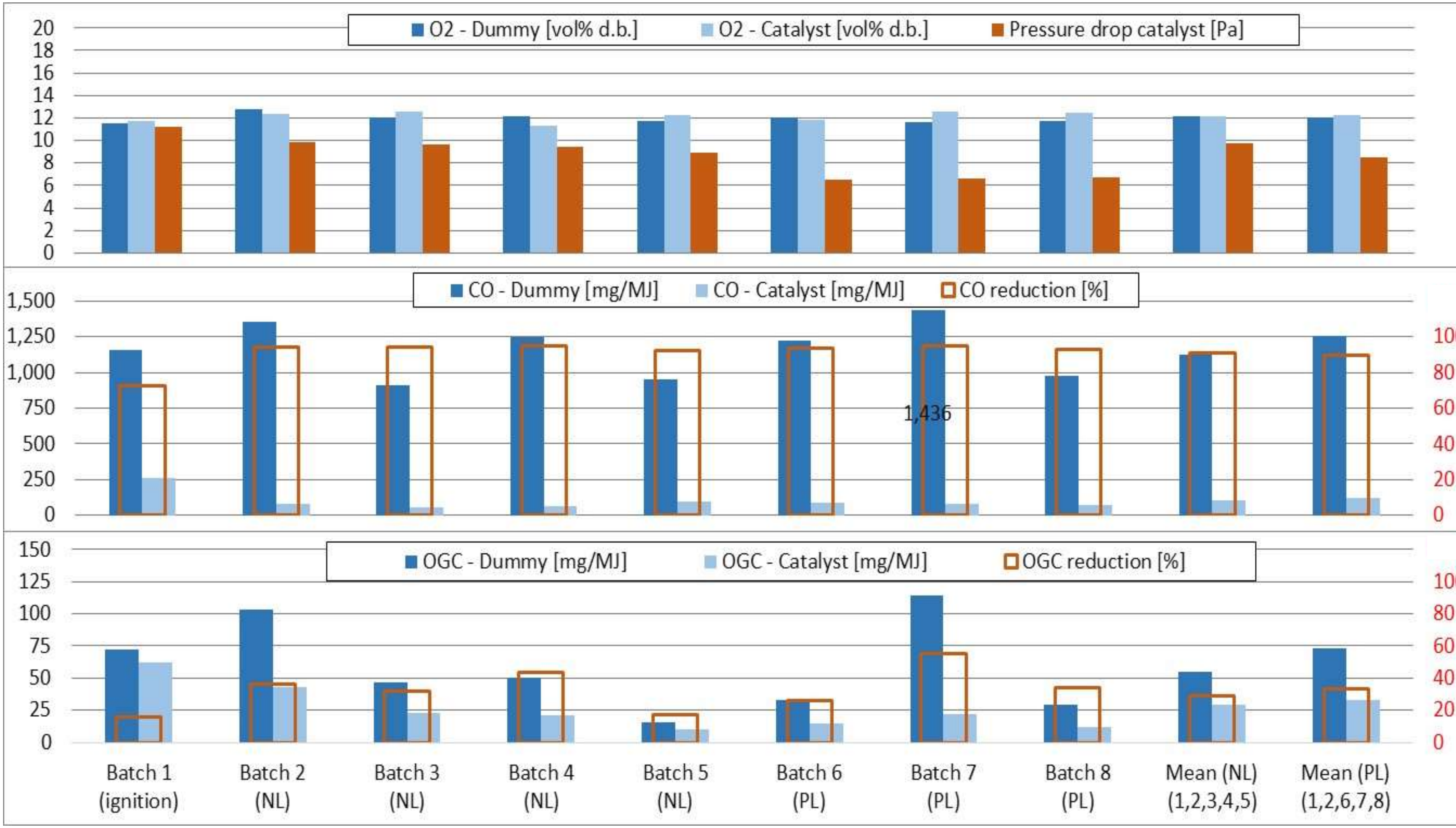
No	3
Name	Tailor-made catalyst II
Substrate	metal
Structure	honeycomb
CPSI [1)]	50
Dimension (HxWxL)	30 x 160 x 50 mm
Washcoat	H1010 (CeO_2)
Active metal	Pt, Pd
Light-off temperature[2)]	not defined yet since the catalysts are prototypes
Max. operation temp	650°C

Explanations: [1)] Cells per square inch (1 CPSI ~ 645 mm^2); [2)] Temperature that marks start of reactions

Catalyst 3 – Tailor-made catalyst II – Day 1: measurements – series 1 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		21/09 09:18	21/09 10:05	21/09 11:14	21/09 12:26	21/09 13:33	21/09 14:47	21/09 15:30	21/09 16:12		
Door opened		21/09 10:04	21/09 11:13	21/09 12:25	21/09 13:32	21/09 14:46	21/09 15:29	21/09 16:11	21/09 16:52		
Fuel input	kg w.b.	2.7	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.3	8.7
O_2 - Dummy	**vol% d.b.**	**11.5**	**12.7**	**12.0**	**12.2**	**11.7**	**12.1**	**11.7**	**11.7**	**12.1**	**12.1**
O_2 - Catalyst	**vol% d.b.**	**11.7**	**12.3**	**12.6**	**11.3**	**12.3**	**11.8**	**12.6**	**12.4**	**12.2**	**12.2**
CO - Dummy	mg/Nm³	1,738.8	2,027.1	1,364.4	1,875.7	1,422.5	1,834.4	2,154.3	1,463.7	1,687.9	1,880.9
CO - Catalyst	mg/Nm³	387.7	116.8	77.7	93.6	136.7	124.9	121.1	102.6	150.2	174.1
CO - Dummy	**mg/MJ**	**1,159.2**	**1,351.4**	**909.6**	**1,250.5**	**948.3**	**1,222.9**	**1,436.2**	**975.8**	**1,125.3**	**1,253.9**
CO - Catalyst	**mg/MJ**	**258.5**	**77.9**	**51.8**	**62.4**	**91.1**	**83.2**	**80.7**	**68.4**	**100.2**	**116.1**
CO reduction	**%**	**72.7**	**94.5**	**94.4**	**95.0**	**92.1**	**93.5**	**94.8**	**92.7**	**91.0**	**89.9**
OGC - Dummy	mg/Nm³	108.9	154.9	70.3	76.0	23.9	48.9	171.3	43.3	82.8	110.1
OGC - Catalyst	mg/Nm³	93.4	64.8	34.8	30.9	14.8	21.4	32.7	17.9	44.4	49.6
CH4 - Catalyst	mg/Nm³	53.7	55.8	31.7	30.2	14.6	20.3	31.3	17.3	36.1	38.8
OGC - Dummy	**mg/MJ**	**72.6**	**103.3**	**46.9**	**50.7**	**15.9**	**32.6**	**114.2**	**28.9**	**55.2**	**73.4**
OGC - Catalyst	**mg/MJ**	**62.3**	**43.2**	**23.2**	**20.6**	**9.9**	**14.3**	**21.8**	**11.9**	**29.6**	**33.1**
CH4 - Catalyst	mg/MJ	35.8	37.2	21.1	20.1	9.7	13.5	20.8	11.5	24.1	25.9
CH4 in OGC	%	57.5	86.1	90.9	97.6	98.5	94.8	95.6	96.8	81.4	78.3
OGC reduction	%	15.8	36.0	31.6	43.2	17.5	26.0	55.5	33.9	29.2	33.1
TSP	**mg/Nm³**	**51.0**	**n.m.**	**14.8**	**n.m.**	**18.3**	**n.m.**	**45.0**	**n.m.**	**23.3**	**48.0**
TSP	**mg/MJ**	**34.0**	**n.m.**	**9.8**	**n.m.**	**12.2**	**n.m.**	**30.0**	**n.m.**	**15.6**	**32.0**
T combustion chamber	°C	619.8	566.4	618.5	618.0	617.3	613.6	614.1	630.2	604.2	601.6
T Catalyst inlet	°C	326.2	456.0	495.6	538.6	529.9	507.8	513.3	513.9	478.7	459.2
T flue gas (EN13240)	°C	68.4	115.7	140.7	156.7	167.1	167.0	169.0	172.7	134.3	134.5
Chimney draught	Pa	11.9	12.0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.0
Pressure drop catalyst	**Pa**	**11.2**	**9.9**	**9.6**	**9.4**	**8.9**	**6.5**	**6.6**	**6.7**	**9.7**	**8.4**
Efficiency (EN13240)	**%**	**95.9**	**92.0**	**88.1**	**88.1**	**85.9**	**86.6**	**85.3**	**85.2**	**89.2**	**89.1**

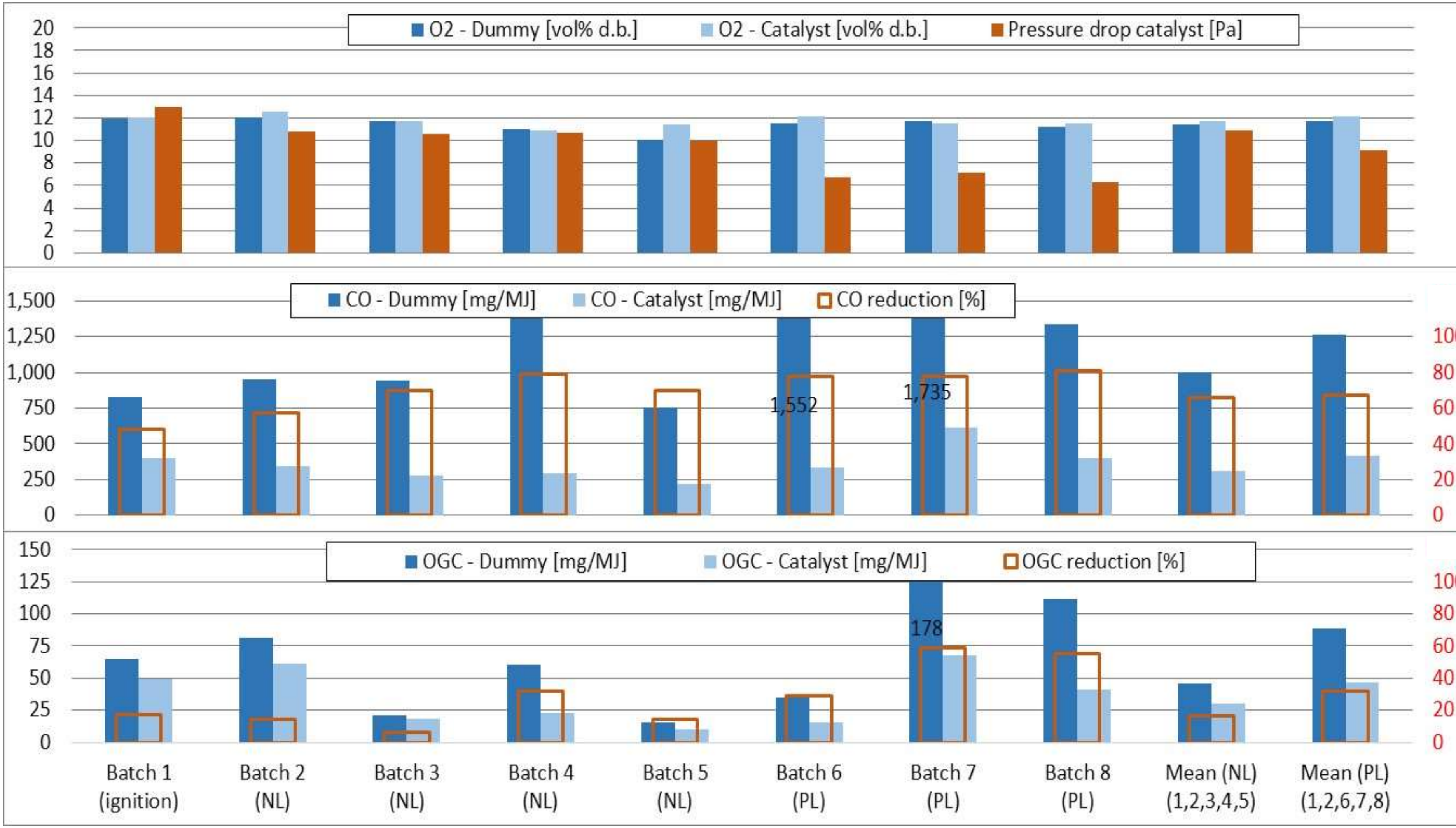
Catalyst 3 – Tailor-made catalyst II – Day 1: measurements – series 1 (II)



Catalyst 3 – Tailor-made catalyst II – Day 6: measurements – series 2 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		29/09 10:19	29/09 11:05	29/09 12:05	29/09 13:12	29/09 14:13	29/09 15:14	29/09 16:03	29/09 16:39		
Door opened		29/09 11:04	29/09 12:04	29/09 13:10	29/09 14:12	29/09 15:13	29/09 16:02	29/09 16:38	29/09 17:15		
Fuel input	kg w.b.	2.8	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.4	8.8
O_2 - Dummy	**vol% d.b.**	**11.9**	**12.1**	**11.7**	**11.0**	**10.1**	**11.5**	**11.7**	**11.2**	**11.4**	**11.8**
O_2 - Catalyst	**vol% d.b.**	**12.0**	**12.5**	**11.7**	**10.9**	**11.4**	**12.2**	**11.6**	**11.5**	**11.8**	**12.1**
CO - Dummy	mg/Nm³	1,247.5	1,425.7	1,415.2	2,137.2	1,134.3	2,328.1	2,602.5	2,004.0	1,505.3	1,890.8
CO - Catalyst	mg/Nm³	599.6	516.2	417.8	440.1	324.4	505.9	926.0	593.4	460.1	620.3
CO - Dummy	**mg/MJ**	**831.7**	**950.5**	**943.5**	**1,424.8**	**756.2**	**1,552.1**	**1,735.0**	**1,336.0**	**1,003.5**	**1,260.5**
CO - Catalyst	**mg/MJ**	**399.7**	**344.1**	**278.5**	**293.4**	**216.3**	**337.3**	**617.3**	**395.6**	**306.7**	**413.6**
CO reduction	**%**	**47.9**	**57.5**	**70.1**	**79.0**	**69.9**	**77.7**	**77.9**	**81.1**	**65.8**	**67.0**
OGC - Dummy	mg/Nm³	97.4	121.9	31.0	90.5	23.2	52.7	267.5	167.6	68.8	132.5
OGC - Catalyst	mg/Nm³	74.0	92.0	26.8	34.0	15.0	23.3	100.8	61.2	45.2	70.1
CH4 - Catalyst	mg/Nm³	29.4	74.6	19.6	20.8	9.5	16.7	76.8	50.9	29.8	49.9
OGC - Dummy	**mg/MJ**	**64.9**	**81.2**	**20.7**	**60.4**	**15.5**	**35.1**	**178.3**	**111.7**	**45.9**	**88.4**
OGC - Catalyst	**mg/MJ**	**49.3**	**61.3**	**17.9**	**22.7**	**10.0**	**15.5**	**67.2**	**40.8**	**30.2**	**46.7**
CH4 - Catalyst	mg/MJ	19.6	49.7	13.1	13.9	6.3	11.1	51.2	33.9	19.9	33.3
CH4 in OGC	%	39.8	81.1	73.2	61.1	63.3	71.8	76.1	83.2	65.9	71.2
OGC reduction	%	17.5	13.9	6.4	31.5	14.3	29.0	58.8	55.0	16.4	31.5
TSP	**mg/Nm³**	**65.5**	**n.m.**	**32.1**	**n.m.**	**30.2**	**n.m.**	**55.5**	**n.m.**	**37.8**	**60.0**
TSP	**mg/MJ**	**43.7**	**n.m.**	**21.4**	**n.m.**	**20.1**	**n.m.**	**37.0**	**n.m.**	**25.2**	**40.0**
T combustion chamber	°C	609.7	591.4	630.0	638.5	657.8	603.8	609.9	622.7	623.2	603.3
T Catalyst inlet	°C	316.2	444.8	512.5	545.9	552.2	517.9	516.2	526.2	482.5	458.8
T flue gas (EN13240)	°C	62.8	113.1	140.9	156.5	165.6	163.8	163.7	166.2	131.5	130.6
Chimney draught	Pa	12.3	12.3	12.3	12.3	12.2	12.3	12.3	12.2	12.3	12.3
Pressure drop catalyst	**Pa**	**13.0**	**10.8**	**10.5**	**10.7**	**10.0**	**6.7**	**7.1**	**6.3**	**10.9**	**9.1**
Efficiency (EN13240)	**%**	**96.3**	**92.3**	**89.5**	**89.0**	**87.8**	**86.8**	**87.4**	**87.4**	**90.2**	**89.8**

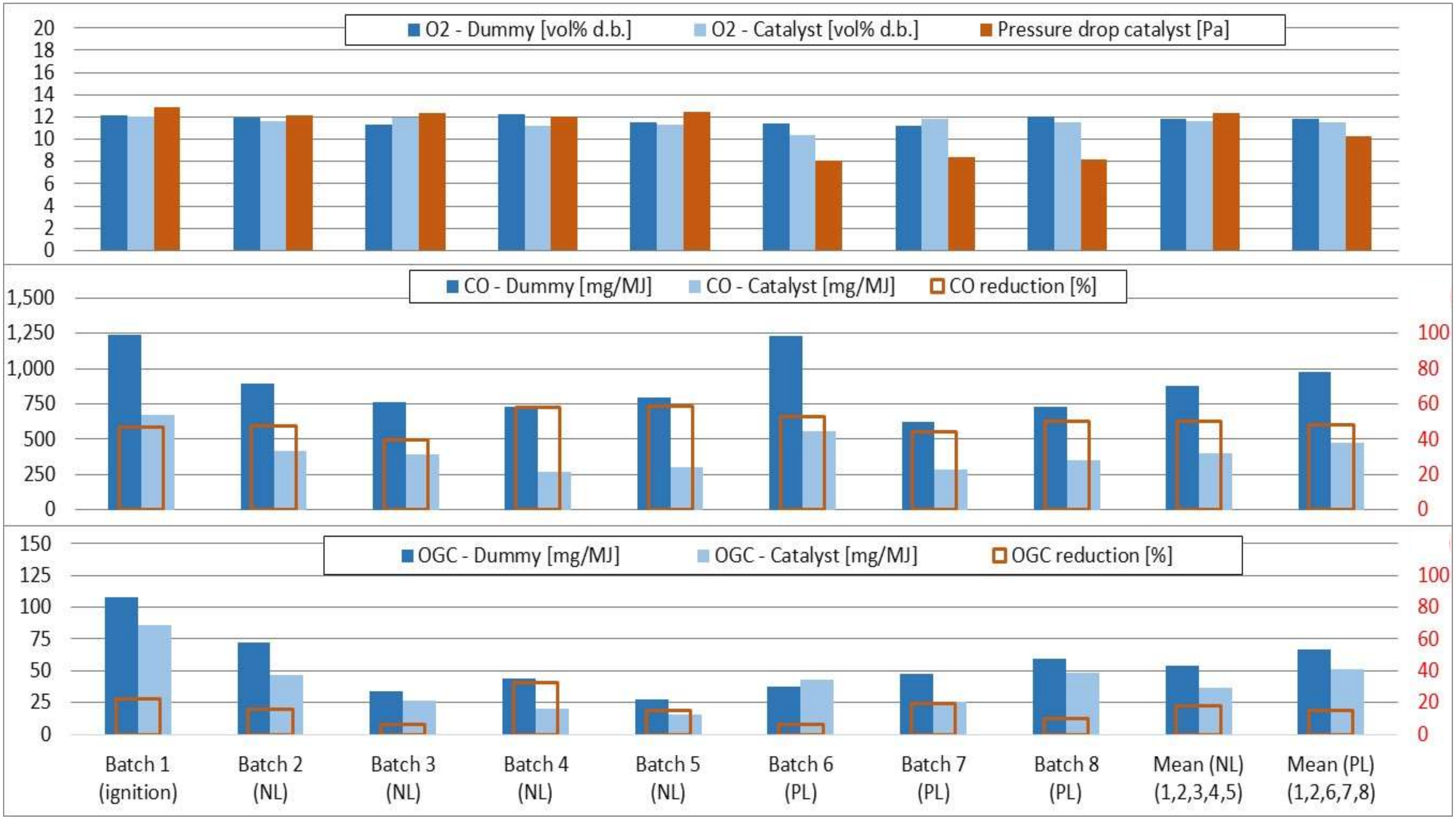
Catalyst 3 – Tailor-made catalyst II – Day 6: measurements – series 2 (II)



Catalyst 3 – Tailor-made catalyst II – Day 11: measurements – series 3 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		08/10 11:02	08/10 11:51	08/10 12:52	08/10 13:55	08/10 14:54	08/10 15:59	08/10 16:40	08/10 17:15		
Door opened		08/10 11:50	08/10 12:52	08/10 13:55	08/10 14:53	08/10 15:58	08/10 16:39	08/10 17:14	08/10 17:51		
Fuel input	kg w.b.	2.7	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.3	8.7
O_2 - Dummy	**vol% d.b.**	**12.2**	**11.9**	**11.3**	**12.3**	**11.5**	**11.4**	**11.2**	**12.0**	**11.9**	**11.9**
O_2 - Catalyst	**vol% d.b.**	**12.0**	**11.7**	**11.9**	**11.2**	**11.3**	**10.4**	**11.8**	**11.5**	**11.7**	**11.6**
CO - Dummy	mg/Nm³	1,852.9	1,345.9	1,143.1	1,090.0	1,191.8	1,844.0	936.9	1,095.3	1,320.0	1,461.3
CO - Catalyst	mg/Nm³	1,004.9	619.7	587.1	404.6	456.2	837.9	430.9	527.7	604.0	710.0
CO - Dummy	**mg/MJ**	**1,235.3**	**897.3**	**762.0**	**726.7**	**794.6**	**1,229.3**	**624.6**	**730.2**	**880.0**	**974.2**
CO - Catalyst	**mg/MJ**	**669.9**	**413.1**	**391.4**	**269.8**	**304.1**	**558.6**	**287.2**	**351.8**	**402.7**	**473.3**
CO reduction	**%**	**47.0**	**47.7**	**39.7**	**57.8**	**58.9**	**52.7**	**44.0**	**50.0**	**50.3**	**48.3**
OGC - Dummy	mg/Nm³	161.9	107.7	51.1	65.4	41.7	55.6	71.3	88.7	81.2	100.6
OGC - Catalyst	mg/Nm³	128.7	70.0	39.9	30.5	23.0	64.4	38.8	72.2	55.0	77.4
CH4 - Catalyst	mg/Nm³	66.0	37.9	23.4	17.1	16.3	49.3	20.9	60.7	30.9	48.0
OGC - Dummy	**mg/MJ**	**108.0**	**71.8**	**34.0**	**43.6**	**27.8**	**37.1**	**47.5**	**59.1**	**54.1**	**67.1**
OGC - Catalyst	**mg/MJ**	**85.8**	**46.6**	**26.6**	**20.4**	**15.4**	**43.0**	**25.9**	**48.1**	**36.7**	**51.6**
CH4 - Catalyst	mg/MJ	44.0	25.2	15.6	11.4	10.8	32.9	13.9	40.5	20.6	32.0
CH4 in OGC	%	51.3	54.1	58.6	55.9	70.7	76.6	53.7	84.2	56.2	62.1
OGC reduction	%	22.2	15.8	6.3	32.3	15.0	6.4	19.3	10.1	17.8	15.0
TSP	**mg/Nm³**	**58.8**	**n.m.**	**23.6**	**n.m.**	**32.5**	**n.m.**	**40.5**	**n.m.**	**35.6**	**50.2**
TSP	**mg/MJ**	**39.2**	**n.m.**	**15.7**	**n.m.**	**21.7**	**n.m.**	**27.0**	**n.m.**	**23.7**	**33.5**
T combustion chamber	°C	575.0	607.8	650.3	637.0	666.0	628.2	628.0	623.6	627.7	608.4
T Catalyst inlet	°C	305.1	453.0	508.4	525.6	551.3	527.4	504.1	514.5	475.6	452.0
T flue gas (EN13240)	°C	62.6	109.0	136.0	150.7	160.8	160.0	158.6	160.8	126.6	124.5
Chimney draught	Pa	12.5	12.4	12.4	12.3	12.4	12.3	12.4	12.2	12.4	12.4
Pressure drop catalyst	**Pa**	**12.9**	**12.1**	**12.4**	**12.1**	**12.4**	**8.0**	**8.4**	**8.2**	**12.4**	**10.3**
Efficiency (EN13240)	**%**	**96.4**	**93.6**	**90.1**	**89.7**	**88.8**	**89.5**	**88.5**	**88.6**	**91.1**	**91.3**

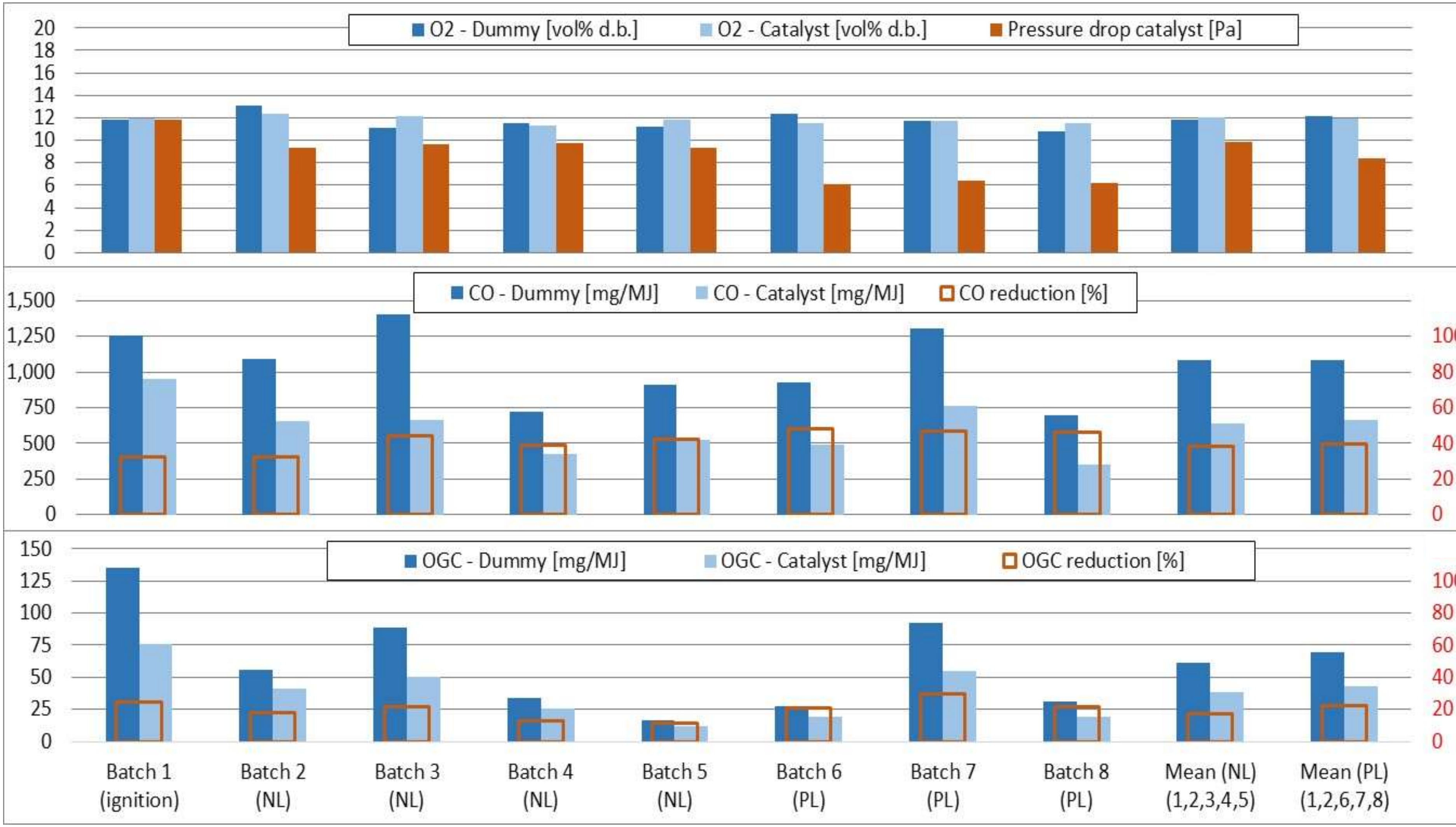
Catalyst 3 – Tailor-made catalyst II – Day 11: measurements – series 3 (II)



Catalyst 3 – Tailor-made catalyst II – Day 12: measurements – series 4 (I)

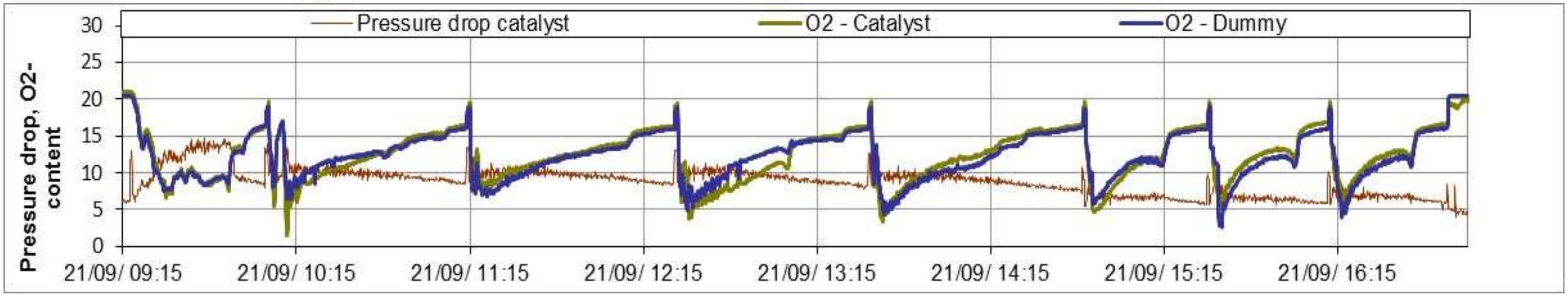
		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		12/10 10:14	12/10 11:02	12/10 12:16	12/10 13:17	12/10 14:14	12/10 15:25	12/10 16:06	12/10 16:44		
Door opened		12/10 11:02	12/10 12:15	12/10 13:17	12/10 14:13	12/10 15:25	12/10 16:05	12/10 16:43	12/10 17:18		
Fuel input	kg w.b.	2.7	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.3	8.7
O_2 - Dummy	**vol% d.b.**	**11.8**	**13.0**	**11.1**	**11.5**	**11.2**	**12.3**	**11.8**	**10.8**	**11.8**	**12.2**
O_2 - Catalyst	**vol% d.b.**	**11.9**	**12.4**	**12.2**	**11.4**	**11.8**	**11.5**	**11.7**	**11.5**	**12.0**	**12.0**
CO - Dummy	mg/Nm³	1,878.8	1,634.4	2,104.2	1,076.9	1,362.4	1,393.0	1,959.5	1,038.4	1,628.6	1,619.6
CO - Catalyst	mg/Nm³	1,427.6	987.7	1,000.6	636.2	780.4	735.7	1,137.5	527.0	958.3	998.0
CO - Dummy	**mg/MJ**	**1,252.5**	**1,089.6**	**1,402.8**	**717.9**	**908.2**	**928.7**	**1,306.4**	**692.2**	**1,085.7**	**1,079.7**
CO - Catalyst	**mg/MJ**	**951.7**	**658.5**	**667.1**	**424.1**	**520.2**	**490.5**	**758.4**	**351.3**	**638.8**	**665.3**
CO reduction	**%**	**32.2**	**32.2**	**44.5**	**38.7**	**42.2**	**48.2**	**47.1**	**45.9**	**38.2**	**39.4**
OGC - Dummy	mg/Nm³	203.2	83.9	132.7	50.2	25.3	41.4	138.2	46.4	92.2	104.8
OGC - Catalyst	mg/Nm³	113.2	61.6	75.7	38.1	18.0	29.5	82.4	28.8	57.8	64.9
CH4 - Catalyst	mg/Nm³	76.4	48.8	38.0	22.2	10.4	16.6	40.2	15.9	37.3	42.7
OGC - Dummy	**mg/MJ**	**135.5**	**55.9**	**88.5**	**33.5**	**16.8**	**27.6**	**92.1**	**30.9**	**61.5**	**69.9**
OGC - Catalyst	**mg/MJ**	**75.4**	**41.0**	**50.4**	**25.4**	**12.0**	**19.6**	**54.9**	**19.2**	**38.5**	**43.3**
CH4 - Catalyst	mg/MJ	50.9	32.5	25.3	14.8	6.9	11.0	26.8	10.6	24.9	28.5
CH4 in OGC	%	67.5	79.2	50.2	58.2	57.5	56.2	48.8	55.3	64.6	65.8
OGC reduction	%	24.6	18.1	21.9	12.9	11.1	21.1	30.0	21.8	17.2	22.2
TSP	**mg/Nm³**	**51.2**	**n.m.**	**43.7**	**n.m.**	**33.3**	**n.m.**	**39.8**	**n.m.**	**41.6**	**47.1**
TSP	**mg/MJ**	**34.1**	**n.m.**	**29.1**	**n.m.**	**22.2**	**n.m.**	**26.5**	**n.m.**	**27.8**	**31.4**
T combustion chamber	°C	561.9	580.3	611.4	635.8	653.1	619.8	622.1	647.0	608.7	598.2
T Catalyst inlet	°C	323.9	446.4	488.7	524.6	544.2	509.0	508.9	521.8	472.0	452.9
T flue gas (EN13240)	°C	74.4	119.2	140.4	156.7	166.5	162.6	163.0	166.8	134.1	131.7
Chimney draught	Pa	12.6	12.3	12.2	12.3	12.3	12.3	12.3	12.4	12.3	12.4
Pressure drop catalyst	**Pa**	**11.8**	**9.3**	**9.7**	**9.8**	**9.3**	**6.1**	**6.4**	**6.2**	**9.9**	**8.4**
Efficiency (EN13240)	**%**	**95.4**	**92.3**	**89.3**	**89.0**	**87.6**	**88.3**	**87.9**	**88.1**	**90.0**	**90.2**

Catalyst 3 – Tailor-made catalyst II – Day 12: measurements – series 4 (II)

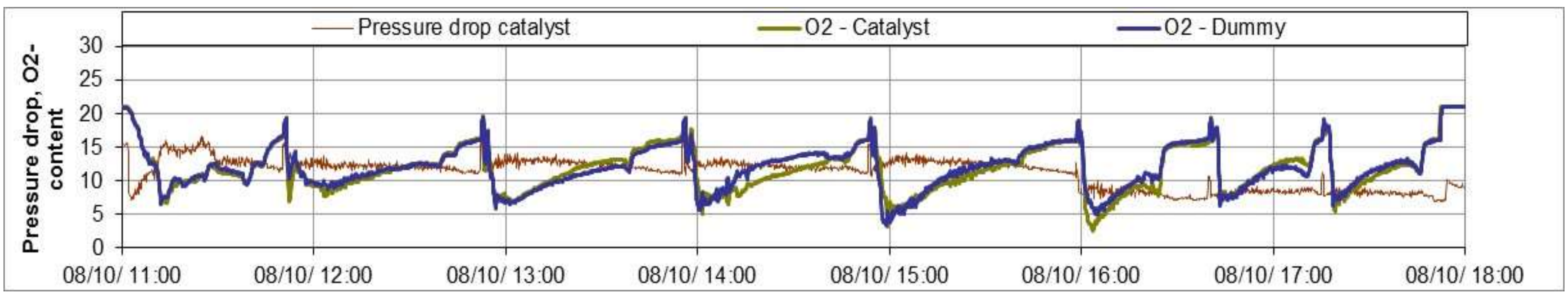


Catalyst 3 – Tailor-made catalyst II – comparisons of day 1, 11 and 12 – pressure drop and O_2 trends

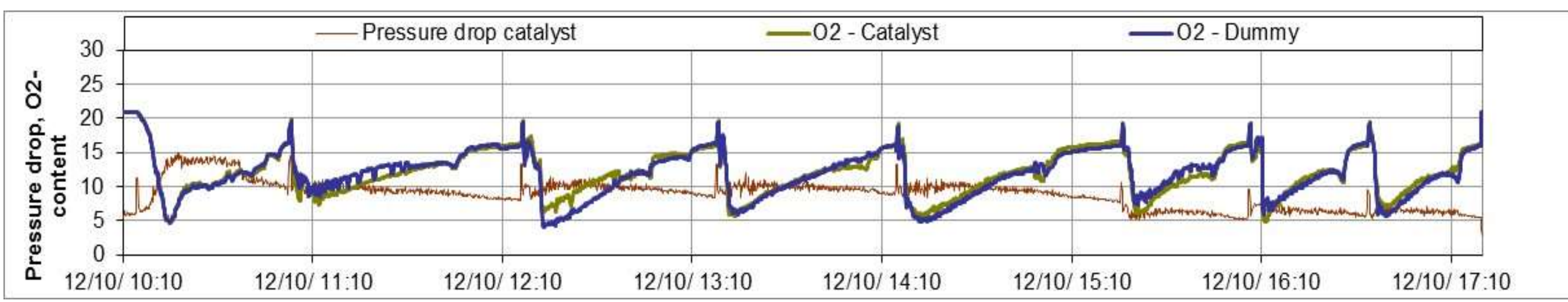
1



11

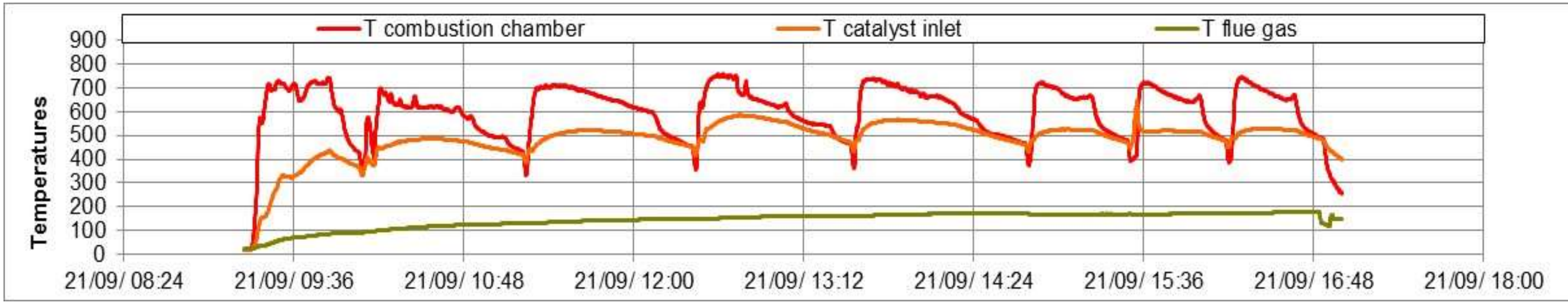


12

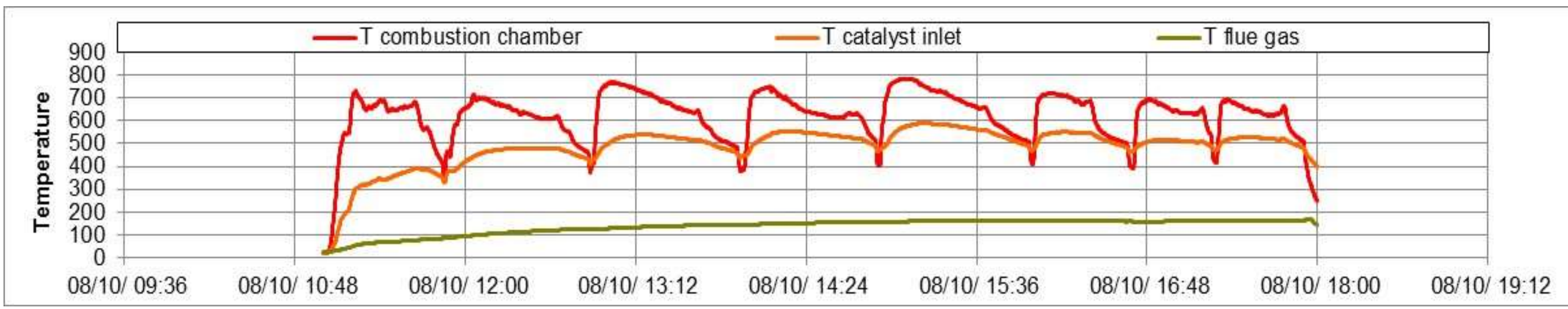


Catalyst 3 – Tailor-made catalyst II – comparisons of day 1, 11 and 12 – Temperatures

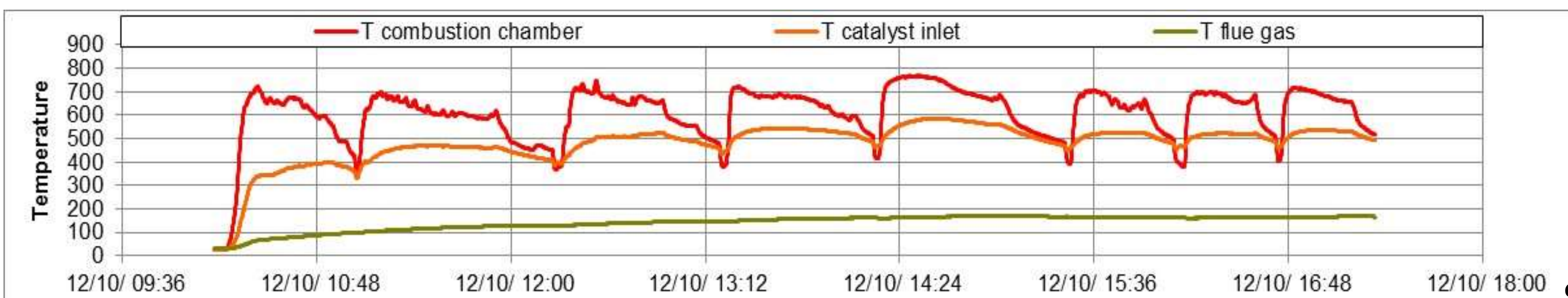
1



11

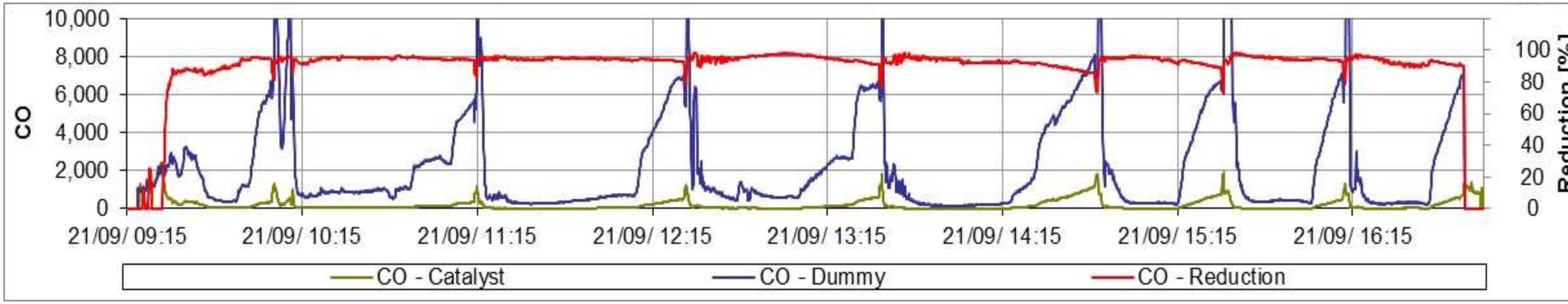


12

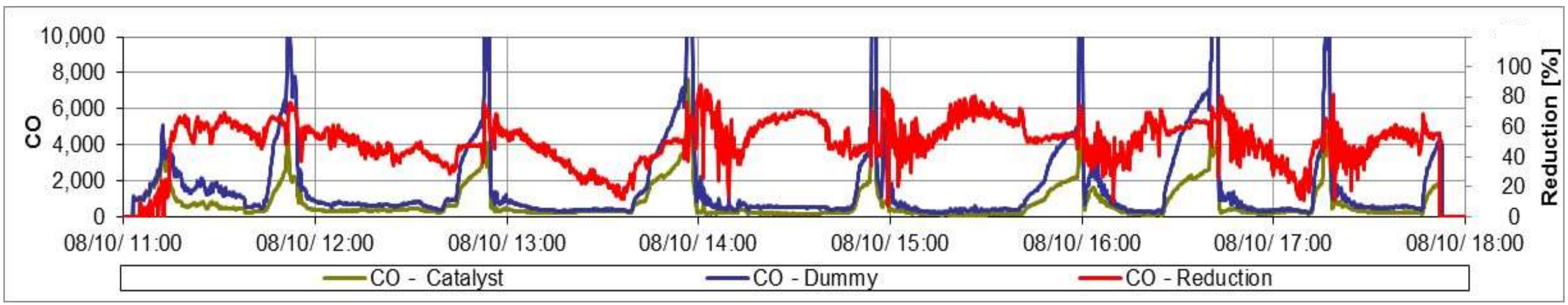


Catalyst 3 – Tailor-made catalyst II – comparisons of day 1, 11 and 12 – CO emission and CO-reduction trends

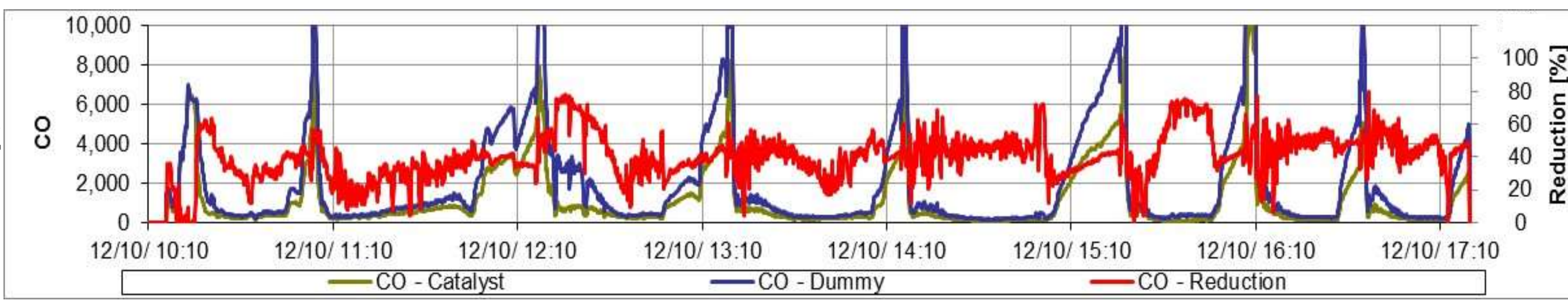
1



11

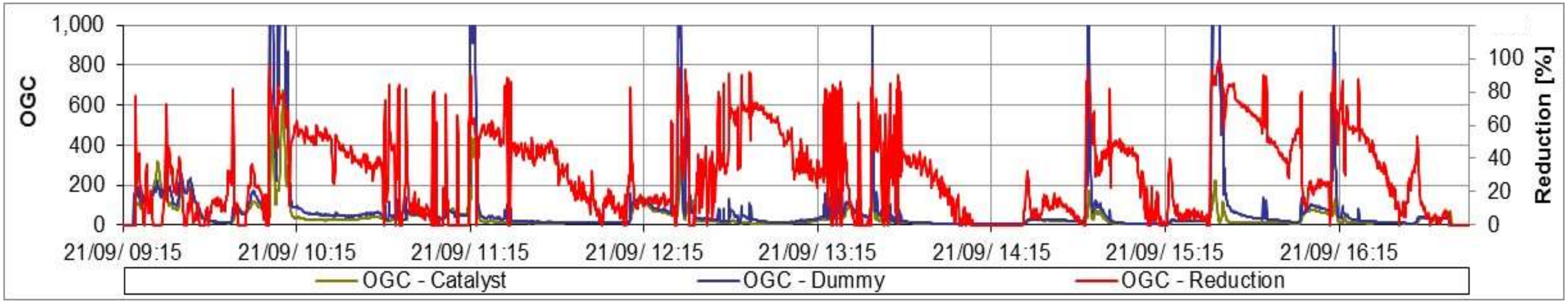


12

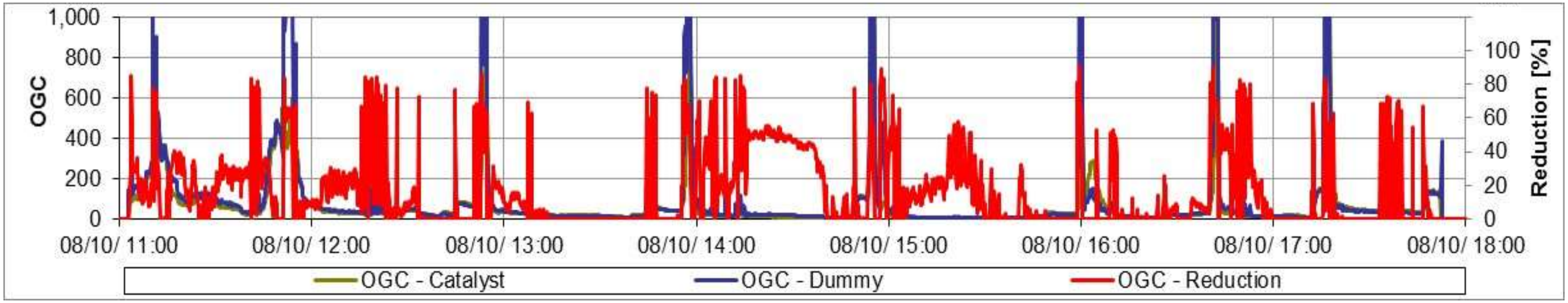


Catalyst 3 – Tailor-made catalyst I – comparisons of day 1, 11 and 12 – OGC emission and OGC-reduction trends

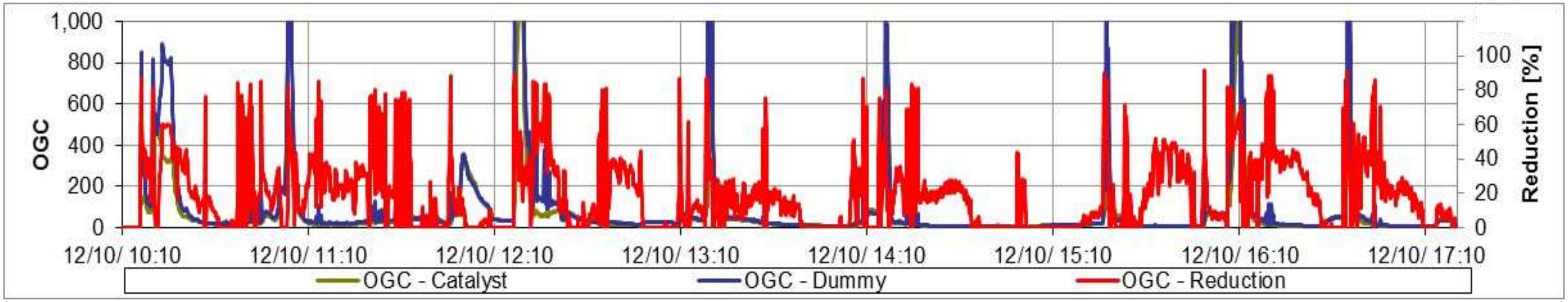
1



11

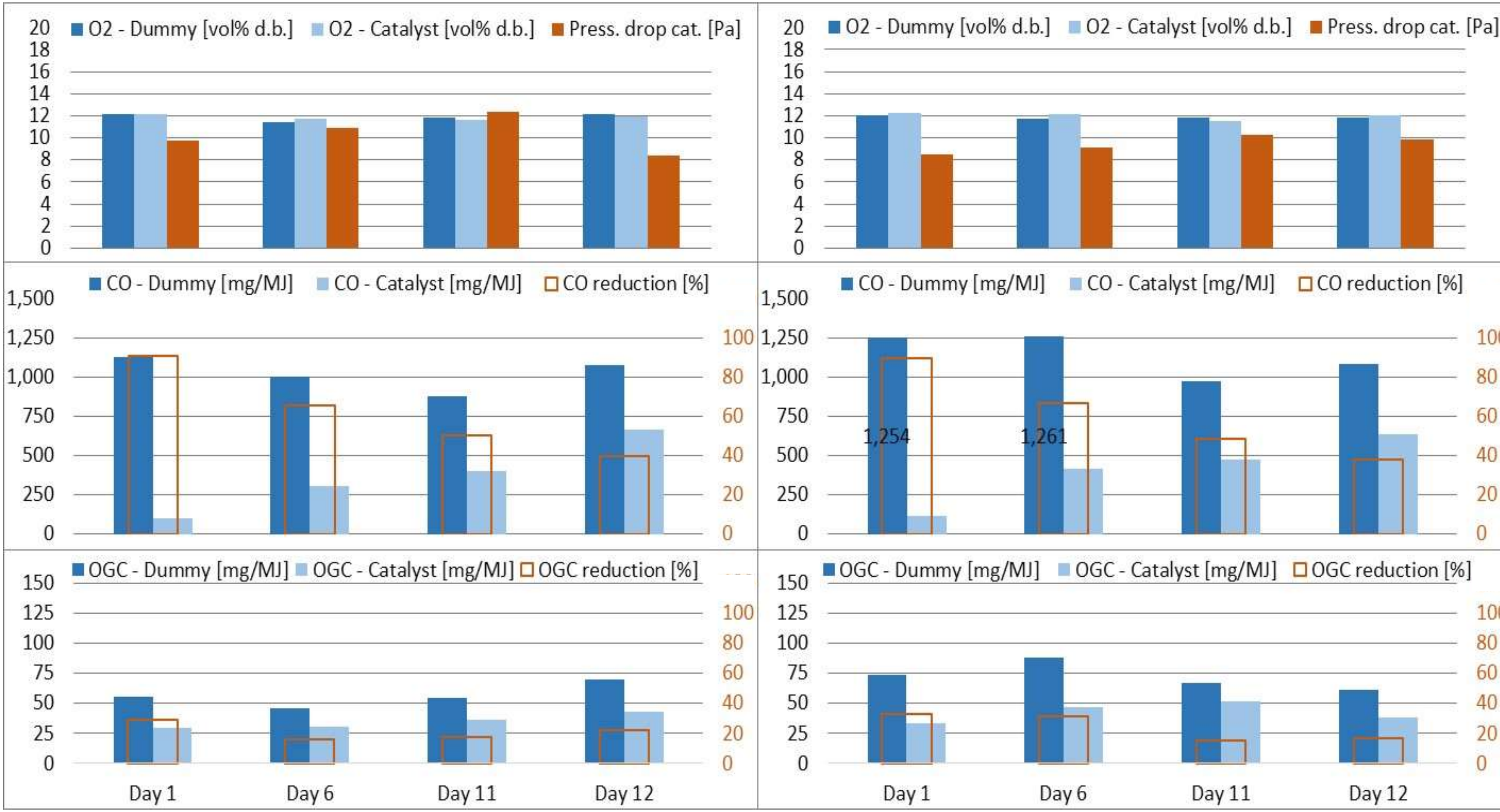


12



Catalyst 3 – Tailor-made catalyst II – comparisons of mean values

Nominal load | **Partial load**

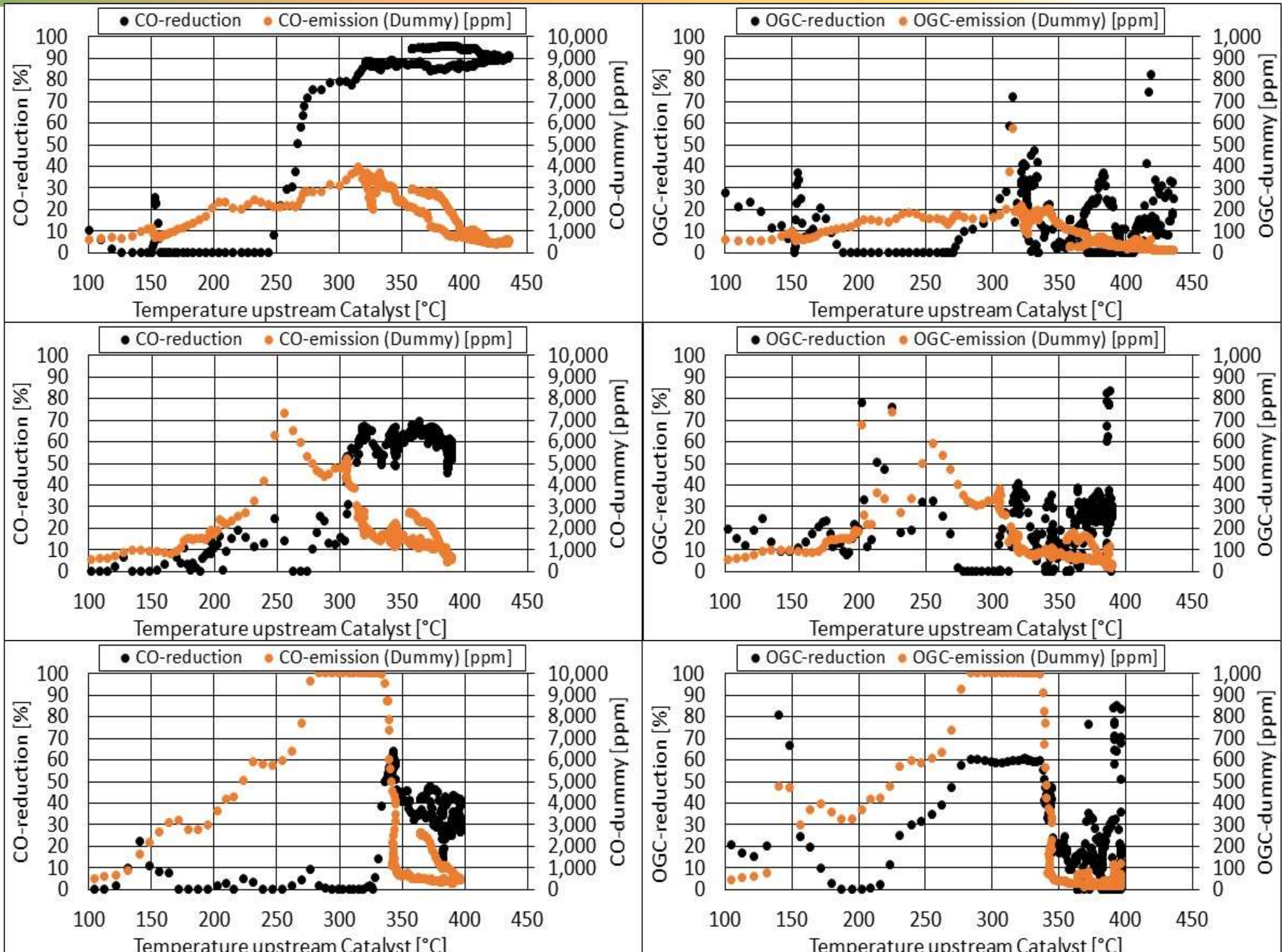


Catalyst 3 – Tailor-made catalyst II – light-off behaviour day 1, 11 and 12 during the ignition batch

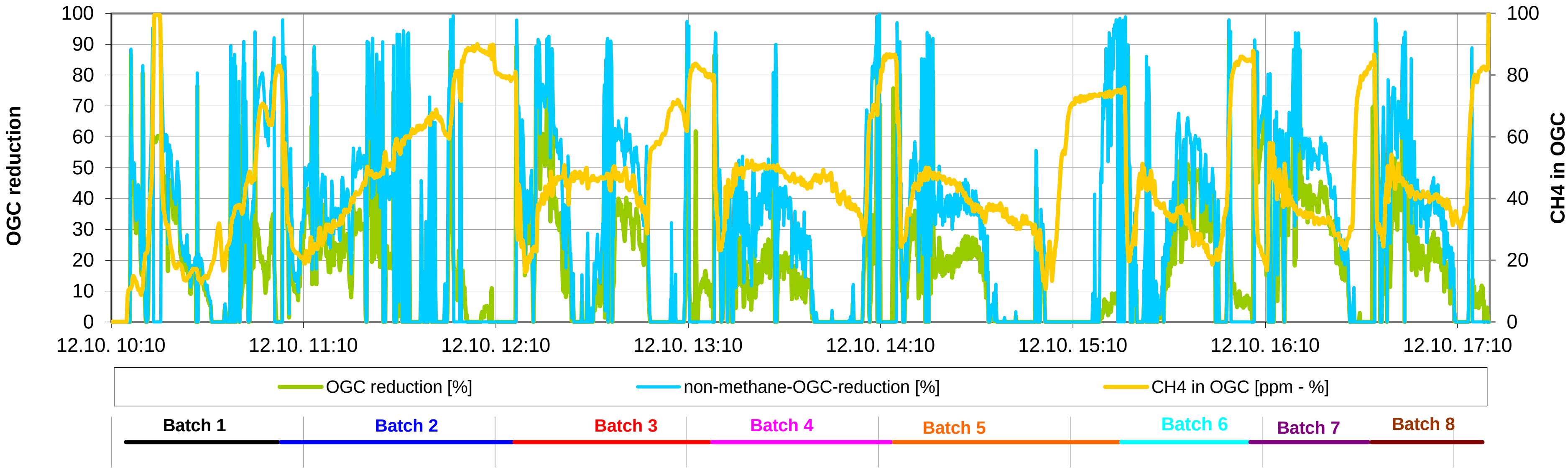
1

11

12



Catalyst 3 – Tailor-made catalyst II – Influence of CH_4 on OGC reduction

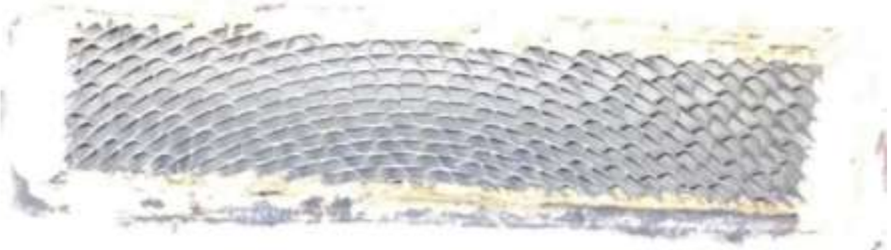


		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)
Door closed		12.10 10:14:28	12.10 11:02:56	12.10 12:16:03	12.10 13:17:56	12.10 14:14:44	12.10 15:25:55	12.10 16:06:18	12.10 16:44:13	12.10 10:14:28	12.10 10:14:28
Door opened		12.10 11:02:03	12.10 12:15:28	12.10 13:17:03	12.10 14:13:54	12.10 15:25:16	12.10 16:05:31	12.10 16:43:14	12.10 17:18:55	12.10 15:25:16	12.10 12:15:28
OGC reduction	[%]	24.6	18.1	21.9	12.9	11.1	21.1	30.0	21.8	17.2	22.2
OGC-nCH4-reduction	[%]	33.8	39.0	35.6	26.2	28.4	32.6	46.2	38.0	32.5	37.7

Explanations: Results of test run at day 1; OGC reduction (green), non-methane OGC reduction (blue);
% CH_4 in OGC = (ppm CH_4 / ppm OGC) * 100

Catalyst 3 – Tailor-made catalyst II – Pictures of catalyst before and after cleaning

Catalyst before the test runs (view at outlet)



Catalyst 2 weeks of operation (view at inlet)

Catalyst after manual cleaning after 2 weeks of operation (view at inlet)

- **Cleaning:**
  - **Step I: scrape off depositions for sampling**

  - **Step 2: cleaning by purging the catalyst with a hot air flow (about 550°C) for 16 hours.**

Catalyst 3 – Tailor-made catalyst II – Summary (I)

- The catalyst was operated for 11 days (88 batches) before cleaning it.
- With the exception of the ignition batch the flue gas temperatures at catalyst inlet were well above the light-off temperature of approx. 260°C (light-off temperature defined based on measurements).
  - In average they amounted to 444 till 552°C (mean values over single batches excluding the ignition batches)
  - Also during re-charging they did not drop below 260°C
  - The maximum operation temperature of 650°C has not been exceeded (Maximum temperature on day 1: 646°C, 601°C for the remaining days)
- The stove could be operated at typical air supply conditions leading to average O_2 contents in the flue gas over a whole batch of between 10.1 and 13.0 vol% (dry flue gas, excluding the ignition batches).

Catalyst 3 – Tailor-made catalyst II – Summary (II)

- At the 1st day of operation for CO very high and for OGC acceptable emission reduction efficiencies could be determined
  - CO (mean value for full load operation): 1,125 → 100 mg/MJ = 91.0%
  - CO (mean value for partial load operation): 1,154 → 116 mg/MJ = 89.9%
  - OGC (mean value for full load operation): 55.2 → 29.6 mg/MJ = 29.2%
  - OGC (mean value for partial load operation): 73.4 → 33.1 mg/MJ = 33.1%
- The pressure drop over the catalyst amounted to in average
  - 9.7 Pa (full load)
  - 8.4 Pa (partial load)
- During full load operation particulate emissions (TSP) amounted to in average 15.6 mg/MJ which are at about the same level as measured during pre-tests without catalyst and dummy (24.4 mg/MJ)

Catalyst 3 – Tailor-made catalyst II – Summary (III)

- During the first week of operation the CO emission reduction efficiency dropped to in average 65.8% (full load) and 67.0% (partial load). Within the second week of operation the CO emission reduction efficiency further dropped to in average 50.3% (full load) and 48.3% (partial load).

- The OGC emission reduction efficiency dropped to in average 16.4% (full load) and 31.5% (partial load) after one week and to 17.8% (full load) and 15.0% (partial load) after two weeks of operation.

- The pressure drop over the catalyst increased to in average 10.9 Pa (full load) and 9.1 Pa (partial load) after one week and to in average 12.4 Pa (full load) and 10.3 Pa (part. load) after two weeks of operation.

- During full load operation particulate emissions (TSP) increased slightly (25.2 mg/MJ after one week and 23.7 mg/MJ after 2 weeks) but remained at about the same level of the measurements performed without catalyst and dummy.

Catalyst 3 – Tailor-made catalyst II – Summary (IV)

- An inspection of the catalyst after 2 weeks of operation revealed only a few fly ash deposits which is in line with the less pronounced increase of the pressure drop compared with the other catalysts.
- After manual cleaning the pressure drop over the catalyst could be reduced again to 9.9 Pa (full load) and 8.4 Pa (partial load). These values are very close to the initial values.
- The catalyst has not only been cleaned but also treated with clean pre-heated air (530 °C, 2x8 h) in order to achieve a regeneration effect. However, no regeneration effect could be observed.
  - **CO emission reduction remained on a rather low level of in average close to 40% (at full and partial load)**
  - **OGC emission reduction remained on a rather low level of in average 17% resp. 22% (full and partial load)**

Catalyst 3 – Tailor-made catalyst II – Summary (V)

- **OGC-emission reduction:**
  - **The share of CH_4 on the OGC emissions increases downstream the catalyst up to 90% as it is well known that CH_4 is hardly converted by the catalyst. Therefore, the evaluation of the methane free OGC reduction showed a significantly higher emission reduction (30 to 150% higher) under the consideration that CH_4 is not converted by the catalyst.**

- **Evaluating the flue gas temperature upstream the catalyst and the CO emission reductions achieved shows:**
  - **Day1: light-off temperature: about 260°C**
  - **Day 10: light-off temperature: about 300°C**
  - **Day 11: light-off temperature: about 330°C (after cleaning)**

  → the light-off temperature increases with operation time

Catalyst 3 – Tailor-made catalyst II – Summary (VI)

- Regarding OGC-emissions, the light-off temperatures seem to be more than 50°C higher, however, an in depth evaluation has to be made since the data significantly scatter.
- Consequently, also the manual cleaning and the regeneration showed no positive effect on the light-off temperatures.

Results of the test runs with a logwood stove and different catalysts

CONCLUSIONS REGARDING THE TEST RUNS WITH METAL CATALYSTS

Conclusions (I)

- Three metal based catalysts with different material properties and different active metal mixtures have been tested.
- The evaluation of the stove operation data showed, that all test runs have been performed under well comparable and representative combustion conditions.
- The catalysts showed only a small effect on PM emissions.
- The catalysts showed no effect on the efficiency of the stove.

Conclusions (II)

- **Pressure drop:**
  - **Catalyst 1 and Catalyst 3 showed about the same initial pressure drops (<10 Pa) while the initial pressure drop of Catalyst 2 was with 13.1 Pa (average for full load operation on day 1) higher.**
  - **For all 3 catalysts the pressure drop increased with operation time**
    - Catalyst 1: strongest increase (up to 20 Pa)
    - Catalyst 2: less pronounced increase (up to 15 Pa)
    - Catalyst 3: less pronounced increase (up to 13 Pa)
  - **The increase of the pressure drop could be correlated with the optically determined degree of fly ash deposit build-up on the catalyst inlet surface.**
  - **Manual cleaning decreased the pressure drop again**
    - Catalyst 1: not all deposits could be removed → the initial pressure drop was not reached again after cleaning
    - Catalyst 2 and 3: successful removal of the ash deposits → the initial pressure drop could be reached after cleaning

Conclusions (III)

- **CO-emission reduction:**
  - **All 3 catalysts showed high CO emission reduction efficiencies during the first operation day. Catalyst 1 was with about 94% (at full load) slightly more efficient than the other two catalysts (about 90%)**
  - **Emission reduction efficiency considerably decreased for all three catalysts and cleaning respectively purging with hot air (regeneration) showed no positive effect.**
    (data for nominal load: at start → after 1 week → after 2 weeks → after cleaning)
    - Catalyst 1: 94% → 64% → 58% → 50%
    - Catalyst 2: 91% → 76% → 64% → 60%
    - Catalyst 3: 91% → 66% → 50% → 40%

    → Consequently, Catalyst 2 showed less de-activation than the other two catalysts
  - **Surprisingly, the Pd in Catalyst 3 did not increase (as initially expected) the CO emission reduction efficiency**

Conclusions (IV)

- **OGC-emission reduction:**
  - **All 3 catalysts showed moderate OGC emission reduction efficiencies during the first operation day. Catalyst 2 was with about 46% (at full load) significantly more efficient than the other two catalysts (19% and 29% for Catalyst 1 and 3)**
  - **Emission reduction efficiency significantly decreased for catalyst 2 and 3 while it surprisingly increased for catalyst 1. Cleaning respectively purging with hot air (regeneration) showed no positive effect.**
    (data for nominal load: at start → after 1 week → after 2 weeks → after cleaning)
    - Catalyst 1: 19% → 24% → 37% → 33%
    - Catalyst 2: 46% → 23% → 20% → 16%
    - Catalyst 3: 29% → 16% → 18% → 22%
  - **The higher Pt-content of catalyst 2 in comparison to catalyst 3 seems to improve the initial OGC-emission reduction efficiency but after 2 weeks almost no difference occurs. Unfortunately, the exact composition of the catalytically active material of Catalyst 1, which showed the best OGC emission reduction efficiency, is not known.**

Conclusions (V)

- **OGC-emission reduction (cont.):**
  - **The share of CH_4 on the OGC emissions increases downstream the catalyst up to 90% as it is well known that CH_4 is hardly converted by the catalyst. Therefore, the evaluation of the methane free OGC reduction showed a significantly higher emission reduction under the consideration that CH_4 is not converted by the applied metal based catalysts.**
- **A deeper evaluation of the 3 catalysts investigated has been performed in order to clarify why the catalysts get partly deactivated so quickly and cleaning does not improves their activity anymore.**
- **Therefore, wet-chemical analyses of selected deposit samples as well as SEM/EDX analyses of the catalyst surface have been performed in order to probably understand the reasons for deactivation.**

Conclusions (VI)

- The performed chemical analyses as well as the SEM/EDX analyses clearly indicated that the catalysts have been deactivated by aerosol deposits (condensation), mainly K_2SO_4 and KCl, which have blocked the active centre of the catalysts.
- Therefore, manual cleaning of the dust in the catalyst did not show an effect on the regeneration of the reduction efficiency. The thermal treatment even had a negative effect on the regeneration, the reduction efficiency was reduced even further. The performance of the catalysts could not be recovered with the cleaning methods used so far.
- Concluding, based on the evaluation of the test runs results and analyses performed the following procedure has been defined:
  - **Design of a new catalyst which is not or only minor affected by aerosol depositions or**
  - **Change of the mounting position of the catalyst to areas of higher temperatures where aerosol condensation should not occur or be of minor relevance.**

Conclusions (VII)

- After an intense discussion together with the manufacturer it has been decided to design a new catalyst (based on a foam ceramic) which can be applied at higher temperatures (up to 800 °C) and which shall be mounted at the outlet of the main combustion chamber where aerosol condensation should not occur or be of minor relevance.
- The commercially available catalyst EnviCat® of Clariant will not be further considered due to the rather high prize (500 € for a single unit).

Results of the test runs with a logwood stove and different catalysts

Results of the test runs performed with Foam ceramic 1 – without catalyst – at catalyst position II

Foam ceramic – Overview

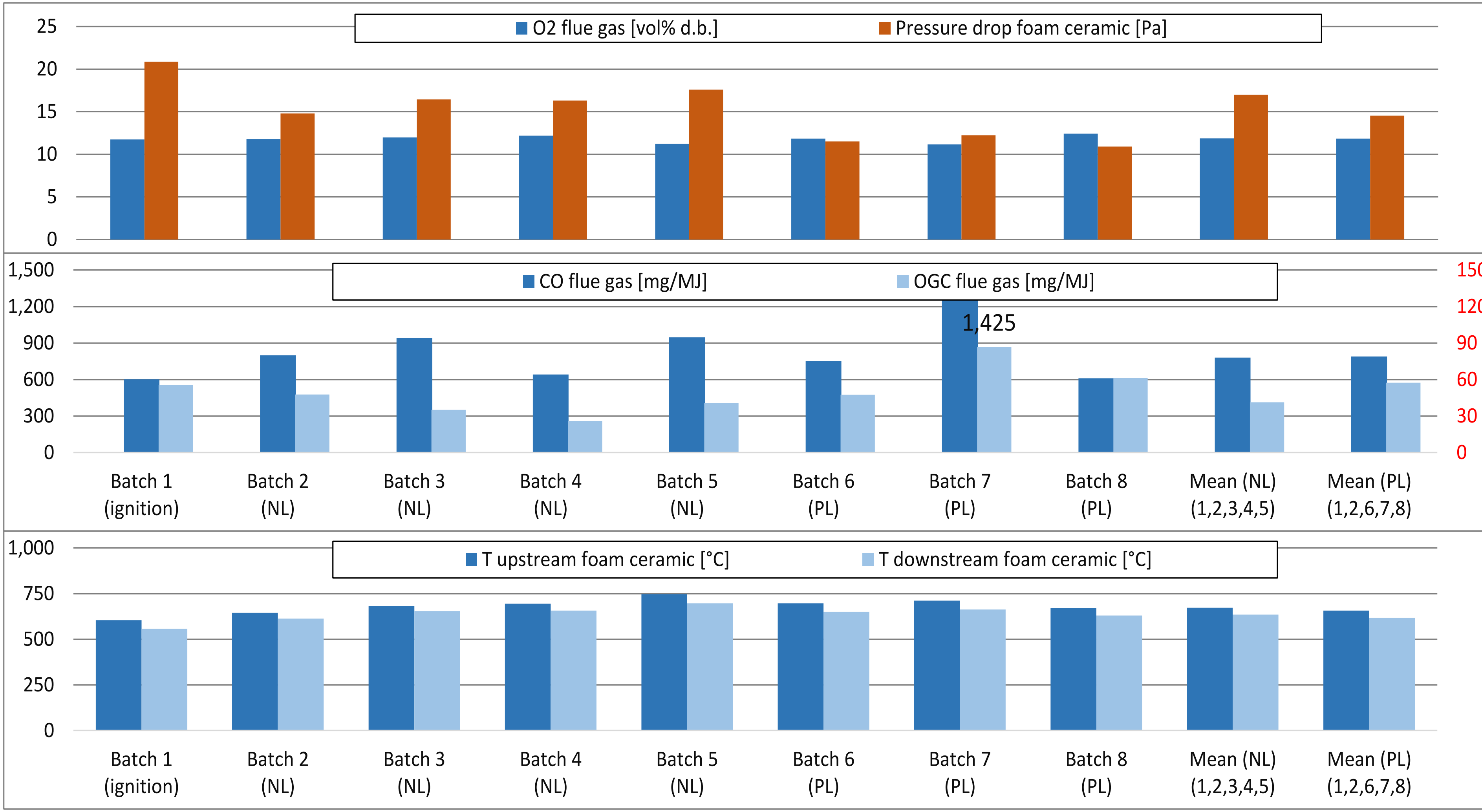
Day	Date	Comments
1	17/03/2016	Operation
2	21/03/2016	Operation
3	24/03/2016	Measurements – series 1
4	30/03/2016	Operation
5	31/03/2016	Operation
6	04/04/2016	Measurements – series 2
7	05/04/2016	Operation
8	06/04/2016	Operation
9	07/04/2016	Operation
10	11/04/2016	Measurements – series 3

Foam ceramic –
Day 3: measurements – series 1 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		24.03 13:41	24.03 14:27	24.03 15:29	24.03 16:29	24.03 17:26	24.03 18:16	24.03 18:51	24.03 19:22			
Door opened		24.03 14:26	24.03 15:28	24.03 16:29	24.03 17:25	24.03 18:15	24.03 18:50	24.03 19:22	24.03 19:57			
Fuel input	kg w.b.	2.8	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.4	8.8	
O2 flue gas	**vol% d.b.**	**11.8**	**11.8**	**12.0**	**12.2**	**11.3**	**11.9**	**11.2**	**12.4**	**11.9**	**11.9**	
Flue gas volume flow	**Nm³ d.b.**	**18.0**	**17.8**	**18.1**	**17.0**	**15.0**	**8.0**	**7.1**	**7.9**	**85.9**	**58.7**	
Fuel input (without remaining char coal)	MJ	39.4	34.3	34.3	34.3	34.3	17.2	17.2	17.2	176.7	125.2	
Evaluation - conventional												
CO flue gas	mg/Nm³	1,115.0	1,276.7	1,553.7	1,157.7	1,830.8	1,420.1	2,895.5	1,266.6	1,412.9	1,538.2	
CO flue gas	**mg/MJ**	**743.4**	**851.1**	**1,035.8**	**771.8**	**1,220.5**	**946.7**	**1,930.3**	**844.4**	**941.9**	**1,025.4**	
OGC flue gas	mg/Nm³	92.5	69.3	54.2	42.8	71.8	82.6	160.8	117.2	65.1	98.5	
OGC flue gas	**mg/MJ**	**61.7**	**46.2**	**36.1**	**28.5**	**47.9**	**55.1**	**107.2**	**78.1**	**43.4**	**65.7**	
CH4 flue gas	mg/Nm³	27.9	29.2	24.3	19.6	37.6	59.9	127.2	84.2	27.7	58.2	
CH4 flue gas	**mg/MJ**	**18.6**	**19.5**	**16.2**	**13.1**	**25.1**	**39.9**	**84.8**	**56.2**	**18.5**	**38.8**	
TSP	mg/Nm³											
TSP	**mg/MJ**											
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**602.0**	**799.1**	**942.1**	**642.0**	**946.3**	**751.8**	**1,425.0**	**611.5**	**781.1**	**790.8**	
OGC flue gas	**mg/MJ**	**55.4**	**47.8**	**35.1**	**25.9**	**40.7**	**47.6**	**86.8**	**61.5**	**41.4**	**57.4**	
T upstream foam ceramic	°C	604.7	645.2	682.9	695.3	746.8	697.6	711.2	670.1	673.1	657.3	
T downstream foam ceramic	°C	557.5	613.2	654.4	657.5	696.9	651.2	662.8	630.8	635.6	616.7	
T flue gas (EN13240)	°C	77.2	129.0	160.0	177.0	189.1	187.0	187.3	189.2	148.1	146.5	
Chimney draught	Pa	11.6	11.6	11.6	11.7	11.6	11.6	11.8	11.7	11.6	11.6	
Pressure drop foam ceramic	**Pa**	**20.9**	**14.8**	**16.4**	**16.3**	**17.6**	**11.5**	**12.3**	**10.9**	**17.0**	**14.5**	
Efficiency (EN13240)	**%**	**94.9**	**90.9**	**86.6**	**85.0**	**84.8**	**84.4**	**84.5**	**83.4**	**88.4**	**87.6**	
Carbon balance												**total**
carbon in CO2	g	839.1	831.1	842.2	807.2	780.7	397.5	371.2	374.6	4,122.2	2,828.6	5,283.1
carbon in CO	g	10.2	11.8	13.9	9.5	14.0	5.6	10.5	4.5	60.9	43.4	82.2
carbon in OGC	g	0.7	0.5	0.4	0.3	0.4	0.2	0.4	0.3	2.2	2.2	3.3
carbon in bottom ash	g											753.9
carbon in fuel	g	1,070.3	934.1	934.1	934.1	934.1	467.0	467.0	467.0	0.0	0.0	6,207.6
deviation of carbon balance	**%**	**20.6**	**9.7**	**8.3**	**12.5**	**14.9**	**13.7**	**18.2**	**18.7**			**1.4**
factor mg/Nm³ --> mg/MJ	-	1.89	1.68	1.69	1.83	1.88	1.88	1.98	2.03	1.80	1.87	1.9

Explanations: TSP measurements have not been performed

Foam ceramic –
Day 3: measurements – series 1 (II)

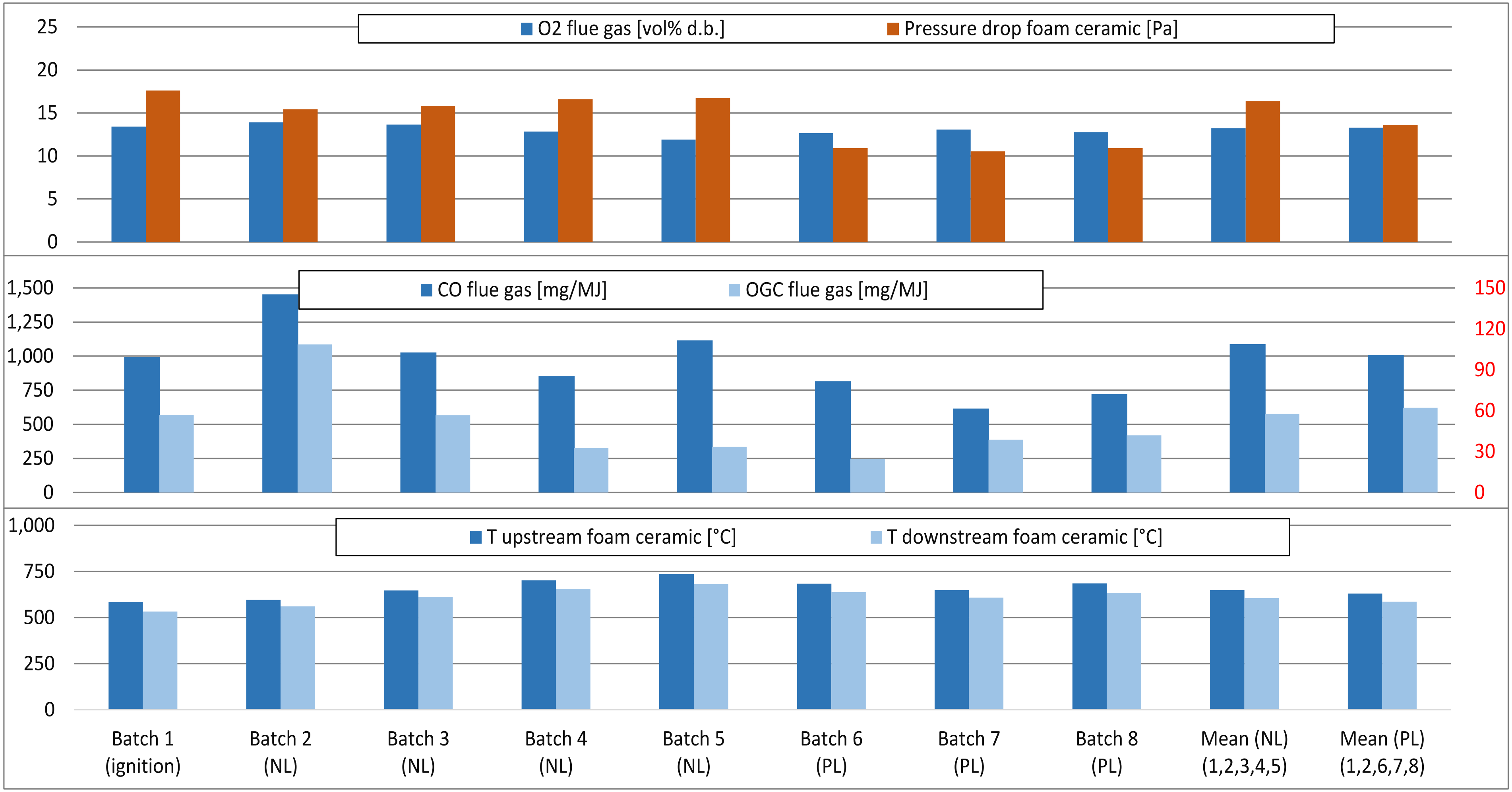


Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic –
Day 6: measurements – series 2 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		04.04 10:06	04.04 10:56	04.04 11:58	04.04 13:02	04.04 13:59	04.04 14:48	04.04 15:28	04.04 16:03			
Door opened		04.04 10:56	04.04 11:58	04.04 13:01	04.04 13:58	04.04 14:47	04.04 15:27	04.04 16:03	04.04 16:38			
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6	
O2 flue gas	**vol% d.b.**	**13.4**	**13.9**	**13.7**	**12.8**	**11.9**	**12.7**	**13.1**	**12.8**	**13.2**	**13.3**	
Flue gas volume flow	**Nm³ d.b.**	**17.9**	**19.6**	**18.6**	**17.2**	**14.1**	**8.7**	**7.4**	**7.5**	**87.3**	**61.1**	
Fuel input (without remaining char coal)	MJ	33.6	31.0	31.0	31.0	31.0	15.5	15.5	15.5	157.7	111.2	
Evaluation - conventional												
CO flue gas	mg/Nm³	2,020.9	2,353.7	1,756.5	1,391.8	2,117.7	1,360.3	1,235.7	1,403.0	1,940.2	1,771.1	
CO flue gas	**mg/MJ**	**1,347.3**	**1,569.1**	**1,171.0**	**927.9**	**1,411.8**	**906.9**	**823.8**	**935.3**	**1,293.5**	**1,180.8**	
OGC flue gas	mg/Nm³	101.3	153.4	89.6	49.7	58.3	38.8	75.8	76.4	90.2	94.5	
OGC flue gas	**mg/MJ**	**67.5**	**102.3**	**59.8**	**33.1**	**38.9**	**25.9**	**50.5**	**50.9**	**60.1**	**63.0**	
CH4 flue gas	mg/Nm³	40.9	58.9	46.6	22.0	28.8	27.8	55.1	52.6	40.0	47.7	
CH4 flue gas	**mg/MJ**	**27.3**	**39.3**	**31.1**	**14.7**	**19.2**	**18.5**	**36.7**	**35.1**	**26.7**	**31.8**	
TSP	mg/Nm³	42.9		11.3		32.8		23.8		28.3	21.9	
TSP	**mg/MJ**	**28.6**		**7.6**		**21.9**		**15.8**		**18.9**	**14.6**	
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**994.4**	**1,453.2**	**1,026.5**	**854.2**	**1,115.7**	**816.3**	**615.4**	**721.7**	**1,087.2**	**1,006.7**	
OGC flue gas	**mg/MJ**	**57.0**	**108.7**	**56.6**	**32.7**	**33.6**	**24.7**	**38.6**	**41.9**	**57.7**	**62.2**	
T upstream foam ceramic	°C	583.9	595.5	646.8	702.5	735.7	683.9	649.9	685.4	649.6	630.2	
T downstream foam ceramic	°C	532.2	561.0	611.9	654.2	682.1	638.8	608.3	633.0	606.3	586.5	
T flue gas (EN13240)	°C	66.1	116.1	148.9	168.6	181.8	178.1	174.8	178.8	136.6	135.2	
Chimney draught	Pa	11.3	11.0	11.4	11.5	11.6	11.6	11.7	11.6	11.3	11.4	
Pressure drop foam ceramic	**Pa**	**17.6**	**15.4**	**15.9**	**16.6**	**16.8**	**10.9**	**10.5**	**10.9**	**16.4**	**13.6**	
Efficiency (EN13240)	**%**	**94.9**	**90.0**	**85.0**	**84.5**	**84.3**	**83.9**	**83.6**	**83.6**	**87.7**	**87.2**	
Carbon balance												**total**
carbon in CO2	g	685.0	699.0	697.1	720.5	660.5	371.9	300.6	317.6	3,477.7	2,385.4	4,476.8
carbon in CO	g	14.3	19.3	13.7	11.4	14.8	5.4	4.1	4.8	75.0	49.1	90.0
carbon in OGC	g	0.6	1.1	0.5	0.3	0.3	0.1	0.2	0.2	2.9	2.2	3.4
carbon in bottom ash	g										0.0	966.6
carbon in fuel	g	914.0	843.7	843.7	843.7	843.7	421.8	421.8	421.8	4,288.8	3,023.2	5,554.3
deviation of carbon balance	**%**	**23.4**	**14.7**	**15.7**	**13.2**	**19.9**	**10.5**	**27.7**	**23.5**			**0.3**
factor mg/Nm³ --> mg/MJ	-	1.98	1.79	1.82	1.77	1.93	1.72	2.12	2.00	1.86	1.89	1.8

Foam ceramic –
Day 6: measurements – series 2 (II)

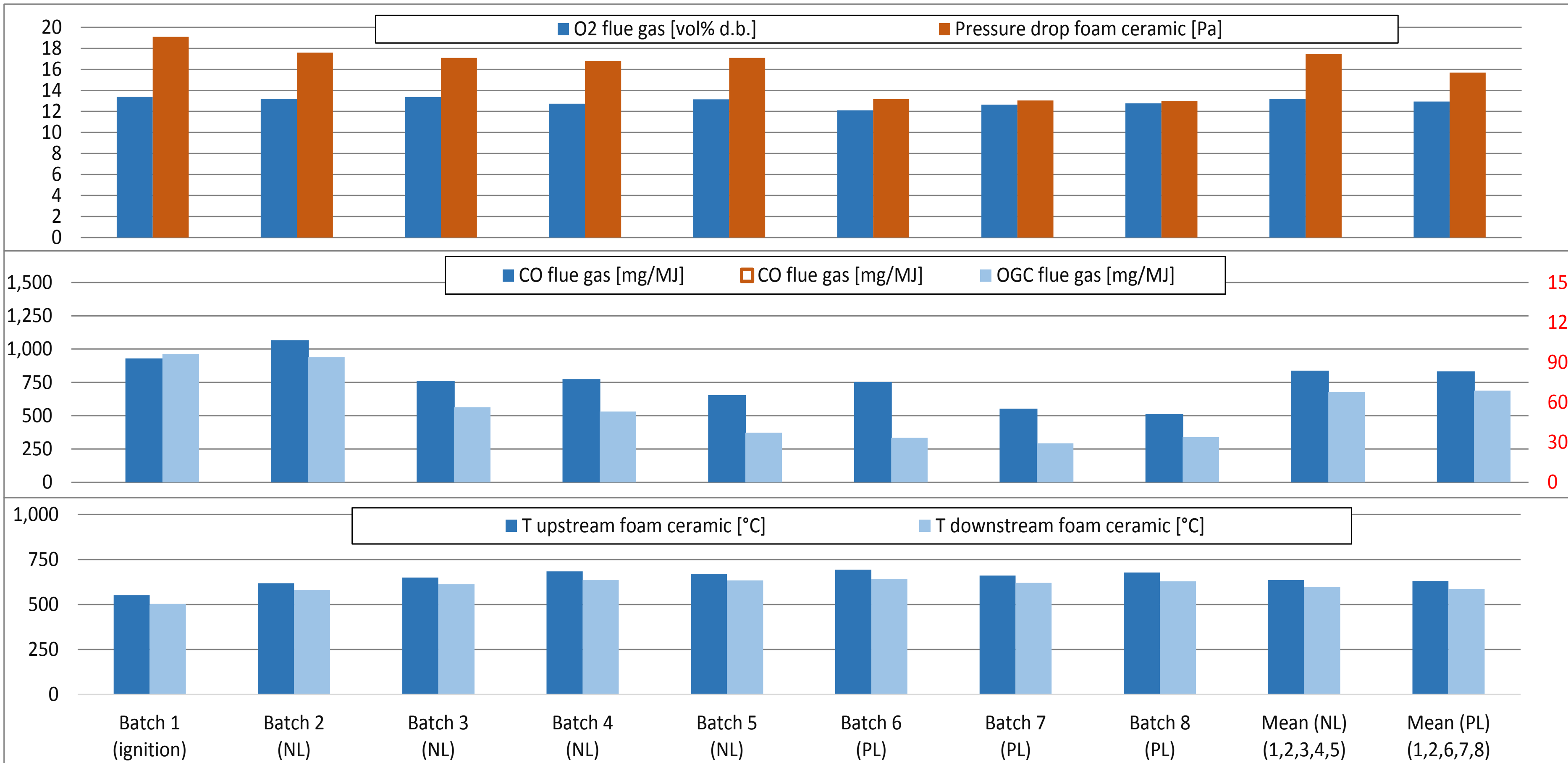


Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic –
Day 10: measurements – series 3 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		11.04 09:25	11.04 10:12	11.04 11:08	11.04 12:08	11.04 13:06	11.04 14:04	11.04 14:38	11.04 15:11			
Door opened		11.04 10:11	11.04 11:08	11.04 12:07	11.04 13:05	11.04 14:03	11.04 14:37	11.04 15:10	11.04 15:44			
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6	
O2 flue gas	**vol% d.b.**	**13.4**	**13.2**	**13.4**	**12.7**	**13.2**	**12.1**	**12.6**	**12.8**	**13.2**	**12.9**	
Flue gas volume flow	**Nm³ d.b.**	**20.1**	**21.7**	**19.6**	**18.2**	**16.9**	**8.1**	**7.5**	**7.6**	**96.5**	**64.9**	
Fuel input (without remaining char coal)	MJ	34.7	31.6	31.5	31.7	31.8	15.8	15.9	15.9	161.3	113.9	
Evaluation - conventional		1,698.3	1,454.5	1,205.5	1,224.2	1,175.3	1,277.0	1,087.8	1,010.0	1,355.5	1,359.3	
CO flue gas	mg/Nm³	1,698.3	1,454.5	1,205.5	1,224.2	1,175.3	1,277.0	1,087.8	1,010.0	1,355.5	1,359.3	
CO flue gas	**mg/MJ**	**1,132.2**	**969.7**	**803.7**	**816.1**	**783.5**	**851.3**	**725.2**	**673.3**	**903.7**	**906.2**	
OGC flue gas	mg/Nm³	159.8	118.0	81.5	75.6	61.4	50.8	52.8	62.6	96.4	94.8	
OGC flue gas	**mg/MJ**	**106.5**	**78.7**	**54.3**	**50.4**	**40.9**	**33.9**	**35.2**	**41.7**	**64.3**	**63.2**	
CH4 flue gas	mg/Nm³	61.4	47.4	33.7	31.1	27.9	27.5	29.8	45.4	39.8	43.9	
CH4 flue gas	**mg/MJ**	**40.9**	**31.6**	**22.4**	**20.8**	**18.6**	**18.3**	**19.9**	**30.2**	**26.5**	**29.3**	
TSP	mg/Nm³	42.3		14.9		22.6		38.8		25.0	21.4	
TSP	**mg/MJ**	**28.2**		**9.9**		**15.0**		**25.9**		**16.7**	**14.3**	
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**929.3**	**1,066.7**	**760.0**	**772.7**	**655.7**	**752.8**	**552.4**	**512.1**	**838.5**	**832.3**	
OGC flue gas	**mg/MJ**	**96.2**	**94.0**	**56.3**	**53.1**	**37.1**	**33.3**	**29.3**	**34.0**	**67.9**	**68.9**	
T upstream foam ceramic	°C	550.6	618.3	649.4	683.8	670.7	693.1	660.1	677.4	636.1	630.1	
T downstream foam ceramic	°C	503.0	579.4	612.9	637.8	633.2	642.5	620.0	629.3	595.8	586.2	
T flue gas (EN13240)	°C	75.3	131.0	165.1	182.8	195.8	192.2	192.8	196.5	153.2	149.2	
Chimney draught	Pa	13.0	12.8	13.0	13.0	13.0	12.9	12.9	12.9	12.9	12.9	
Pressure drop foam ceramic	**Pa**	**19.1**	**17.6**	**17.1**	**16.8**	**17.1**	**13.2**	**13.1**	**13.0**	**17.5**	**15.7**	
Efficiency (EN13240)	**%**	**94.2**	**89.8**	**84.2**	**83.5**	**81.4**	**83.6**	**82.7**	**82.2**	**86.6**	**86.5**	
Carbon balance		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**total**
carbon in CO2	g	782.9	877.2	780.8	787.6	697.8	375.7	329.8	328.2	3,947.4	2,706.2	4,991.2
carbon in CO	g	13.8	14.5	10.3	10.5	9.0	5.1	3.8	3.5	59.4	41.4	72.4
carbon in OGC	g	1.0	0.9	0.6	0.5	0.4	0.2	0.1	0.2	3.4	2.5	3.9
carbon in bottom ash	g	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	929.6
carbon in fuel	g	953.7	868.2	864.6	870.0	873.7	434.3	435.7	435.4	4,430.1	3,127.3	5,735.5
deviation of carbon balance	**%**	**16.4**	**-2.8**	**8.4**	**8.2**	**19.1**	**12.3**	**23.4**	**23.8**			**-4.6**
factor mg/Nm³ --> mg/MJ	-	1.83	1.49	1.69	1.68	1.92	1.76	2.03	2.03	1.72	1.74	1.7

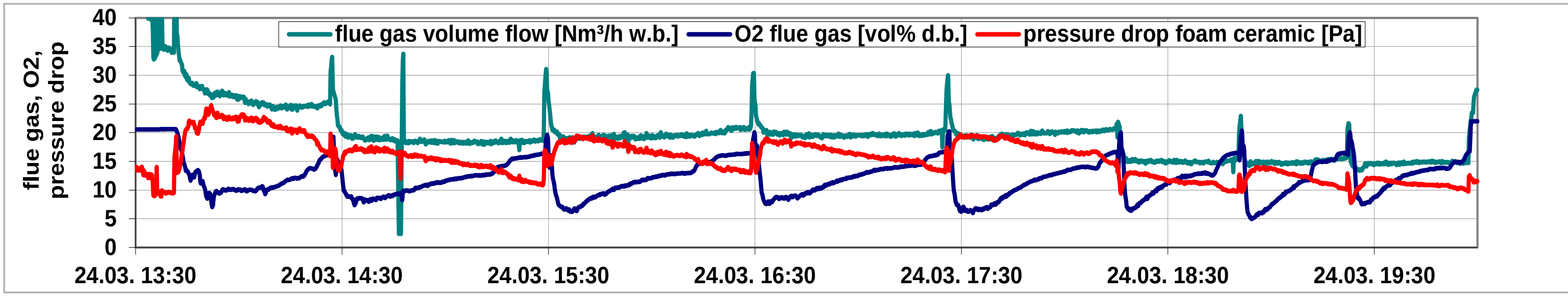
Foam ceramic –
Day 10: measurements – series 3 (II)



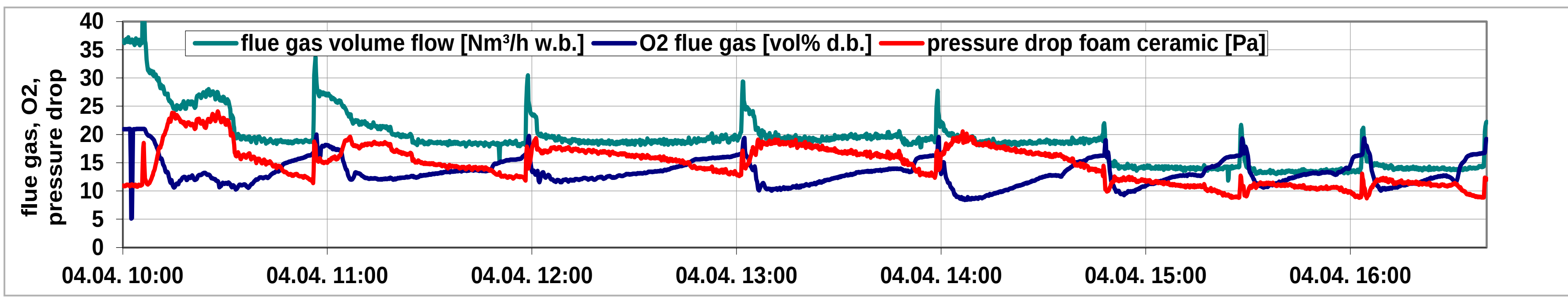
Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic – comparisons of day 3, 6 and 10 – flue gas, pressure drop and O_2 trends

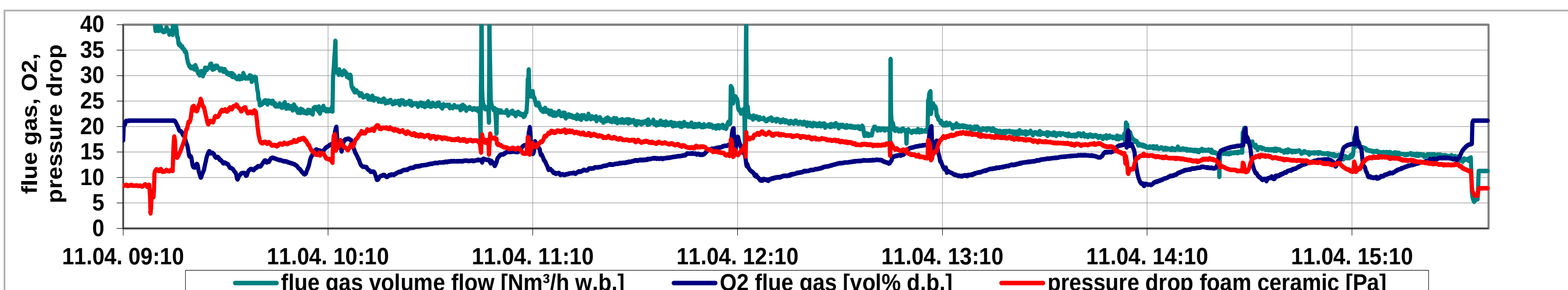
3



6

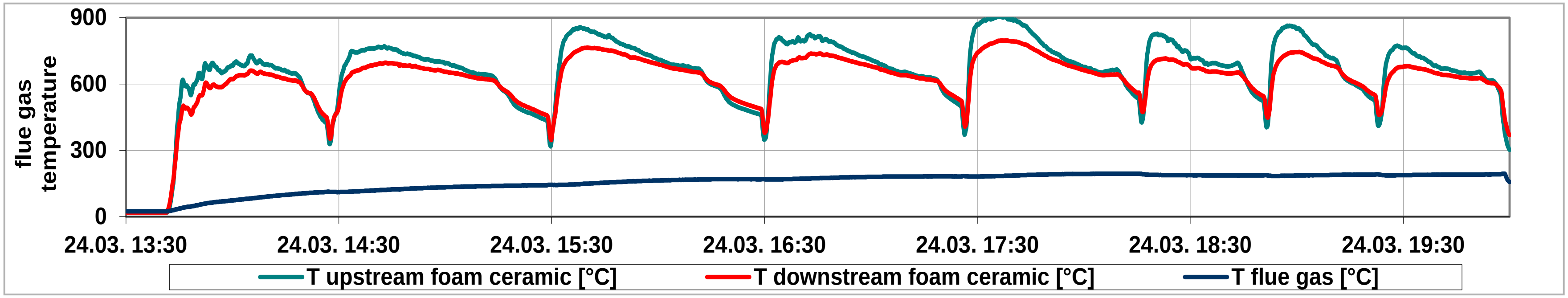


10

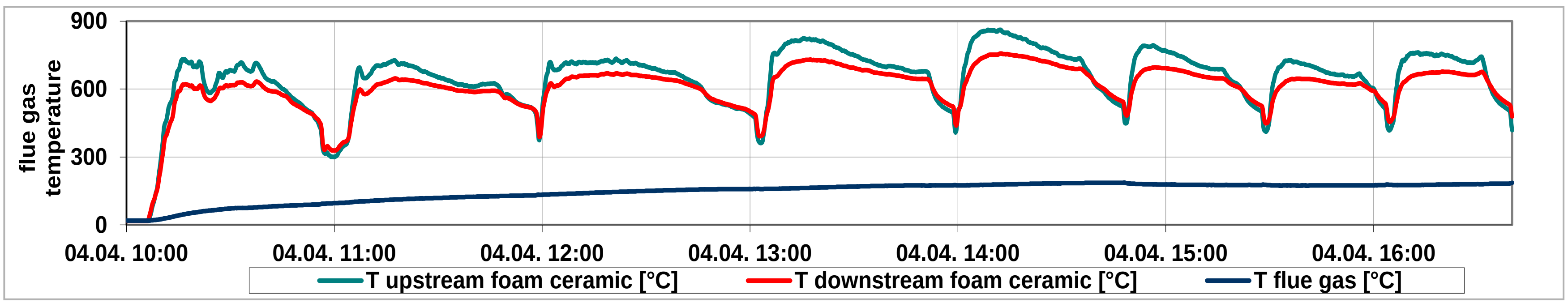


Foam ceramic – comparisons of day 3, 6 and 10 – temperatures

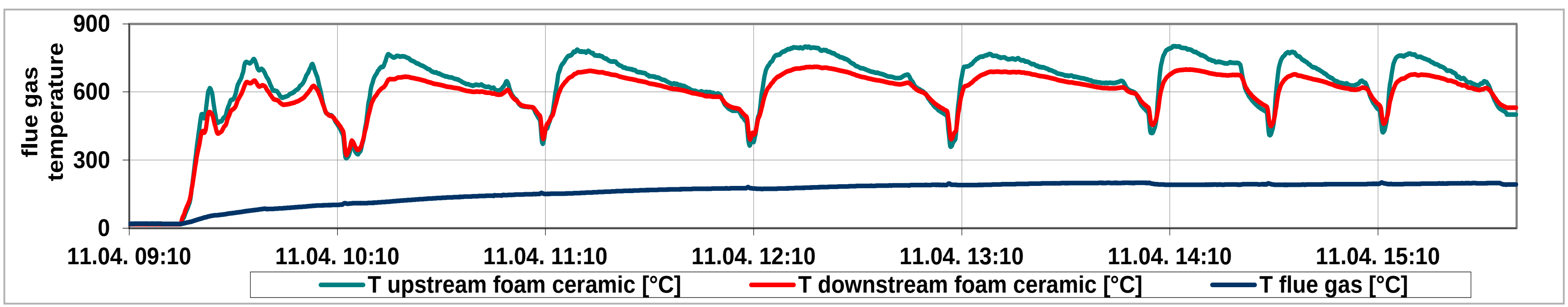
3



6



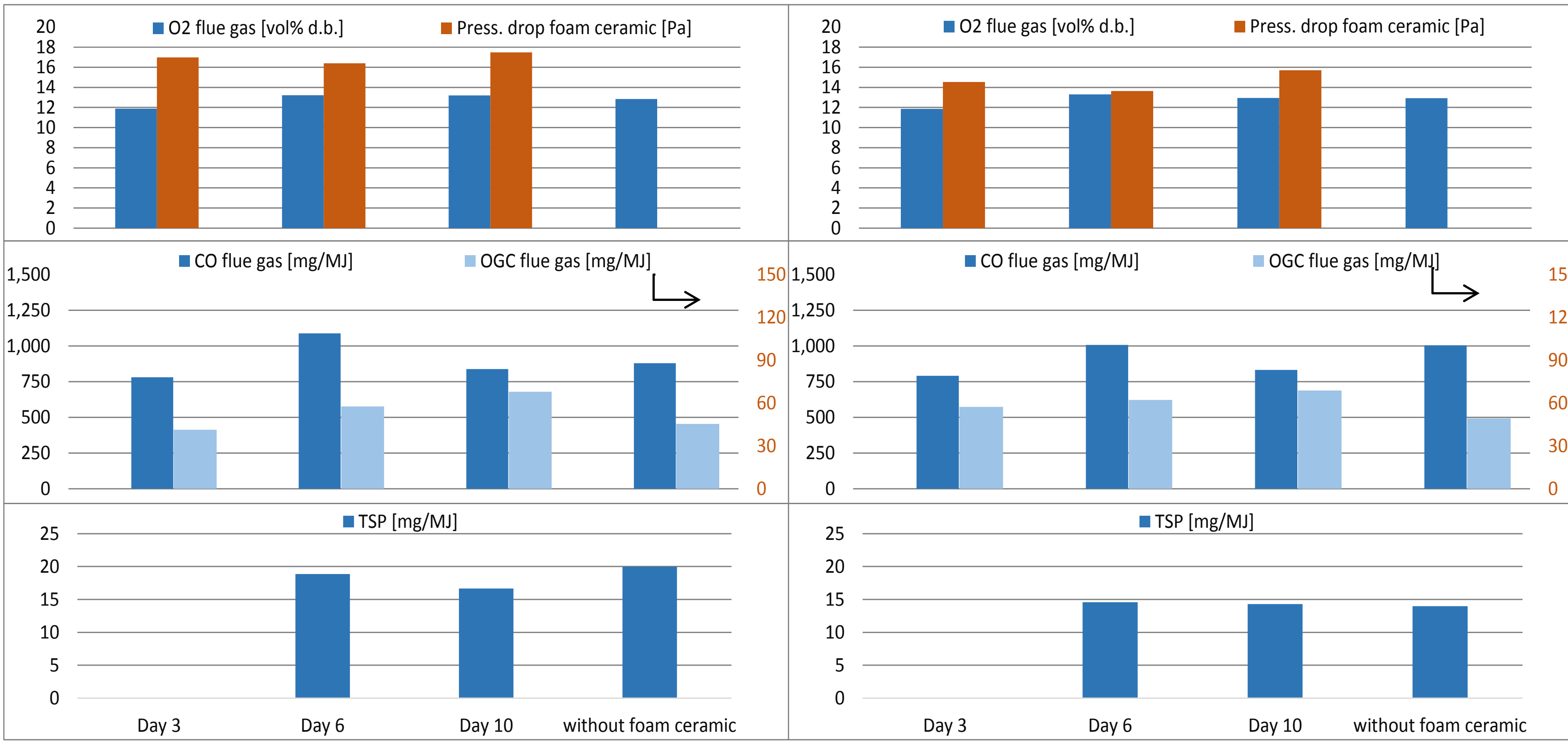
10



Foam ceramic – comparisons of mean values

Nominal load

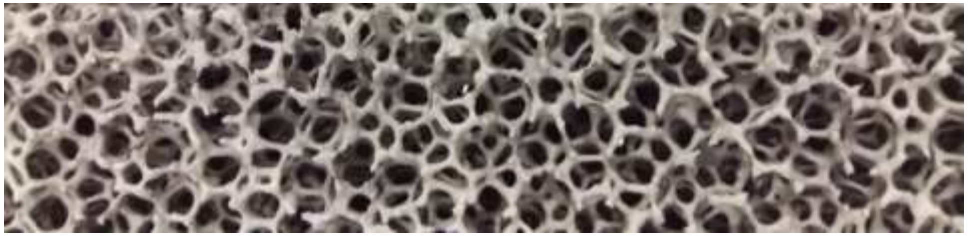
Partial load



Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation; without foam ceramic … test run with stove without integrated foam ceramic

Foam ceramic – Pictures of catalyst before and after cleaning

Foam ceramic before the test runs



Foam ceramic after 2 weeks of operation

Foam ceramic after manual cleaning after 2 weeks of operation (view at inlet)

- **Cleaning:**
  - **Step 1: cleaning with a soft brush**
  - **Step 2: purging the foam ceramic with compressed air**

Foam ceramic – Summary (I)

- The foam ceramic without catalyst was operated for 10 days (59 batches).
- The stove could be operated at typical air supply conditions leading to average O_2 contents in the flue gas over a whole batch of between 11.2 and 13.9 vol% (dry flue gas, excluding the ignition batches).
- Over the entire operation of the stove no emission reduction efficiencies regarding CO and OGC could be determined, a negative influence on stove operation could not be determined as well.
- During full load operation the particulate emissions (TSP) amounted to 16.7 to 19.0 mg/MJ which is slightly lower than the level measured during the test run without foam ceramic (20.0 mg/MJ).
- However, during partial load operation the particulate emissions (TSP) amounted to 14.3 to 15.0 mg/MJ which is about the same level as measured during the test run without foam ceramic (14.0 mg/MJ).

Foam ceramic – Summary (II)

- At the 3rd day of operation the pressure drop over the foam ceramic amounted to in average
  - 17.0 Pa (full load)
  - 14.5 Pa (partial load)
- The pressure drop over the foam ceramic only slightly increased to in average
  - 17.5 Pa (full load) and
  - 15.7 Pa (partial load)

  after two weeks of operation.
- An inspection of the foam ceramic after 2 weeks of operation revealed only some fly ash deposits on the surface of the foam ceramic
  ➔ reason for the increasing pressure losses.
- By manual cleaning most of the fly ash deposits could be successfully removed.

Foam ceramic – Summary (III)

- Concluding, the non-catalytic foam ceramic showed no emission reduction efficiencies regarding CO, OGC and TSP and showed no influence on stove operation.
- The pressure drop over the foam ceramic is quite high and slightly increased after two weeks of operation due to fly ash deposits on the surface of the foam ceramic.

Results of the test runs with a logwood stove and different catalysts

Results of the test runs performed with Foam ceramic 2 – coated with tailor made catalyst I – at catalyst position II

Foam ceramic 2 – coated with tailor made catalyst I – Overview (I)

Day	Date	Comments
1	18/04/2016	Operation
2	19/04/2016	Operation
3	20/04/2016	Measurements – series 1
4	21/04/2016	Operation
5	22/04/2016	Operation
6	25/04/2016	Operation
7	27/04/2016	Operation
8	28/04/2016	Operation
9	29/04/2016	Operation
10	02/05/2016	Operation
11	03/05/2016	Measurements – series 2 Manual cleaning of the foam ceramic

No	2
Name	Tailor-made catalyst I
Substrate	SSiC
Structure	Foam ceramic
PPI [1)]	10
Dimension (HxWxL)	380 x 50 x 50 mm
Active metal	Pt

Explanations: [1)] Pores per inch

Foam ceramic 2 – coated with tailor made catalyst I – Overview (II)

Day	Date	Comments
12	09/05/2016	Operation
13	10/05/2016	Operation
14	11/05/2016	Operation
15	12/05/2016	Operation
16	13/05/2016	Operation
17	17/05/2016	Operation
18	18/05/2016	Measurements – series 3 Manual cleaning of the foam ceramic

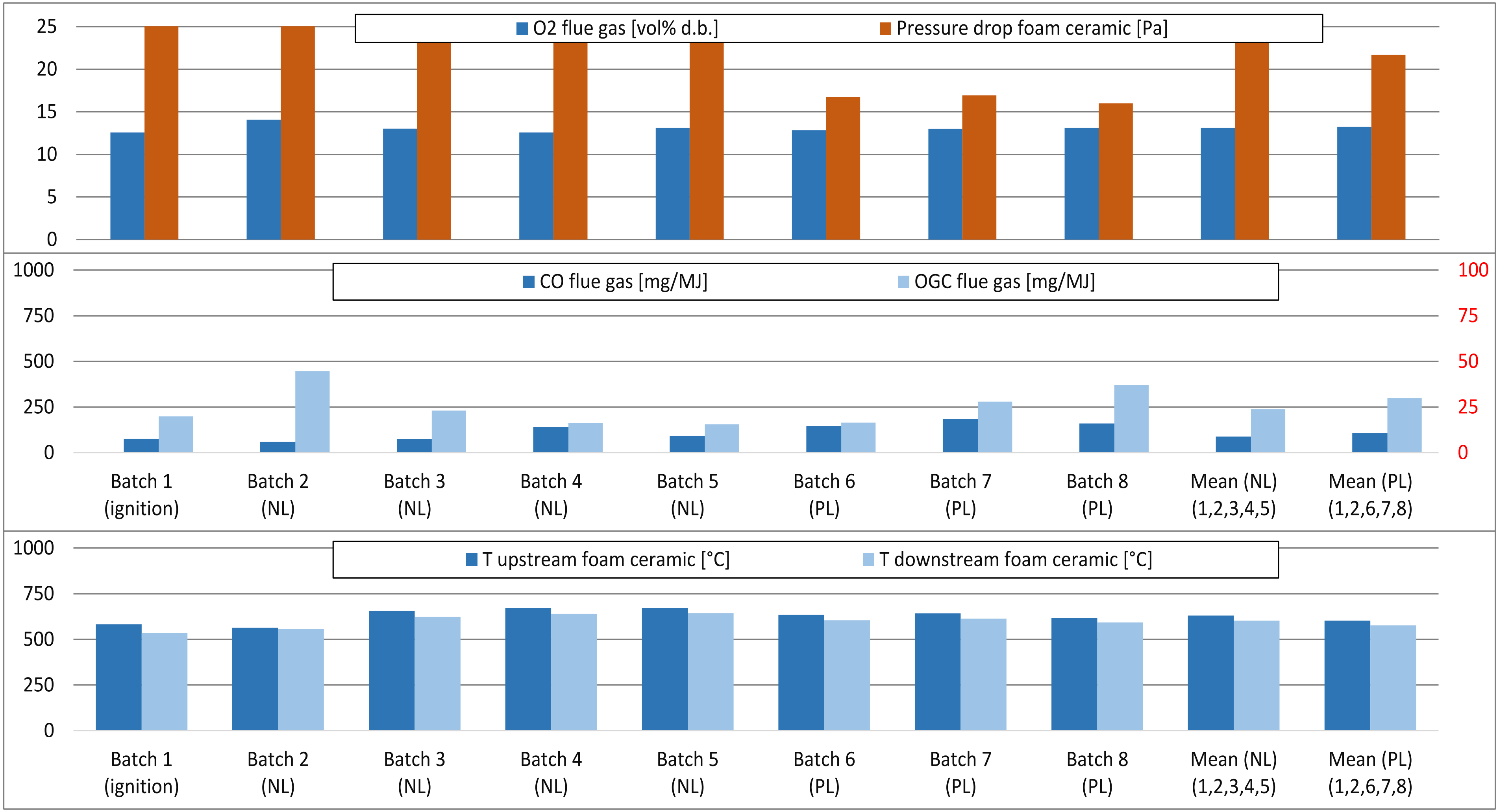
No	2
Name	Tailor-made catalyst I
Substrate	SSiC
Structure	Foam ceramic
PPI [1)]	10
Dimension (HxWxL)	380 x 50 x 50 mm
Active metal	Pt

Explanations: [1)] Pores per inch

Foam ceramic 2 – coated with tailor made catalyst I – Day 3: measurements – series 1 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		20.04 08:46	20.04 09:30	20.04 10:34	20.04 11:34	20.04 12:38	20.04 13:41	20.04 14:22	20.04 15:05			
Door opened		20.04 09:30	20.04 10:33	20.04 11:33	20.04 12:37	20.04 13:40	20.04 14:21	20.04 15:04	20.04 15:44			
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6	
O2 flue gas	**vol% d.b.**	**12.6**	**14.1**	**13.0**	**12.6**	**13.1**	**12.9**	**13.0**	**13.1**	**13.1**	**13.2**	
Flue gas volume flow	**Nm^3 d.b.**	**18.2**	**23.3**	**20.3**	**21.2**	**20.8**	**11.0**	**11.1**	**10.3**	**103.9**	**74.0**	
Fuel input (without remaining char coal)	MJ	35.8	33.0	33.0	33.0	33.0	16.5	16.5	16.5	167.7	118.2	
Evaluation - conventional												
CO flue gas	mg/Nm^3	128.2	94.2	122.6	210.2	149.6	214.2	273.6	260.4	144.5	187.1	
CO flue gas	**mg/MJ**	**85.5**	**62.8**	**81.7**	**140.1**	**99.7**	**142.8**	**182.4**	**173.6**	**96.4**	**124.7**	
OGC flue gas	mg/Nm^3	32.2	66.4	33.7	22.2	22.9	22.3	38.2	55.9	34.9	43.9	
OGC flue gas	**mg/MJ**	**21.4**	**44.3**	**22.5**	**14.8**	**15.2**	**14.8**	**25.5**	**37.3**	**23.3**	**29.2**	
CH4 flue gas	mg/Nm^3	22.2	65.5	30.5	17.7	20.8	23.5	35.9	52.7	31.1	40.9	
CH4 flue gas	**mg/MJ**	**14.8**	**43.7**	**20.3**	**11.8**	**13.9**	**15.7**	**23.9**	**35.1**	**20.7**	**27.2**	
TSP	mg/Nm^3	29.0		25.1		24.1		26.3		25.7	25.0	
TSP	**mg/MJ**	**19.4**		**16.7**		**16.1**		**17.5**		**17.2**	**16.7**	
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**75.9**	**59.2**	**75.0**	**140.2**	**92.7**	**145.5**	**184.8**	**159.6**	**88.4**	**107.8**	
OGC flue gas	**mg/MJ**	**19.9**	**44.6**	**23.0**	**16.4**	**15.5**	**16.5**	**28.0**	**37.1**	**23.8**	**29.8**	
T upstream foam ceramic	°C	582.7	562.7	655.6	671.7	671.1	633.3	642.5	617.9	629.8	602.0	
T downstream foam ceramic	°C	535.6	556.4	623.0	639.9	643.9	604.4	613.4	591.9	602.5	576.8	
T flue gas (EN13240)	°C	84.7	135.0	161.1	176.5	185.0	180.8	182.4	185.2	152.4	150.8	
Chimney draught	Pa	12.8	12.6	12.1	12.0	11.9	12.0	12.6	11.8	12.2	12.4	
Pressure drop foam ceramic	**Pa**	**30.2**	**25.7**	**25.1**	**24.2**	**24.6**	**16.7**	**16.9**	**16.0**	**25.7**	**21.7**	
Efficiency (EN13240)	**%**	**94.4**	**88.4**	**85.2**	**84.3**	**82.4**	**83.4**	**82.9**	**82.3**	**86.9**	**86.3**	
Carbon balance												**total**
carbon in CO2	g	768.0	809.8	812.0	890.1	816.8	446.2	442.1	402.5	4,116.7	2,881.2	5,419.2
carbon in CO	g	1.2	0.8	1.1	2.0	1.3	1.0	1.3	1.1	6.4	5.5	9.9
carbon in OGC	g	0.2	0.5	0.2	0.2	0.2	0.1	0.1	0.2	1.3	1.1	1.7
carbon in bottom ash	g											707.6
carbon in fuel	g	981.5	904.3	904.3	904.3	904.3	452.1	452.1	452.1	4,598.6	3,242.2	5,955.0
deviation of carbon balance	**%**	**21.6**	**10.3**	**10.1**	**1.3**	**9.5**	**1.1**	**1.9**	**10.7**			**-3.1**
factor mg/Nm^3 --> mg/MJ	-	1.87	1.63	1.63	1.48	1.61	1.47	1.48	1.63	1.64	1.65	1.7

Foam ceramic 2 – coated with tailor made catalyst I – Day 3: measurements – series 1 (II)

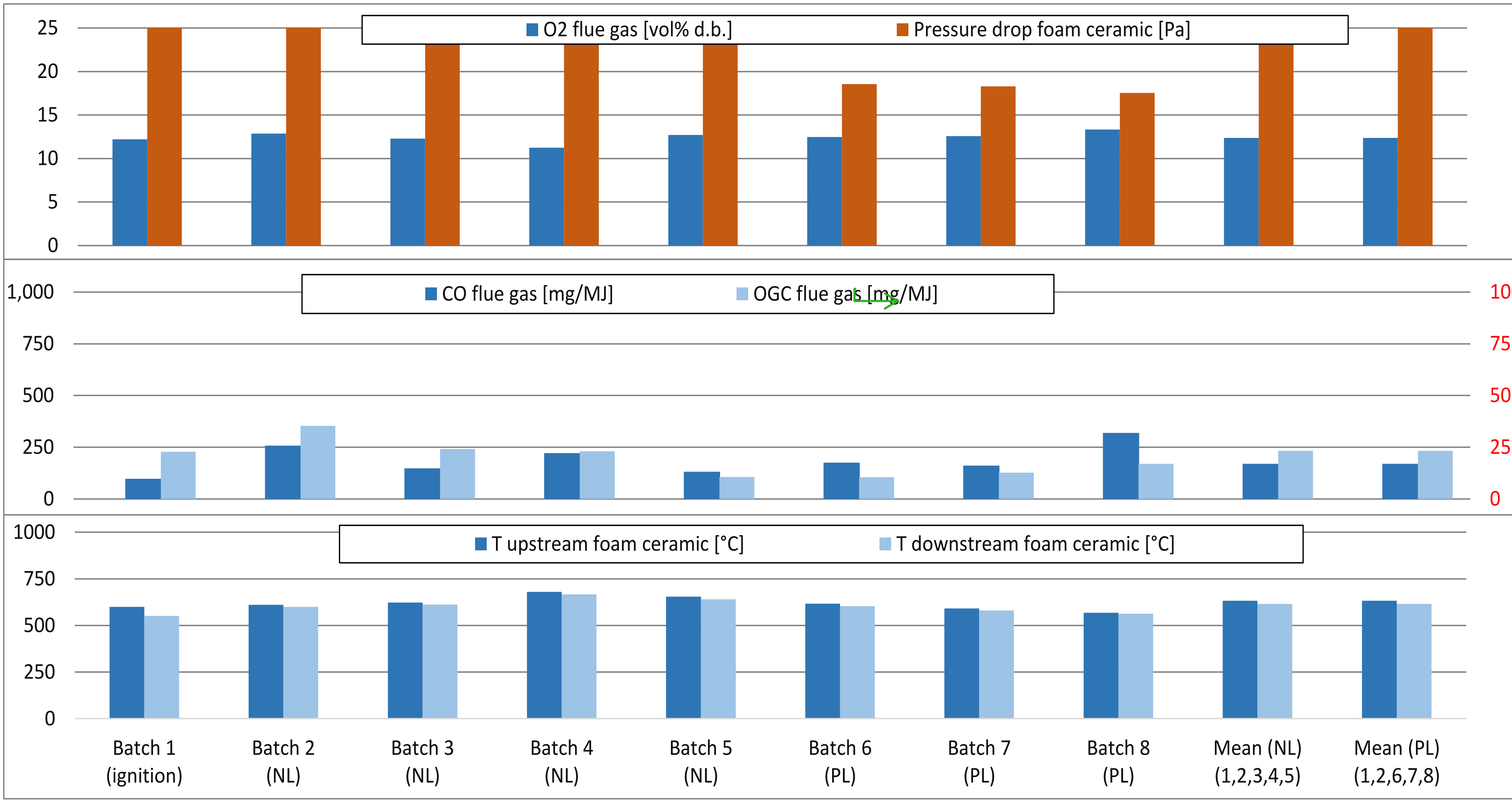


Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic 2 – coated with tailor made catalyst I – Day 11: measurements – series 2 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		03.05 09:16	03.05 10:01	03.05 11:15	03.05 12:17	03.05 13:14	03.05 14:22	03.05 15:10	03.05 15:54			
Door opened		03.05 10:00	03.05 11:14	03.05 12:16	03.05 13:13	03.05 14:21	03.05 15:09	03.05 15:53	03.05 16:51			
Fuel input	kg w.b.	2,6	2,4	2,4	2,4	2,4	1,2	1,2	1,2	12,2	8,6	
O_2 flue gas	**vol% d.b.**	**12,2**	**12,9**	**12,3**	**11,2**	**12,7**	**12,5**	**12,6**	**13,3**	**12,4**	**12,8**	
Flue gas volume flow	**Nm^3 d.b.**	**17,0**	**24,3**	**18,9**	**16,4**	**20,3**	**11,0**	**9,9**	**13,6**	**96,9**	**75,7**	
Fuel input (without remaining char coal)	MJ	36,6	33,7	33,7	33,7	33,7	16,9	16,9	16,9	171,6	121,0	
Evaluation - conventional												
CO flue gas	mg/Nm^3	191,9	337,7	227,8	381,2	204,9	245,0	255,1	396,7	278,7	296,3	
CO flue gas	**mg/MJ**	**127,9**	**225,1**	**151,9**	**254,1**	**136,6**	**163,3**	**170,0**	**264,4**	**185,8**	**197,5**	
OGC flue gas	mg/Nm^3	41,4	42,6	34,2	35,3	15,5	13,5	18,8	20,4	33,6	28,9	
OGC flue gas	**mg/MJ**	**27,6**	**28,4**	**22,8**	**23,6**	**10,3**	**9,0**	**12,5**	**13,6**	**22,4**	**19,3**	
CH_4 flue gas	mg/Nm^3	30,5	34,3	25,8	27,4	13,3	12,5	17,3	18,9	26,4	24,1	
CH_4 flue gas	**mg/MJ**	**20,3**	**22,9**	**17,2**	**18,3**	**8,9**	**8,3**	**11,5**	**12,6**	**17,6**	**16,1**	
TSP	mg/Nm^3	29,7		23,5		21,4		19,6		24,6	21,7	
TSP	**mg/MJ**	**19,8**		**15,7**		**14,2**		**13,0**		**16,4**	**14,4**	
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**98,1**	**258,0**	**147,6**	**221,1**	**131,8**	**175,8**	**160,8**	**319,4**	**170,1**	**193,2**	
OGC flue gas	**mg/MJ**	**22,8**	**35,3**	**24,2**	**23,1**	**10,7**	**10,5**	**12,7**	**17,0**	**23,2**	**22,4**	
T upstream foam ceramic	°C	599,7	610,3	622,4	680,1	653,9	617,2	591,1	568,4	632,0	596,4	
T downstream foam ceramic	°C	550,7	599,7	612,0	666,2	639,6	603,5	579,6	563,4	615,0	580,4	
T flue gas (EN13240)	°C	86,3	137,7	160,6	173,3	182,4	179,8	180,9	183,2	151,6	153,7	
Chimney draught	Pa	12,3	12,3	12,3	12,5	12,6	12,5	12,5	11,9	12,4	12,2	
Pressure drop foam ceramic	**Pa**	**35,4**	**28,7**	**28,0**	**27,9**	**27,3**	**18,6**	**18,3**	**17,5**	**29,0**	**23,9**	
Efficiency (EN13240)	**%**	**94,2**	**89,1**	**85,7**	**85,8**	**82,8**	**83,5**	**83,1**	**81,3**	**87,5**	**86,2**	
Carbon balance												**total**
carbon in CO_2	g	757,3	1.011,3	847,1	819,0	857,0	472,8	414,8	479,8	4.313,4	3.148,6	5.692,6
carbon in CO	g	1,5	3,7	2,1	3,2	1,9	1,3	1,2	2,3	12,8	10,2	17,7
carbon in OGC	g	0,3	0,4	0,3	0,2	0,1	0,1	0,1	0,1	1,2	0,8	1,4
carbon in bottom ash	g											508,8
carbon in fuel	g	995,8	919,2	919,2	919,2	919,2	459,6	461,5	459,6	4.672,8	3.295,9	6.094,5
deviation of carbon balance	**%**	**23,8**	**-10,5**	**7,6**	**10,5**	**6,5**	**-3,2**	**9,9**	**-4,9**			**-2,1**
factor mg/Nm^3 --> mg/MJ	-	1,96	1,37	1,64	1,69	1,61	1,44	1,63	1,29	1,64	1,55	1,6

Foam ceramic 2 – coated with tailor made catalyst I – Day 11: measurements – series 2 (II)

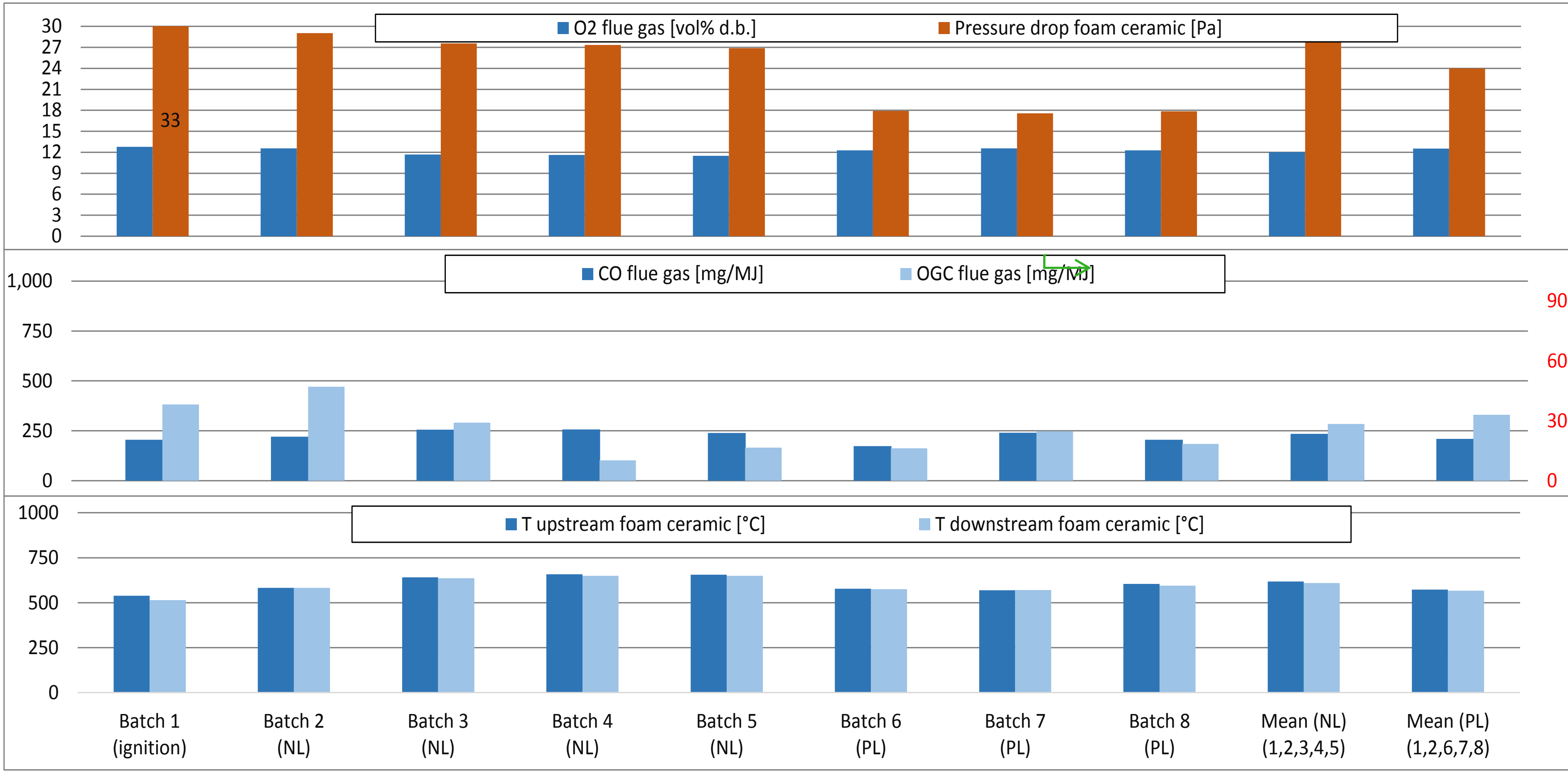


Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic 2 – coated with tailor made catalyst I – Day 18: measurements – series 2 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		18.05 10:24	18.05 11:17	18.05 12:23	18.05 13:29	18.05 14:39	18.05 15:47	18.05 16:31	18.05 17:18			
Door opened		18.05 11:16	18.05 12:22	18.05 13:29	18.05 14:38	18.05 15:46	18.05 16:30	18.05 17:17	18.05 18:01			
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6	
O2 flue gas	**vol% d.b.**	**12.8**	**12.6**	**11.7**	**11.6**	**11.5**	**12.3**	**12.6**	**12.3**	**12.0**	**12.5**	
Flue gas volume flow	**Nm³ d.b.**	**19.4**	**21.0**	**19.5**	**20.7**	**19.5**	**11.2**	**12.0**	**11.1**	**100.2**	**74.8**	
Fuel input (without remaining char coal)	MJ	38.4	34.9	34.9	34.9	34.9	17.4	17.4	17.4	178.0	125.7	
Evaluation - conventional		385.3	336.7	380.5	361.0	353.2	241.5	322.4	285.9	367.3	320.4	
CO flue gas	mg/Nm³	385.3	336.7	380.5	361.0	353.2	241.5	322.4	285.9	367.3	320.4	
CO flue gas	**mg/MJ**	**256.9**	**224.5**	**253.7**	**240.7**	**235.5**	**161.0**	**214.9**	**190.6**	**244.9**	**213.6**	
OGC flue gas	mg/Nm³	66.3	65.6	39.6	13.2	22.6	21.2	31.5	24.2	38.8	44.3	
OGC flue gas	**mg/MJ**	**44.2**	**43.7**	**26.4**	**8.8**	**15.0**	**14.1**	**21.0**	**16.1**	**25.9**	**29.5**	
CH4 flue gas	mg/Nm³	44.3	45.9	26.9	14.9	24.7	19.1	29.7	21.6	30.0	33.6	
CH4 flue gas	**mg/MJ**	**29.5**	**30.6**	**17.9**	**10.0**	**16.4**	**12.8**	**19.8**	**14.4**	**20.0**	**22.4**	
TSP	mg/Nm³	38.9		25.2		30.9		21.2		30.1	25.8	
TSP	**mg/MJ**	**25.9**		**16.8**		**20.6**		**14.1**		**20.0**	**17.2**	
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**205.1**	**221.0**	**255.3**	**256.2**	**239.1**	**173.5**	**240.4**	**204.6**	**234.7**	**209.9**	
OGC flue gas	**mg/MJ**	**38.2**	**47.1**	**29.0**	**10.2**	**16.5**	**16.2**	**24.8**	**18.5**	**28.4**	**33.0**	
T upstream foam ceramic	°C	538.9	582.8	641.1	658.5	655.4	578.2	569.4	604.8	617.6	573.4	
T downstream foam ceramic	°C	514.7	582.4	636.7	649.9	650.2	575.2	570.1	595.3	610.1	566.4	
T flue gas (EN13240)	°C	82.9	133.9	159.8	174.2	182.6	181.1	181.8	183.6	149.8	148.9	
Chimney draught	Pa	13.7	13.6	13.2	13.4	13.3	13.7	13.0	12.4	13.4	13.3	
Pressure drop foam ceramic	**Pa**	**33.4**	**29.0**	**27.6**	**27.3**	**26.9**	**17.9**	**17.6**	**17.9**	**28.6**	**24.0**	
Efficiency (EN13240)	**%**	**94.0**	**89.5**	**86.4**	**85.1**	**84.5**	**83.4**	**82.8**	**83.1**	**87.9**	**86.6**	
Carbon balance		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**total**
carbon in CO2	g	783.5	876.4	902.8	968.1	915.3	477.9	486.2	470.9	4,461.9	3,101.4	5,903.2
carbon in CO	g	3.4	3.3	3.8	3.8	3.6	1.3	1.8	1.5	18.3	11.4	23.0
carbon in OGC	g	0.5	0.5	0.3	0.1	0.2	0.1	0.1	0.1	1.6	1.3	1.9
carbon in bottom ash	g	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	370.0
carbon in fuel	g	1,046.5	949.5	949.5	949.5	949.5	474.8	474.8	474.8	4,844.5	3,420.3	6,268.8
deviation of carbon balance	**%**	**24.8**	**7.3**	**4.5**	**-2.4**	**3.2**	**-1.0**	**-2.8**	**0.5**			**-0.5**
factor mg/Nm³ --> mg/MJ	-	1.93	1.57	1.54	1.43	1.50	1.43	1.38	1.44	1.58	1.59	1.5

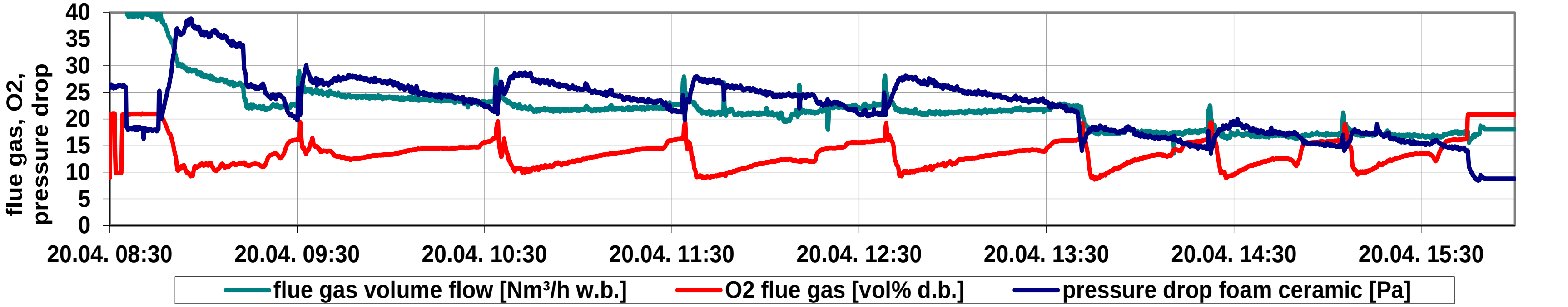
Foam ceramic 2 – coated with tailor made catalyst I – Day 18: measurements – series 2 (II)



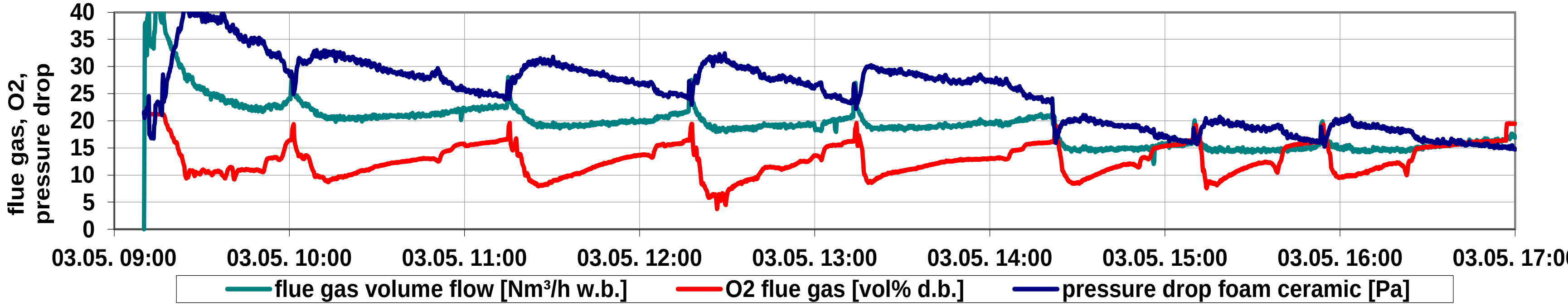
Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic 2 - coated with tailor made catalyst I – comparisons of day 3, 11 and 18 – flue gas, pressure drop and O_2 trends

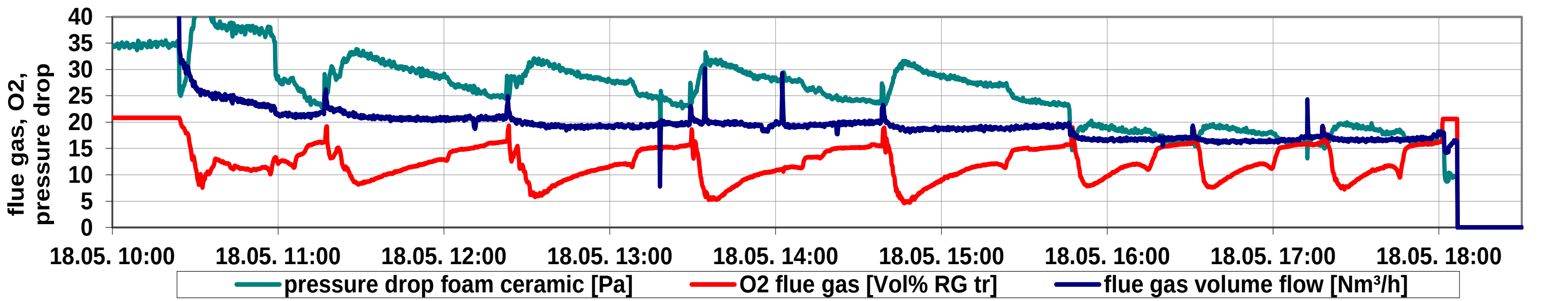
3



11

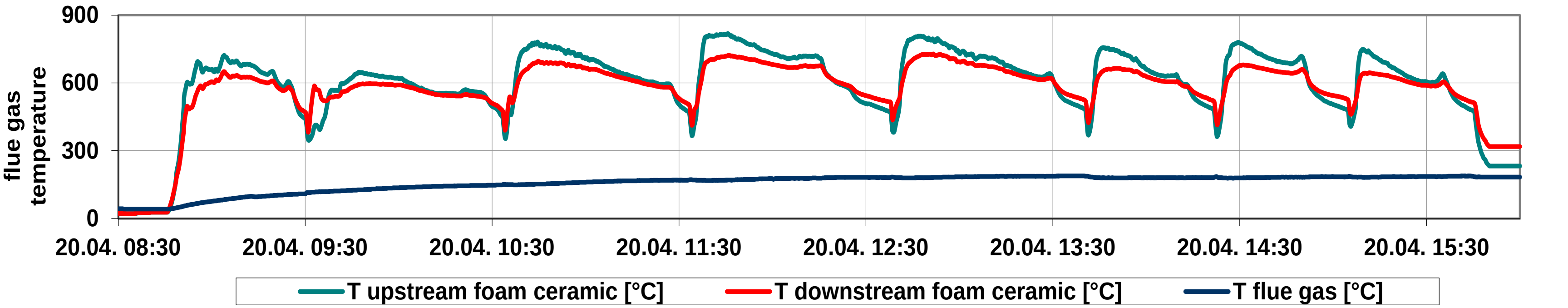


18

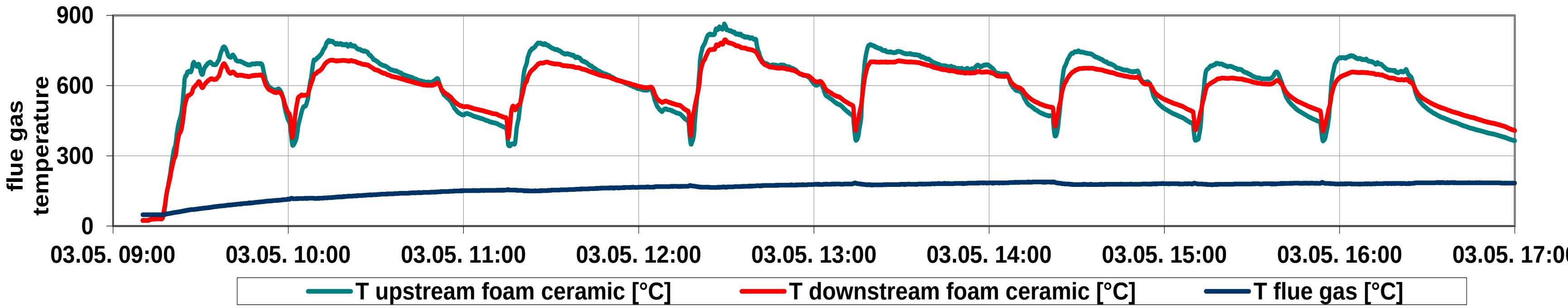


Foam ceramic 2 - coated with tailor made catalyst I – comparisons of day 3, 11 and 18 – temperatures

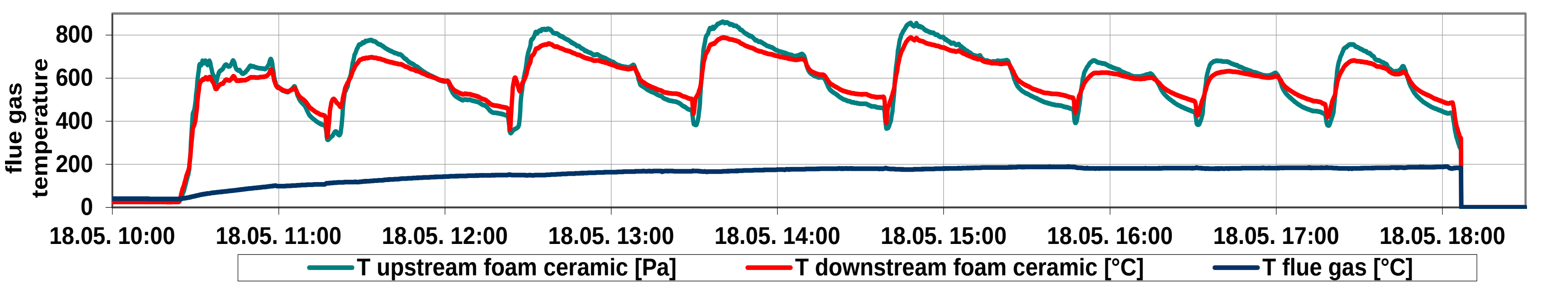
3



11

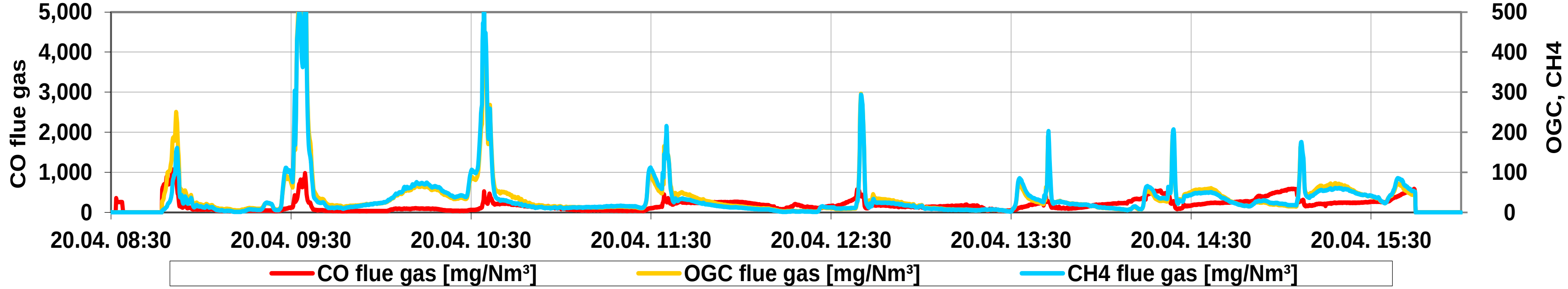


18

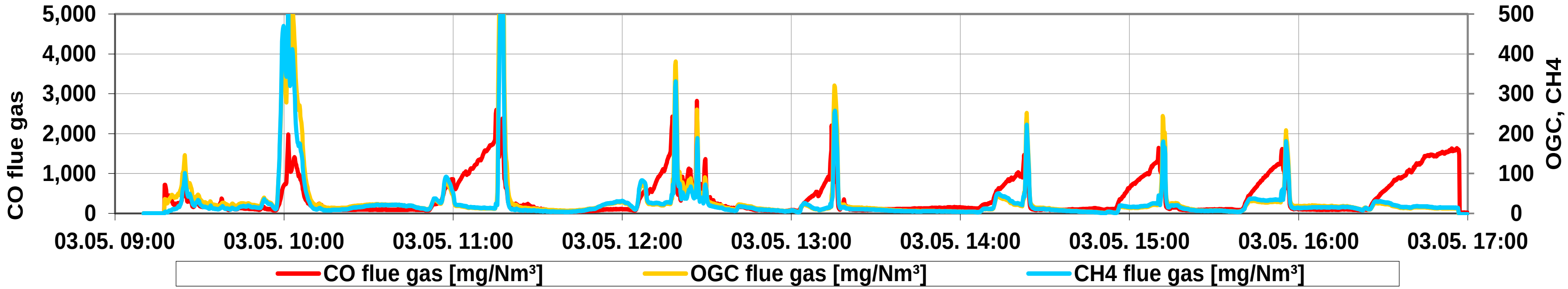


Foam ceramic 2 - coated with tailor made catalyst I– comparisons of day 3, 11 and 18 – CO and OGC emission trends

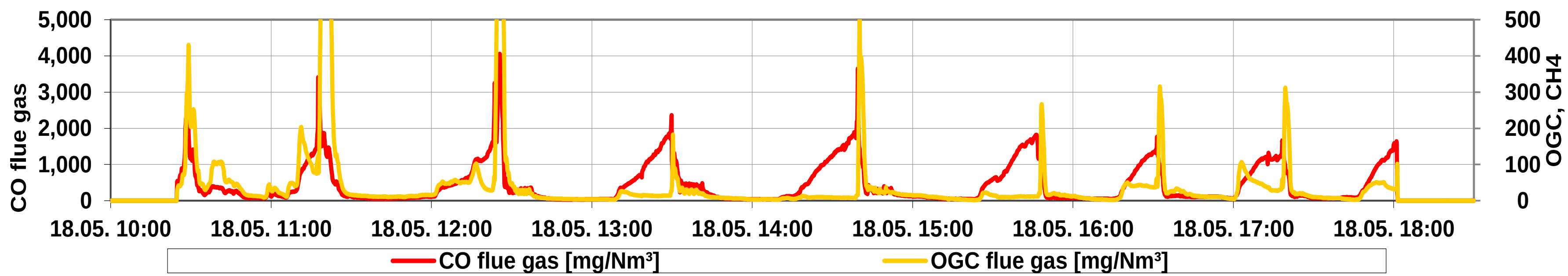
3



11

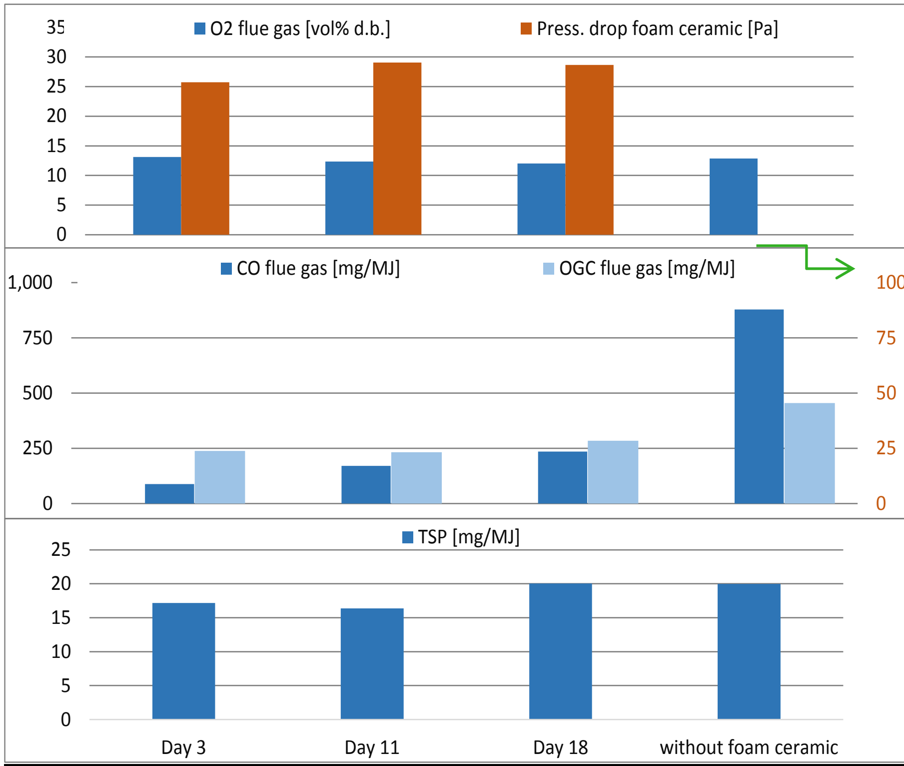


18

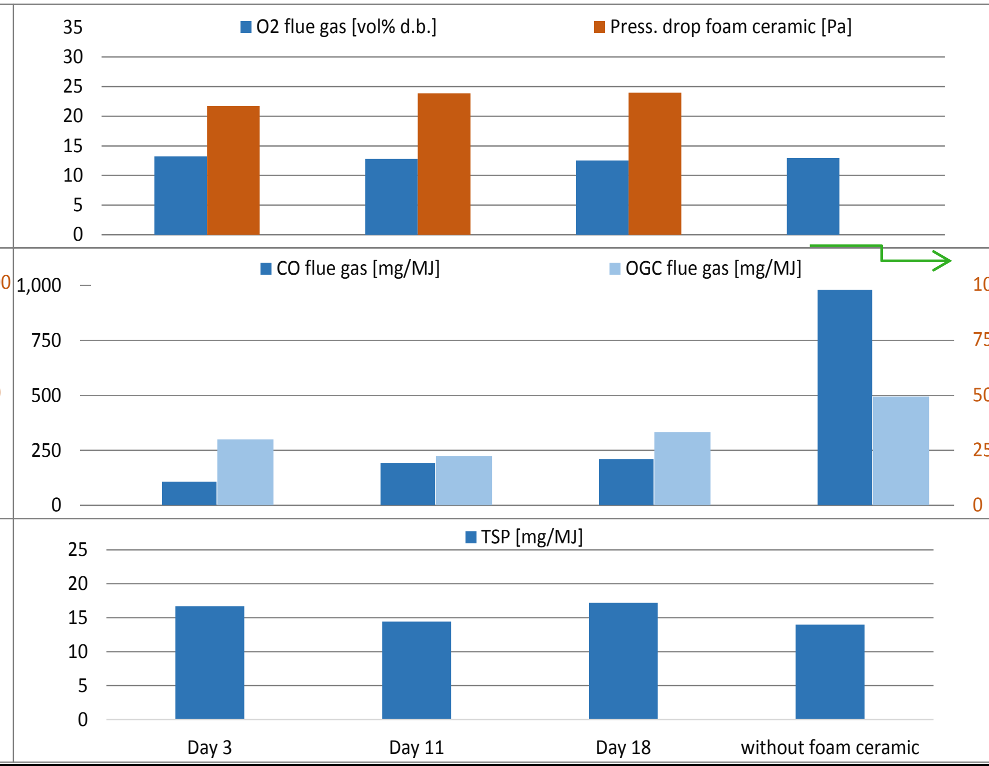


Foam ceramic 2 – coated with tailor made catalyst I – comparisons of mean values

Nominal load



Partial load



Foam ceramic 2		Day 3	Day 11	Day 18	without foam ceramic	Day 3	Day 11	Day 18	without foam ceramic
		Mean (NL) (0,1,2,3,4)	Mean (NL) (0,1,2,3,4)	Mean (NL) (0,1,2,3,4)	Mean (NL) (0,1,2,3,4)	Mean (PL) (0,5,6,7)	Mean (PL) (0,5,6,7)	Mean (PL) (0,5,6,7)	Mean (PL) (0,5,6,7)
CO flue gas	[mg/MJ]	88.4	170	234.7	878.5	107.8	193	209.9	1003.8
OGC flue gas	[mg/MJ]	23.8	23	28.4	45.5	29.8	22	33.0	49.2
OGC without CH4	[mg/MJ]	2.5	4.8	7.1	25.4	2.0	3.2	7.1	25.0

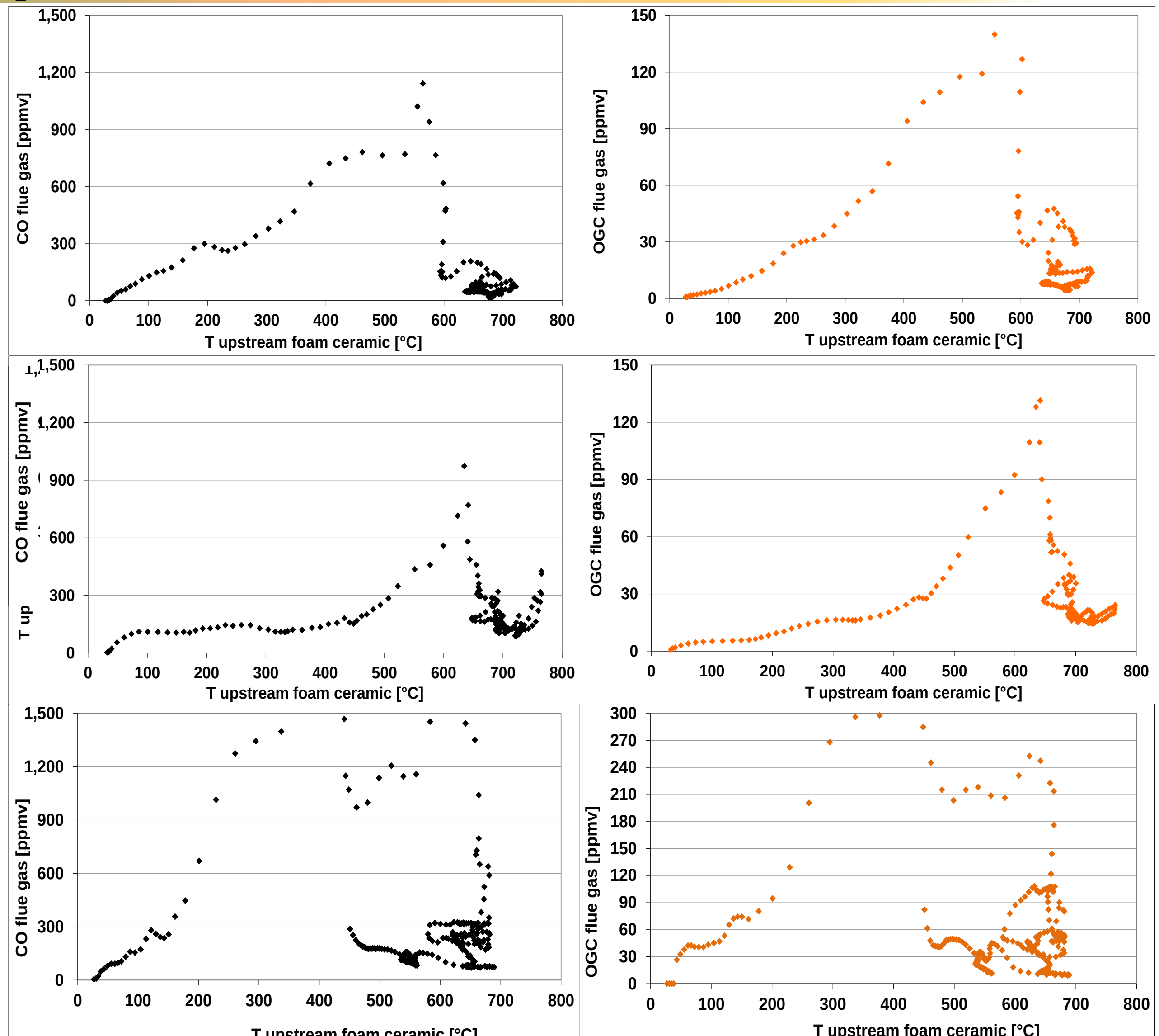
Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation; without foam ceramic … test run with stove without integrated foam ceramic

Foam ceramic 2 - coated with tailor made catalyst I – light-off behaviour day 3, 11 and 18 during the ignition batch

3

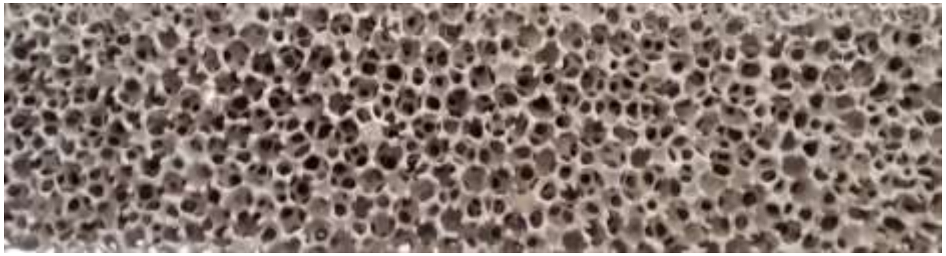
11

18



Foam ceramic 2 - coated with tailor made catalyst I – Pictures of foam ceramic before and after cleaning

Foam ceramic before the test runs

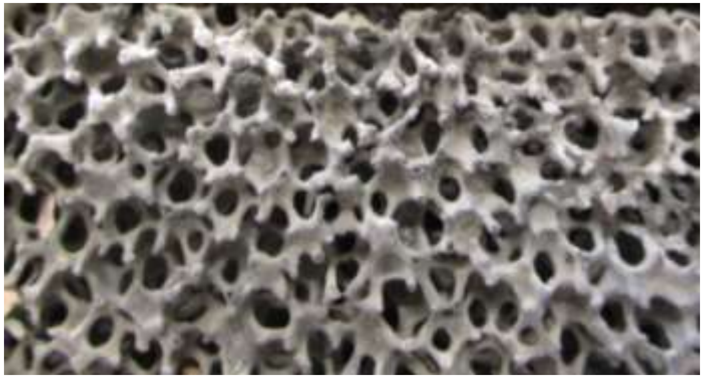


Foam ceramic after 2 weeks of operation

Foam ceramic after manual cleaning after 2 weeks of operation (view at inlet)

- **Cleaning:**
  - **Step 1: cleaning with a soft brush**
  - **Step 2: purging the foam ceramic with compressed air**

Foam ceramic after 18 days of operation



Foam ceramic 2 – coated with tailor made catalyst I – Summary (I)

- The catalyst was operated for 18 days (94 batches).
- The stove could be operated at typical air supply conditions leading to average O_2 contents in the flue gas over a whole batch of between 11.2 and 14.1 vol% (dry flue gas, excluding the ignition batches).
- At the beginning of the test (3rd day of operation) for CO very high and for OGC high emission reduction efficiencies could be determined (comparison with stove operation without foam ceramic).
  - **CO (mean value for full load operation): 879 → 88 mg/MJ = 89.9%**
  - **CO (mean value for partial load operation): 1,004 → 108 mg/MJ = 89.3%**
  - **OGC (mean value for full load operation): 45.5 → 23.8 mg/MJ = 47.6%**
  - **OGC (mean value for partial load operation): 49.2 → 29.8 mg/MJ = 39.4%**

Foam ceramic 2 – coated with tailor made catalyst I – Summary (II)

- The pressure drop over the catalyst amounted to in average
  - 25.7 Pa (full load)
  - 21.7 Pa (partial load)

  which is in the expected range (due to smaller pores compared with the non-coated foam ceramic)

- After two weeks of operation for CO and for OGC high emission reduction efficiencies could still be determined (comparison with stove operation without foam ceramic).
  - CO (mean value for full load operation): 879 ➔ 170 mg/MJ = 80.6%
  - CO (mean value for partial load operation): 1,004 ➔ 193 mg/MJ = 80.8%
  - OGC (mean value for full load operation): 45.5 ➔ 23.2 mg/MJ = 49.0%
  - OGC (mean value for partial load operation): 49.2 ➔ 22.2 mg/MJ = 54.6%

- The pressure drop over the catalyst increased to in average 29 Pa (full load) and 21.7 Pa (partial load) after two weeks of operation.

Foam ceramic 2 – coated with tailor made catalyst I – Summary (III)

- After 18 days of operation for CO and for OGC still high emission reduction efficiencies could still be determined (comparison with stove operation without foam ceramic).
  - CO (mean value for full load operation): 879 → 235 mg/MJ = 73.3%
  - CO (mean value for partial load operation): 1,004 → 210 mg/MJ = 79.1%
  - OGC (mean value for full load operation): 45.5 → 28.4 mg/MJ = 37.6%
  - OGC (mean value for partial load operation): 49.2 → 33.0 mg/MJ = 32.9%
- The pressure drop over the catalyst increased to in average 29 Pa (full load, 25.7 Pa at the beginning) and 24 Pa (partial load, 21 Pa at the beginning) after 18 days of operation.
- During full load operation particulate emissions (TSP) amounted to 16.0 to 17.2 mg/MJ which is at the same level as measured during the test runs with the foam ceramic without catalyst (16.7 to 19.0 mg/MJ) and which is slightly lower than the level measured during the test run without foam ceramic (20.0 mg/MJ).

Foam ceramic 2 – coated with tailor made catalyst I – Summary (IV)

- **However, during partial load operation particulate emissions (TSP) amounted to 14.0 to 16.7 mg/MJ which is at the same level as measured during the test runs with the non-coated foam ceramic (14.3 to 15.0 mg/MJ) and during the test run without foam ceramic (14.0 mg/MJ).**

- **OGC-emission reduction:**
  - **The share of CH_4 on the OGC emissions increases downstream the catalyst up to 90% as it is well known that CH_4 is hardly converted by the catalyst. Therefore, the evaluation of the methane free OGC reduction showed a significantly higher emission reduction (in the range of 72 to 92%) under the consideration that CH_4 is not converted by the foam ceramic.**

Foam ceramic 2 – coated with tailor made catalyst I – Summary (V)

- **Evaluating the flue gas temperature upstream the catalyst and the CO emission reductions achieved shows:**
  - **Day 3: light-off temperature: about 600°C**
  - **Day 11: light-off temperature: about 650°C**
  - **Day 18: light-off temperature: about 680°C**

  → **it seems that the light-off temperature depends on the operation time which could be due to a certain deposit formation and re-evaporation**

- **Regarding OGC-emissions the light-off temperatures seem to be in the same range as the CO light-off temperatures.**

- **An inspection of the foam ceramic after 2 weeks of operation revealed some fly ash deposits on the surface of the foam ceramic → reason for the increasing pressure losses.**

Foam ceramic 2 – coated with tailor made catalyst I – Summary (VI)

- By manual cleaning most of the fly ash deposits could be successfully removed. After manual cleaning the pressure drop over the foam ceramic could be reduced again.
- **Therefore, manual cleaning of the foam ceramic at least every two weeks of operation is recommended in order to reduce the pressure drop over the foam ceramic (based on the test run results so far).**
- Concluding, the catalytically-coated foam ceramic showed sufficiently high and almost stable emission reduction efficiencies regarding CO and OGC and therefore this catalyst seems basically to be suitable for wood stoves.
- However, the pressure drop over the coated foam ceramic is quite high and moderately increased after two weeks of operation due to fly ash deposits on the surface of the foam ceramic.
- Therefore, the pressure drop of the foam ceramic has to be reduced in order to be implemented in natural draft logwood stoves.

Results of the test runs with a logwood stove and different catalysts

Results of the test runs performed with Foam ceramic 3 – coated with tailor made catalyst II – at catalyst position II

Foam ceramic 3 – coated with tailor-made catalyst II – Overview (I)

Day	Date	Comments
1	24/05/2016	Operation
2	25/05/2016	Measurements – series 1
3	30/05/2016	Operation
4	31/05/2016	Operation
5	01/06/2016	Operation
6	02/06/2016	Operation
7	03/06/2016	Operation
8	06/06/2016	Operation
9	07/06/2016	Operation
10	08/05/2016	Measurements – series 2 Manual cleaning of the foam ceramic

No	3
Name	Tailor-made catalyst II
Substrate	SSiC
Structure	Foam ceramic
PPI [1)]	10
Dimension (HxWxL)	380 x 50 x 50 mm
Active metal	Pt

Explanations: [1)] Pores per inch

Foam ceramic 3 – coated with tailor-made catalyst II – Overview (II)

Day	Date	Comments
11	09/06/2016	Operation
12	10/06/2016	Operation
13	13/06/2016	Operation
14	14/06/2016	Operation
15	20/06/2016	Operation
16	21/06/2016	Measurements – series 3 Manual cleaning of the foam ceramic

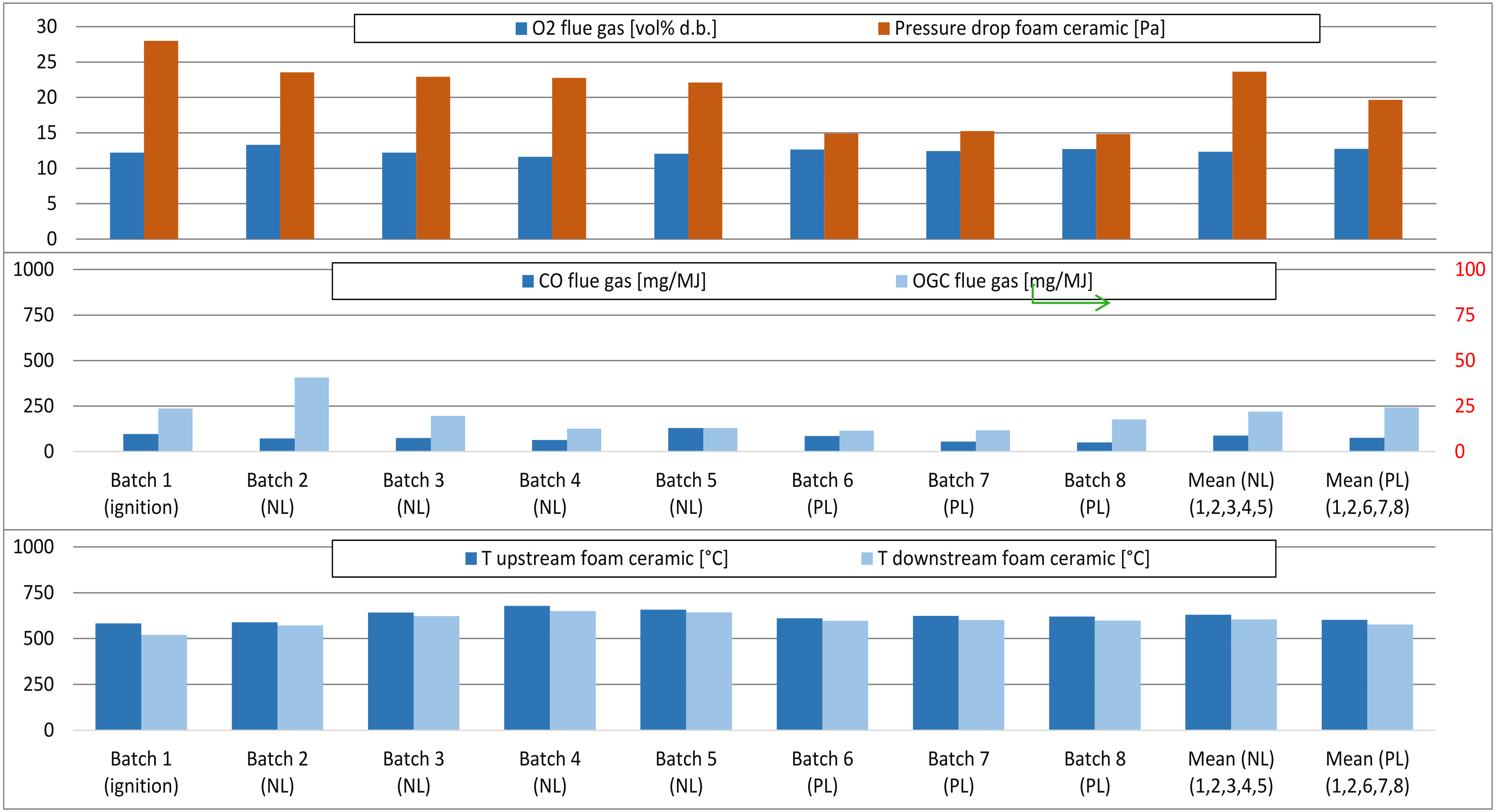
No	3
Name	Tailor-made catalyst II
Substrate	SSiC
Structure	Foam ceramic
PPI [1)]	10
Dimension (HxWxL)	380 x 50 x 50 mm
Active metal	Pt

Explanations: [1)] Pores per inch

Foam ceramic 3 – coated with tailor-made catalyst II – Day 2: measurements – series 1 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		25.05 10:17	25.05 11:06	25.05 12:13	25.05 13:21	25.05 14:23	25.05 15:29	25.05 16:21	25.05 17:06			
Door opened		25.05 11:05	25.05 12:13	25.05 13:20	25.05 14:22	25.05 15:28	25.05 16:20	25.05 17:05	25.05 17:49			
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6	
O2 flue gas	**vol% d.b.**	**12.2**	**13.3**	**12.2**	**11.6**	**12.1**	**12.7**	**12.4**	**12.7**	**12.3**	**12.7**	
Flue gas volume flow	**Nm³ d.b.**	**19.0**	**23.8**	**22.0**	**19.6**	**20.7**	**13.0**	**10.9**	**11.0**	**105.1**	**77.7**	
Fuel input (without remaining char coal)	MJ	38.1	34.8	34.8	34.8	34.8	17.4	17.4	17.4	177.3	125.1	
Evaluation - conventional												
CO flue gas	mg/Nm³	167.9	106.8	104.4	93.8	199.7	107.3	80.2	75.7	134.1	109.5	
CO flue gas	**mg/MJ**	**111.9**	**71.2**	**69.6**	**62.5**	**133.1**	**71.5**	**53.5**	**50.5**	**89.4**	**73.0**	
OGC flue gas	mg/Nm³	38.5	55.6	24.9	16.5	17.3	13.4	15.6	24.5	29.5	31.0	
OGC flue gas	**mg/MJ**	**25.7**	**37.1**	**16.6**	**11.0**	**11.5**	**9.0**	**10.4**	**16.3**	**19.7**	**20.7**	
CH4 flue gas	mg/Nm³	27.0	53.9	22.3	13.8	14.7	12.7	15.1	25.9	25.7	28.3	
CH4 flue gas	**mg/MJ**	**18.0**	**35.9**	**14.9**	**9.2**	**9.8**	**8.5**	**10.0**	**17.3**	**17.1**	**18.9**	
TSP	mg/Nm³	35.5		22.6		32.7		15.0		30.1	24.0	
TSP	**mg/MJ**	**23.7**		**15.1**		**21.8**		**10.0**		**20.0**	**16.0**	
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**96.4**	**72.1**	**75.2**	**64.2**	**129.4**	**85.4**	**55.5**	**50.9**	**87.6**	**76.1**	
OGC flue gas	**mg/MJ**	**23.7**	**40.8**	**19.7**	**12.6**	**12.9**	**11.5**	**11.7**	**17.8**	**21.9**	**24.2**	
T upstream foam ceramic	°C	582.9	588.5	641.8	678.4	657.3	610.2	623.8	620.1	630.0	602.3	
T downstream foam ceramic	°C	520.2	572.3	622.5	649.9	643.2	597.0	600.4	598.0	604.5	576.2	
T flue gas (EN13240)	°C	96.8	142.0	165.1	179.3	188.5	186.7	187.3	190.4	157.3	158.9	
Chimney draught	Pa	12.7	13.1	12.9	12.5	13.6	12.9	13.6	12.3	13.0	12.9	
Pressure drop foam ceramic	**Pa**	**28.0**	**23.6**	**22.9**	**22.8**	**22.1**	**14.9**	**15.3**	**14.9**	**23.6**	**19.7**	
Efficiency (EN13240)	**%**	**93.2**	**88.0**	**85.1**	**84.6**	**82.9**	**82.1**	**82.5**	**81.6**	**86.8**	**85.4**	
Carbon balance												**total**
carbon in CO2	g	849.5	922.2	978.3	935.8	930.8	541.8	472.0	461.3	4,635.6	3,257.1	6,120.1
carbon in CO	g	1.6	1.1	1.1	1.0	1.9	0.6	0.4	0.4	6.7	4.1	8.2
carbon in OGC	g	0.3	0.4	0.2	0.1	0.1	0.1	0.1	0.1	1.2	0.9	1.4
carbon in bottom ash	g											351.5
carbon in fuel	g	1,038.4	947.6	947.6	947.6	947.6	473.8	473.8	473.8	4,829.0	3,407.5	6,250.4
deviation of carbon balance	**%**	**18.0**	**2.5**	**-3.4**	**1.1**	**1.6**	**-14.5**	**0.3**	**2.5**			**-3.7**
factor mg/Nm³ --> mg/MJ	-	1.83	1.52	1.44	1.52	1.51	1.29	1.49	1.53	1.56	1.56	1.5

Foam ceramic 3 –
coated with tailor-made catalyst II –
Day 2: measurements – series 1 (II)

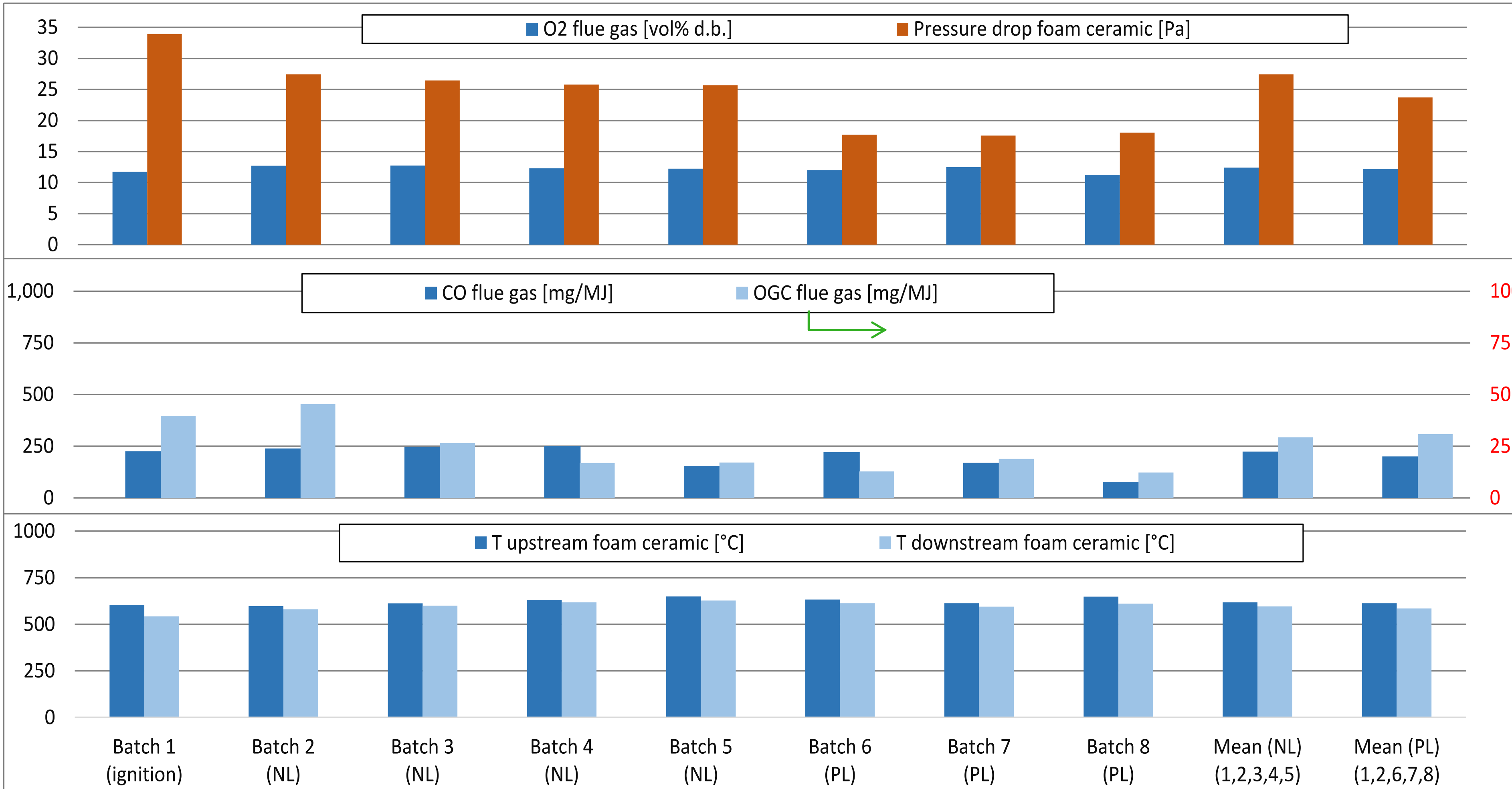


Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic 3 – coated with tailor-made catalyst II – Day 10: measurements – series 2 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		08.06 08:56	08.06 09:41	08.06 10:44	08.06 11:53	08.06 13:01	08.06 14:05	08.06 14:52	08.06 15:34			
Door opened		08.06 09:41	08.06 10:43	08.06 11:53	08.06 13:00	08.06 14:04	08.06 14:51	08.06 15:34	08.06 16:20			
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6	
O_2 flue gas	**vol% d.b.**	**11.7**	**12.7**	**12.8**	**12.3**	**12.2**	**12.0**	**12.5**	**11.3**	**12.4**	**12.2**	
Flue gas volume flow	**Nm^3 d.b.**	**17.7**	**21.5**	**22.8**	**22.0**	**20.0**	**11.8**	**10.4**	**6.4**	**104.1**	**67.8**	
Fuel input (without remaining char coal)	MJ	36.7	33.7	33.7	33.7	33.7	16.9	16.9	16.9	171.6	121.0	
Evaluation - conventional												
CO flue gas	mg/Nm^3	395.8	353.9	339.5	339.3	228.1	272.1	248.7	155.8	332.9	305.9	
CO flue gas	**mg/MJ**	**263.9**	**235.9**	**226.3**	**226.2**	**152.0**	**181.4**	**165.8**	**103.9**	**221.9**	**203.9**	
OGC flue gas	mg/Nm^3	63.7	61.6	33.9	21.4	23.5	14.4	26.0	23.3	39.1	40.6	
OGC flue gas	**mg/MJ**	**42.5**	**41.1**	**22.6**	**14.3**	**15.7**	**9.6**	**17.3**	**15.6**	**26.1**	**27.1**	
CH_4 flue gas	mg/Nm^3	41.1	45.4	23.8	16.1	18.9	12.0	24.6	18.3	28.1	30.3	
CH_4 flue gas	**mg/MJ**	**27.4**	**30.3**	**15.9**	**10.7**	**12.6**	**8.0**	**16.4**	**12.2**	**18.8**	**20.2**	
TSP	mg/Nm^3	32.9		15.5		15.2		21.5		19.9	16.7	
TSP	**mg/MJ**	**22.0**		**10.4**		**10.1**		**14.4**		**13.3**	**11.1**	
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**225.6**	**239.4**	**246.3**	**251.2**	**154.6**	**221.6**	**170.1**	**75.9**	**223.5**	**200.3**	
OGC flue gas	**mg/MJ**	**39.8**	**45.4**	**26.5**	**16.9**	**17.1**	**12.8**	**18.9**	**12.2**	**29.3**	**30.8**	
T upstream foam ceramic	°C	603.0	597.1	611.8	631.9	649.5	632.1	613.3	648.1	618.2	613.1	
T downstream foam ceramic	°C	542.2	580.0	599.5	617.6	628.2	613.3	594.6	610.8	596.1	584.8	
T flue gas (EN13240)	°C	86.8	133.8	159.3	174.0	180.3	179.5	180.7	182.7	151.2	148.6	
Chimney draught	Pa	12.2	11.6	12.2	11.6	12.1	12.1	12.3	12.2	11.9	12.0	
Pressure drop foam ceramic	**Pa**	**33.9**	**27.4**	**26.4**	**25.8**	**25.7**	**17.7**	**17.6**	**18.1**	**27.4**	**23.7**	
Efficiency (EN13240)	**%**	**94.4**	**89.8**	**85.3**	**84.5**	**84.1**	**84.5**	**83.7**	**85.4**	**87.6**	**87.6**	
Carbon balance												**total**
carbon in CO_2	g	820.8	891.2	929.4	950.9	873.2	522.6	436.4	317.8	4,484.2	3,000.7	5,772.5
carbon in CO	g	3.6	3.5	3.6	3.6	2.2	1.6	1.2	0.5	16.8	10.6	20.4
carbon in OGC	g	0.4	0.5	0.3	0.2	0.2	0.1	0.1	0.1	1.6	1.2	1.8
carbon in bottom ash	g											578.1
carbon in fuel	g	998.8	916.7	916.7	916.7	916.7	458.3	458.3	458.3	4,665.5	3,290.5	6,040.5
deviation of carbon balance	**%**	**17.4**	**2.4**	**-1.8**	**-4.1**	**4.5**	**-14.4**	**4.5**	**30.5**			**-5.5**
factor mg/Nm^3 --> mg/MJ	-	1.79	1.51	1.44	1.41	1.54	1.28	1.52	2.16	1.54	1.62	1.5

Foam ceramic 3 – coated with tailor-made catalyst II – Day 10: measurements – series 2 (II)

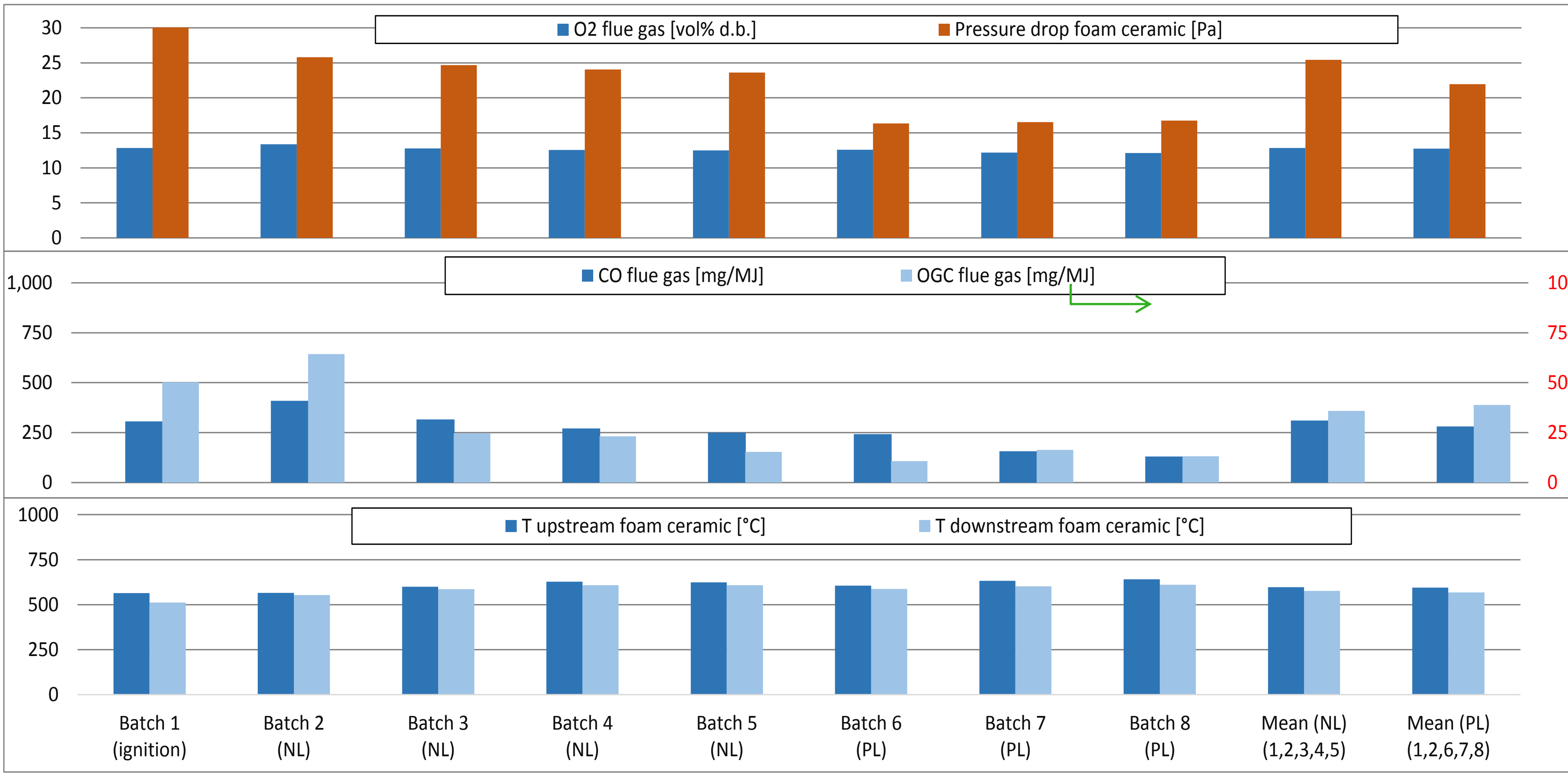


Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic 3 – coated with tailor-made catalyst II – Day 16: measurements – series 2 (I)

		Batch 1 (ignition)	Batch 2 (NL)	Batch 3 (NL)	Batch 4 (NL)	Batch 5 (NL)	Batch 6 (PL)	Batch 7 (PL)	Batch 8 (PL)	Mean (NL) (1,2,3,4,5)	Mean (PL) (1,2,6,7,8)	
Door closed		21.06 10:27	21.06 11:19	21.06 12:31	21.06 13:42	21.06 14:52	21.06 16:05	21.06 16:54	21.06 17:36			
Door opened		21.06 11:19	21.06 12:30	21.06 13:41	21.06 14:51	21.06 16:05	21.06 16:54	21.06 17:36	21.06 18:17			
Fuel input	kg w.b.	2.6	2.4	2.4	2.4	2.4	1.2	1.2	1.2	12.2	8.6	
O_2 flue gas	**vol% d.b.**	**12.8**	**13.4**	**12.8**	**12.6**	**12.5**	**12.6**	**12.2**	**12.1**	**12.8**	**12.7**	
Flue gas volume flow	**Nm^3 d.b.**	**21.2**	**24.6**	**22.9**	**22.9**	**23.0**	**13.1**	**10.6**	**10.7**	**114.6**	**80.3**	
Fuel input (without remaining char coal)	MJ	38.4	34.9	34.9	34.9	34.9	17.4	17.4	17.4	178.0	125.6	
Evaluation - conventional		550.5	594.6	451.1	380.2	345.6	293.7	225.6	184.2	462.1	396.3	
CO flue gas	mg/Nm^3	550.5	594.6	451.1	380.2	345.6	293.7	225.6	184.2	462.1	396.3	
CO flue gas	**mg/MJ**	**367.0**	**396.4**	**300.7**	**253.5**	**230.4**	**195.8**	**150.4**	**122.8**	**308.1**	**264.2**	
OGC flue gas	mg/Nm^3	82.9	86.1	32.9	30.5	19.8	12.4	22.0	17.2	47.6	48.1	
OGC flue gas	**mg/MJ**	**55.2**	**57.4**	**21.9**	**20.4**	**13.2**	**8.2**	**14.6**	**11.5**	**31.7**	**32.0**	
CH_4 flue gas	mg/Nm^3	56.3	52.6	19.9	21.6	12.8	9.8	17.7	14.4	30.7	32.4	
CH_4 flue gas	**mg/MJ**	**37.6**	**35.1**	**13.3**	**14.4**	**8.5**	**6.5**	**11.8**	**9.6**	**20.5**	**21.6**	
TSP	mg/Nm^3	37.7		17.9		17.8		22.5		21.6	18.9	
TSP	**mg/MJ**	**25.2**		**11.9**		**11.9**		**15.0**		**14.4**	**12.6**	
Evaluation - flue gas volume based												
CO flue gas	**mg/MJ**	**306.2**	**409.6**	**315.5**	**270.4**	**250.1**	**242.3**	**156.3**	**130.0**	**310.3**	**280.8**	
OGC flue gas	**mg/MJ**	**50.2**	**64.3**	**24.7**	**23.2**	**15.4**	**10.8**	**16.4**	**13.2**	**35.8**	**38.8**	
T upstream foam ceramic	°C	564.6	565.1	599.5	627.2	624.1	605.3	632.5	640.8	596.7	594.9	
T downstream foam ceramic	°C	512.4	553.9	586.5	608.4	608.8	587.0	602.3	610.9	576.6	568.1	
T flue gas (EN13240)	°C	90.5	137.7	162.8	176.4	184.6	184.4	184.8	187.9	153.9	152.8	
Chimney draught	Pa	12.2	12.5	12.7	12.0	12.5	12.0	12.1	12.5	12.4	12.3	
Pressure drop foam ceramic	**Pa**	**30.4**	**25.8**	**24.7**	**24.1**	**23.6**	**16.4**	**16.5**	**16.7**	**25.4**	**22.0**	
Efficiency (EN13240)	**%**	**93.1**	**88.1**	**84.4**	**83.4**	**82.6**	**82.6**	**83.3**	**83.1**	**86.3**	**86.0**	
Carbon balance		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**total**
carbon in CO_2	g	857.2	937.2	938.6	965.1	965.8	539.0	463.7	467.8	4,679.4	3,275.1	6,159.6
carbon in CO	g	5.1	6.1	4.7	4.0	3.7	1.8	1.2	1.0	24.1	15.3	28.3
carbon in OGC	g	0.6	0.7	0.3	0.3	0.2	0.1	0.1	0.1	2.0	1.5	2.2
carbon in bottom ash	g	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	383.9
carbon in fuel	g	1,045.9	949.0	949.0	949.0	949.0	474.5	474.5	474.5	4,841.9	3,418.4	6,265.4
deviation of carbon balance	**%**	**17.5**	**0.5**	**0.6**	**-2.1**	**-2.2**	**-14.0**	**2.0**	**1.2**			**-4.9**
factor mg/Nm^3 --> mg/MJ	-	1.78	1.48	1.48	1.45	1.43	1.26	1.49	1.46	1.52	1.51	1.4

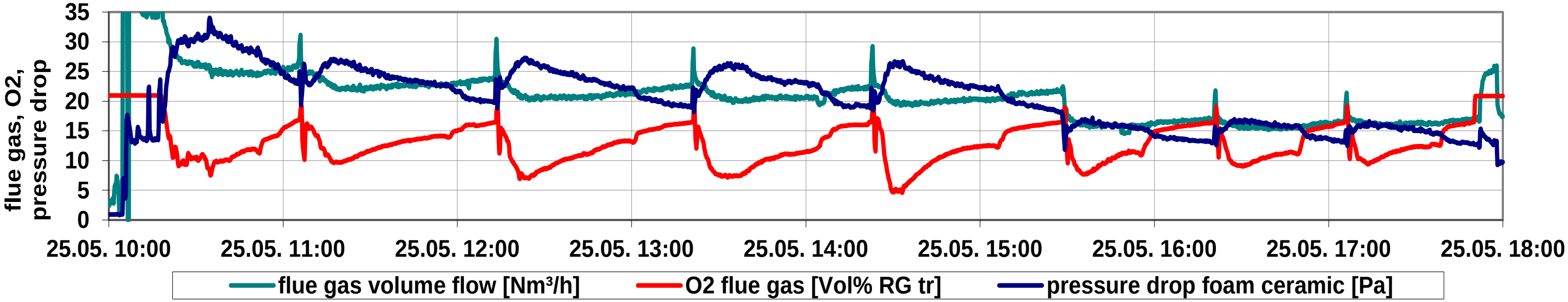
Foam ceramic 3 – coated with tailor-made catalyst II – Day 16: measurements – series 2 (II)



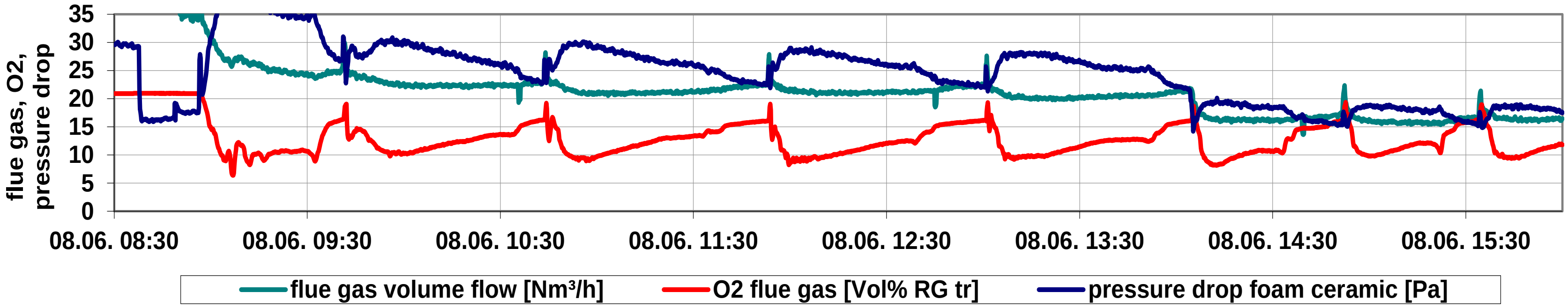
Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation

Foam ceramic 3 – coated with tailor-made catalyst II – comparisons of day 2, 10 and 16 – flue gas, pressure drop and O_2 trends

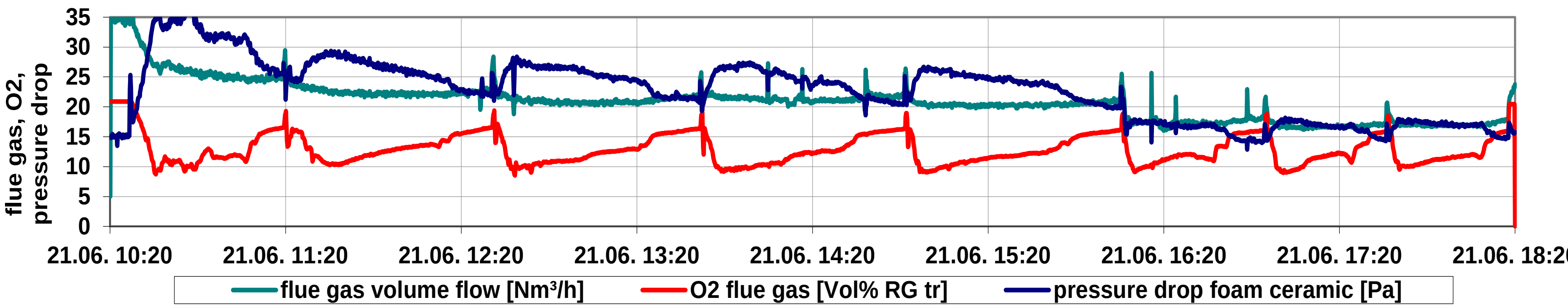
2



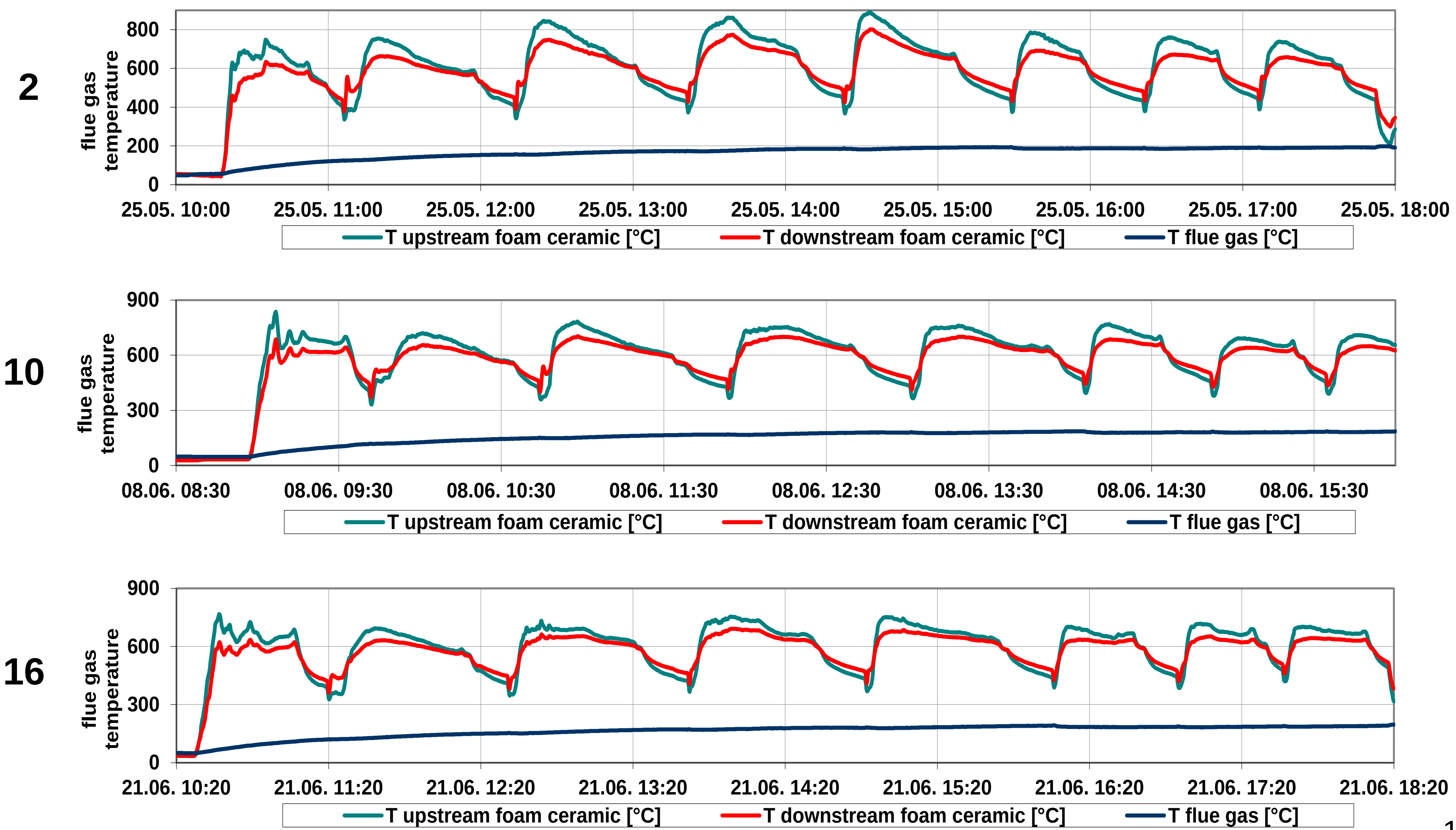
10



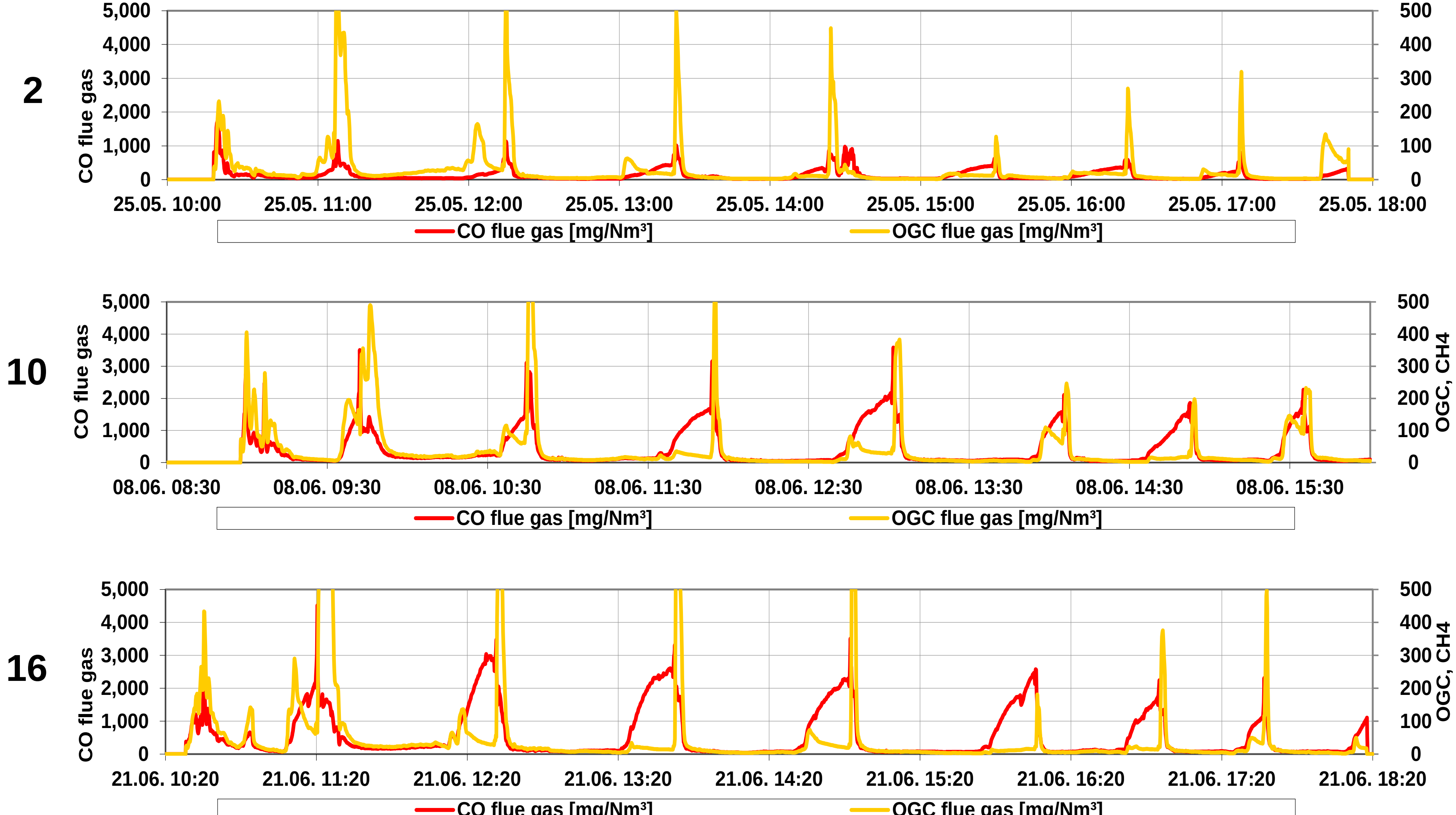
16



Foam ceramic 3 – coated with tailor-made catalyst II – comparisons of day 2, 10 and 16 – temperatures



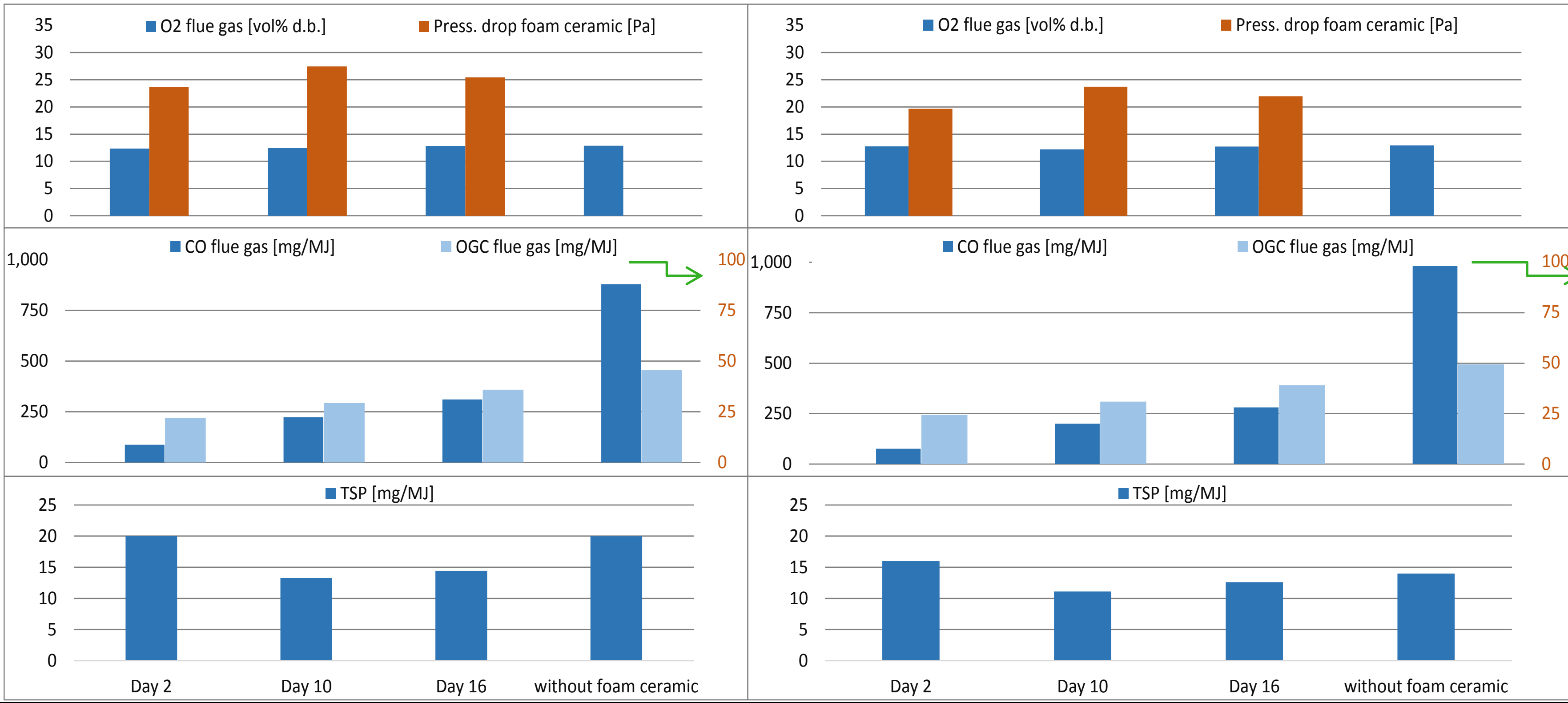
Foam ceramic 3 – coated with tailor-made catalyst II – comparisons of day 2, 10 and 16 – CO and OGC emission trends



Foam ceramic 3 – coated with tailor-made catalyst II – comparisons of mean values

Nominal load

Partial load

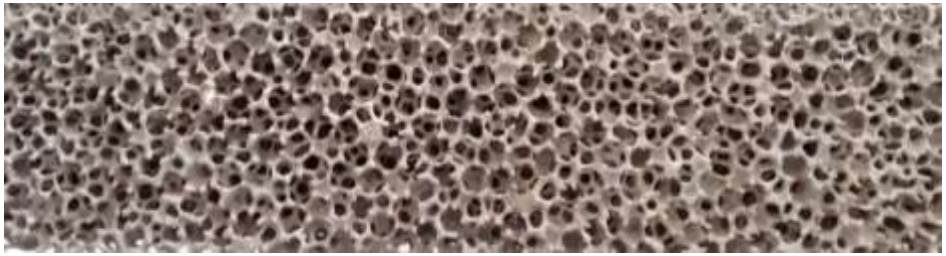


Foam ceramic 3		Day 2	Day 10	Day 16	without foam ceramic	Day 2	Day 10	Day 16	without foam ceramic
		Mean (NL) (0,1,2,3,4)	Mean (NL) (0,1,2,3,4)	Mean (NL) (0,1,2,3,4)	Mean (NL) (0,1,2,3,4)	Mean (PL) (0,5,6,7)	Mean (PL) (0,5,6,7)	Mean (PL) (0,5,6,7)	Mean (PL) (0,5,6,7)
CO flue gas	[mg/MJ]	87.6	223	310.3	878.5	76.1	200	280.8	1003.8
OGC flue gas	[mg/MJ]	21.9	29	35.8	45.5	24.2	31	38.8	49.2
OGC without CH4	[mg/MJ]	2.6	7	11.2	25.4	1.8	10	10.4	25.0

Explanations: CO and OGC in mg/MJ based on flue gas volume based evaluation; without foam ceramic … test run with stove without integrated foam ceramic

Foam ceramic 3 – coated with tailor-made catalyst II – Pictures of foam ceramic before and after cleaning

Foam ceramic before the test runs



Foam ceramic after 2 weeks of operation

Foam ceramic after manual cleaning after 2 weeks of operation (view at inlet)

- **Cleaning:**
  - **Step 1: cleaning with a soft brush**
  - **Step 2: purging the foam ceramic with compressed air**

Foam ceramic after 16 days of operation

Foam ceramic 3 – coated with tailor-made catalyst II – Summary (I)

- The catalyst was operated for 16 days (84 batches).
- The stove could be operated at typical air supply conditions leading to average O_2 contents in the flue gas over a whole batch of between 11.3 and 13.4 vol% (dry flue gas, excluding the ignition batches).
- At the beginning of the test (2nd day of operation) for CO very high and for OGC high emission reduction efficiencies could be determined (comparison with stove operation without foam ceramic).
  - **CO (mean value for full load operation): 879 → 88 mg/MJ = 90.0%**
  - **CO (mean value for partial load operation): 1,004 → 76.1 mg/MJ = 92.4%**
  - **OGC (mean value for full load operation): 45.5 → 21.9 mg/MJ = 51.7%**
  - **OGC (mean value for partial load operation): 49.2 → 24.2 mg/MJ = 50.7%**

Foam ceramic 3 – coated with tailor-made catalyst II – Summary (II)

- The pressure drop over the catalyst amounted to in average
  - 23.6 Pa (full load)
  - 19.7 Pa (partial load)

  which is in the expected range (due to smaller pores compared with the non-coated foam ceramic)

- After 10 days of operation for CO a high emission reduction efficiency and for OGC a moderate emission reduction efficiency could still be determined (comparison with stove operation without foam ceramic).
  - CO (mean value for full load operation): 879 → 224 mg/MJ = 77.7%
  - CO (mean value for partial load operation): 1,004 → 200 mg/MJ = 80.0%
  - OGC (mean value for full load operation): 45.5 → 29.3 mg/MJ = 40.4%
  - OGC (mean value for partial load operation): 49.2 → 30.8 mg/MJ = 37.4%

- The pressure drop over the catalyst increased to in average 27.4 Pa (full load) and 23.7 Pa (partial load) after two weeks of operation.

Foam ceramic 3 – coated with tailor-made catalyst II – Summary (III)

- **After 16 days of operation for CO a satisfying emission reduction efficiency and for OGC a moderate emission reduction efficiency could be determined (comparison with stove operation without foam ceramic).**
  - **CO (mean value for full load operation): 879 ➔ 310 mg/MJ = 69.1%**
  - **CO (mean value for partial load operation): 1,004 ➔ 281 mg/MJ = 72.0%**
  - **OGC (mean value for full load operation): 45.5 ➔ 35.8 mg/MJ = 27.2%**
  - **OGC (mean value for partial load operation): 49.2 ➔ 38.8 mg/MJ = 21.1%**

- **The pressure drop over the catalyst increased to in average 25.4 Pa (full load, 23.6 Pa at the beginning) and 22 Pa (partial load, 19.7 Pa at the beginning) after 16 days of operation. Due to the manual cleaning of the catalyst after two weeks of operation the pressure drop over the catalyst increased only slightly over the entire operation period.**

Foam ceramic 3 – coated with tailor-made catalyst II – Summary (IV)

- During full load operation particulate emissions (TSP) amounted to 13.0 to 20.0 mg/MJ which is at the same level as measured during the test runs with the non-coated foam ceramic (16.7 to 19.0 mg/MJ) and during the test run without foam ceramic (20.0 mg/MJ).

- During partial load operation particulate emissions (TSP) amounted to 11.0 to 16.0 mg/MJ which is at the same level as measured during the test runs with the non-coated foam ceramic (14.3 to 15.0 mg/MJ) and during the test run without foam ceramic (14.0 mg/MJ).

- The share of CH_4 on the OGC emissions increases downstream the catalyst to up to 96% during the test run at the 2nd day of operation (in the range of 45 to 55% without catalyst) as it is well known that CH_4 is hardly converted by the catalyst). Therefore, the evaluation of the methane free OGC reduction showed a significantly higher emission reduction (in the range of 56 to 93%) under the consideration that CH_4 is not converted by the foam ceramic.

Foam ceramic 3 – coated with tailor-made catalyst II – Summary (V)

- The evaluation of the flue gas temperature upstream the catalyst and the CO emission reductions achieved shows, that the light-off temperature of the catalyst is in the range of about 630°C. There no clear indication that the light-off temperature depends on the operation time.

- Regarding OGC-emissions the light-off temperatures seem to be in the same range as for the CO emissions.

- An inspection of the foam ceramic after 2 weeks of operation revealed some fly ash deposits on the surface of the foam ceramic ➔ reason for the increasing pressure losses.

- By manual cleaning most of the fly ash deposits could be successfully removed. After manual cleaning the pressure drop over the foam ceramic could be reduced again.

Foam ceramic 3 – coated with tailor-made catalyst II – Summary (VI)

- Therefore, manual cleaning of the foam ceramic at least every two weeks of operation would be necessary in order to stabilise the pressure drop over the foam ceramic (based on the test run results so far).

- Concluding, the catalytically-coated foam ceramic II showed sufficiently high emission reduction efficiencies regarding CO and OGC only at the beginning of the operation. The emission reduction efficiency decreased for the catalyst over the operation time. After 16 days of operation the reduction efficiency regarding CO was still sufficiently high (73% at nominal load and 79 % at partial load) but regarding OCG the reduction efficiency was only at a moderate level (38% at nominal load and 33 % at partial load).

- As tailor-made catalyst I showed more stable reduction efficiencies regarding CO and OGC, although the Pt content of catalyst I is lower than for catalyst II, tailor-made catalyst II will not be further considered (also due to the higher costs regarding Pt doping).

Foam ceramic 3 – coated with tailor-made catalyst II – Summary (VII)

- Furthermore, the pressure drop over the coated foam ceramic is quite high and moderately increased after two weeks of operation due to fly ash deposits on the surface of the foam ceramic.
- In general, the pressure of the foam ceramic has to be considerably reduced in order to be implemented in a natural draft logwood stove.

Results of the test runs with a logwood stove and different catalysts

CONCLUSIONS REGARDING THE TEST RUNS

WITH FOAM CERAMICS

(non coated and catalytically coated)

Conclusions (I)

- Test runs with a non-coated and two catalytically coated foam ceramics (Tailor-made catalyst I and II) as well as a test run with the stove without integrated foam ceramic have been performed.
- The evaluation of the stove operation data showed, that all test runs have been performed under well comparable and representative combustion conditions.
- The foam ceramics showed no effect on the efficiency of the stove (as expected).
- The non-coated foam ceramic showed no emission reduction efficiencies regarding CO, OGC and TSP and showed no relevant influence on the stove operation (except the increased pressure drop).

Conclusions (I)

- **Pressure drop:**
  - **The catalytically coated foam ceramics showed a higher initial pressure drop (+8.7 Pa at full load) compared to the non-coated foam ceramic due to the coating of the foam ceramic with the washcoat and the catalyst.**
  - **For all three foam ceramics the pressure drop increased with operation time**
    - Non-coated foam ceramic: slight increase (from 17.0 to 17.5 Pa)
    - Catalyst I: slightly higher increase (from 26 to 29 Pa after 2 weeks)
    - Catalyst II: slightly higher increase (from 24 to 27 Pa after 2 weeks)
  - **The increase of the pressure drop seems most likely due to the optically determined fly ash deposits built-up on the foam ceramic surface.**
  - **Manual cleaning decreased the pressure drop again**
    - Catalyst I and II: successful removal of the ash deposits → the initial pressure drop could be reached after cleaning
  - **Manual cleaning of the foam ceramic at least every two weeks of operation would be necessary in order to stabilise the pressure drop over the foam ceramic (based on the test run results so far).**

Conclusions (III)

- **CO-emission reduction:**
  - **Both catalysts showed high CO emission reduction efficiencies during the first days of operation (of about 90%).**
  - **The emission reduction efficiency considerably decreased for both catalysts and manual cleaning showed no positive effect. However, the reduction efficiencies have been still sufficiently high after 2-3 weeks of operation.**
    (data for nominal load: at start → after 2 weeks → after 3 weeks)
    - Catalyst I: 90% → 80% → 73%
    - Catalyst II: 90% → 78% → 69%
  - **Consequently, Catalyst I showed a more stable CO reduction efficiency and less deactivation than catalyst II.**

Conclusions (IV)

- **OGC-emission reduction:**
  - **Both catalysts showed good OGC emission reduction efficiencies during the first days of operation. Catalyst II was with about 52% (at full load) slightly more efficient than catalyst I (about 48%) probably due to the higher Pt doping.**
  - **The emission reduction efficiency significantly decreased for catalyst II while it only slightly decreased for catalyst I. Manual cleaning showed no positive effect.**
    (data for nominal load: at start → after 2 weeks → after 3 weeks)
    - Catalyst I: 48% → 49% → 38%
    - Catalyst II: 52% → 40% → 27%
  - **The higher Pt-content of catalyst II in comparison to catalyst I seems to improve the initial OGC-emission reduction efficiency but after 3 weeks the reduction efficiency of catalyst II was considerably lower than for catalyst I.**

BIOS

Conclusions (V)

ERA-NET Bioenergy

- **OGC emission reduction (cont.):**
  - **Again, the share of CH_4 on the OGC emissions increases downstream the catalyst up to 90% as it is well known that CH_4 is hardly converted by the catalyst (same behaviour as for metal based catalysts). Therefore, the evaluation of the methane free OGC reduction showed a significantly higher emission reduction (in the range of 52 to 92%) under the consideration that CH_4 is not converted by the tested catalytically coated foam ceramics or the applied metal based catalysts.**
- **Concluding, the catalytically-coated foam ceramic I showed sufficiently high and rather stable emission reduction efficiencies regarding CO and OGC and therefore this catalyst seems basically to be suitable for logwood fired stoves. Tailor-made catalyst II will not be further considered (also due to the higher costs regarding Pt doping).**
- **However, the pressure drop over the coated foam ceramic is quite high and moderately increased after two weeks of operation due to fly ash deposits on the surface of the foam ceramic.**

Conclusions (VI)

- Although the performance of the catalyst seems to be satisfactory so far, the pressure drop of the foam ceramic is currently too high for natural draft systems and has to be considerably reduced.
- By changing the geometry of the ceramic structure or by applying a foam ceramic with wider pores the tailor made catalyst I seems to be suitable for the implementation into logwood fired stoves.

Results of the test runs with a logwood stove and different catalysts

Recommendations

Recommendations (I)

- The commercially available catalyst EnviCat® of Clariant is not recommended due to the rather high prize (500 € for a single unit) and its moderate emission reduction efficiency.

- The implementation of a high temperature catalyst at the outlet of the post combustion chamber (temperature range of about 500 °C) is not recommended as tests showed unstable reduction efficiencies.

→ **Decreasing reduction efficiencies over time can most likely be attributed to catalyst de-activation as a consequence of blocking of active centres caused by aerosol condensation**

- High temperature catalysts, which are mounted at the outlet of the main combustion chamber (temperature range 600 - 800 °C) showed sufficiently high emission reduction efficiencies regarding CO (69 – 73%) and OGC (27 – 38%) and seem basically to be suitable for logwood stoves.

Recommendations (II)

- In particular, a catalytically-coated foam ceramic, which was mounted at the outlet of the main combustion chamber (temperature range 600 - 800 °C), showed sufficiently high and almost stable emission reduction efficiencies regarding CO and OGC over 3 weeks and therefore this catalyst seems basically to be suitable for logwood stoves.
- However, the emission reduction efficiency decreased for the catalysts over the testing period of about 100 hours of operation and manual cleaning showed no positive effect
- Tests over a whole heating period would be needed to be able to evaluate the long-term performance of catalysts in wood stoves as well as the possible need of cleaning.

Recommendations (III)

- Furthermore, catalysts need enough surface to achieve a sufficient reduction efficiency. This is usually provided by narrow channels which cause a certain pressure drop. The pressure drops are usually too high for an operation of the stove with natural draught only.
- Therefore, either a flue gas fan is needed if a catalyst should be integrated or the dimension of the catalyst needs to be increased.
- In general, the mounting position of integrated catalysts has to be carefully evaluated in terms of operating conditions (existing temperature), materials used and the availability to clean the catalyst.

ERA-NET Bioenergy

Evaluation of the long-term feasibility of foam ceramic filters or their replacement by a catalyst insert

Prepared by: Robert Mack, Hans Hartmann (TFZ Straubing)

Table of contents

- Material and Methods
  - Dummy production
  - Pretesting of flue gas flow path
  - Testing procedure used and evaluation
- Test results
  - Foam ceramics
  - Catalytic coated foam ceramics
- “Long term” test cycle
  - Method description
  - Test results
- Final conclusions

Filter material for measurement of long-term feasibility

New foam ceramic

Porosity: 35 ppi

Foam ceramic
after 200 batches

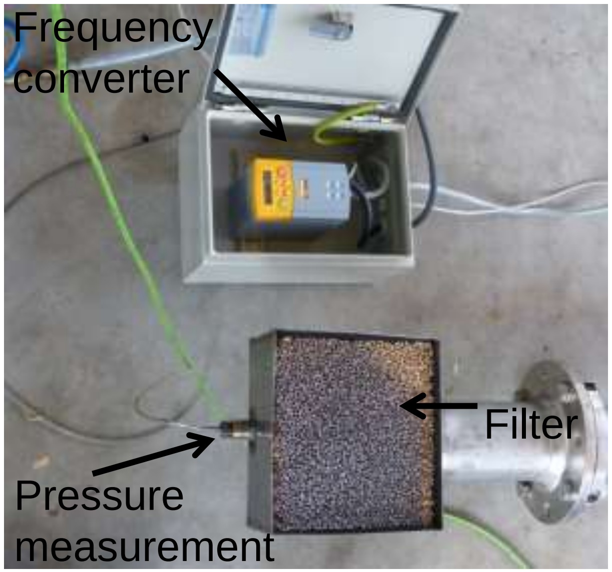
Foam ceramic after
2 heating seasons
Approx. 550 batches
(Filter had been washed after
1st heating season)

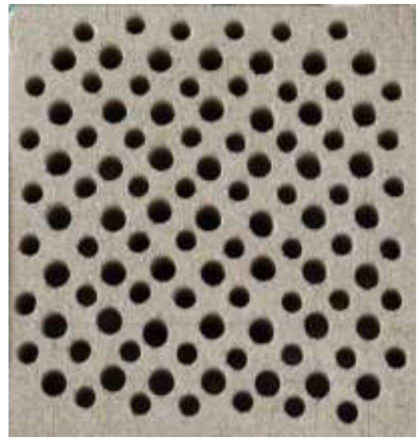
Retrofit catalyst for stoves using foam ceramic filters

Product specification data as declared by manufacturer:

Manufacturer	Linder Katalysatoren GmbH
Thermal resistance	> 1450 °C
Carrier material	SiC- foam ceramic (SiC – SiO_2 + 3 C → SiC + 2 CO and Al_2O_3) (Al_2O_3 components fired at 2300-2500°C)
Coating	Platinum (Pt78), Palladium (Pa45), Rhodium (Rh46)
Reduction	CO, OGC, NO_x, PM
Structure	> 70% open porous surface
Porosity	PPI 8, PPI 10, PPI 20, PPI 30,

Construction of an equivalent flow reduction ("Dummy"-Filter)



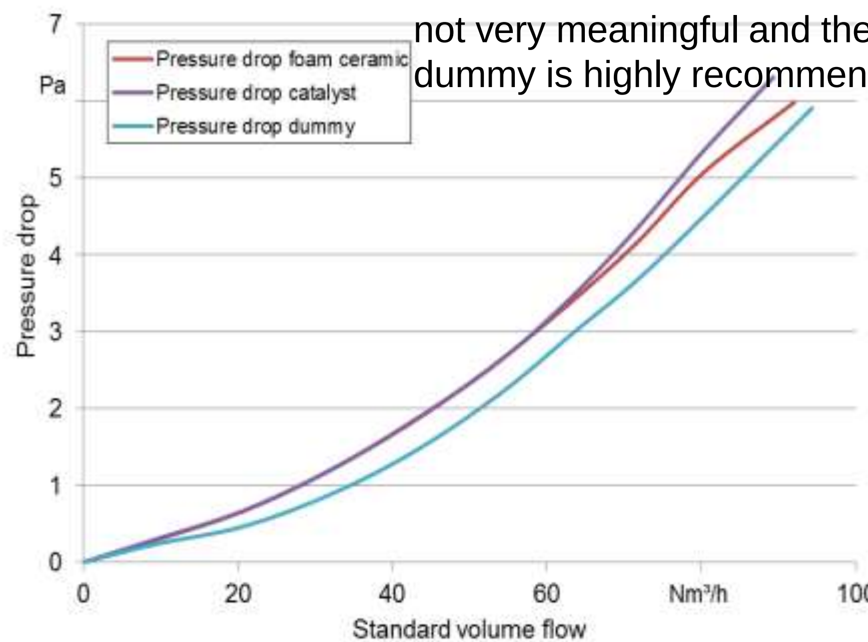


TFZ-Dummy:

Material: Vermiculite (25 mm)

Drill holes: 8 and 10 mm

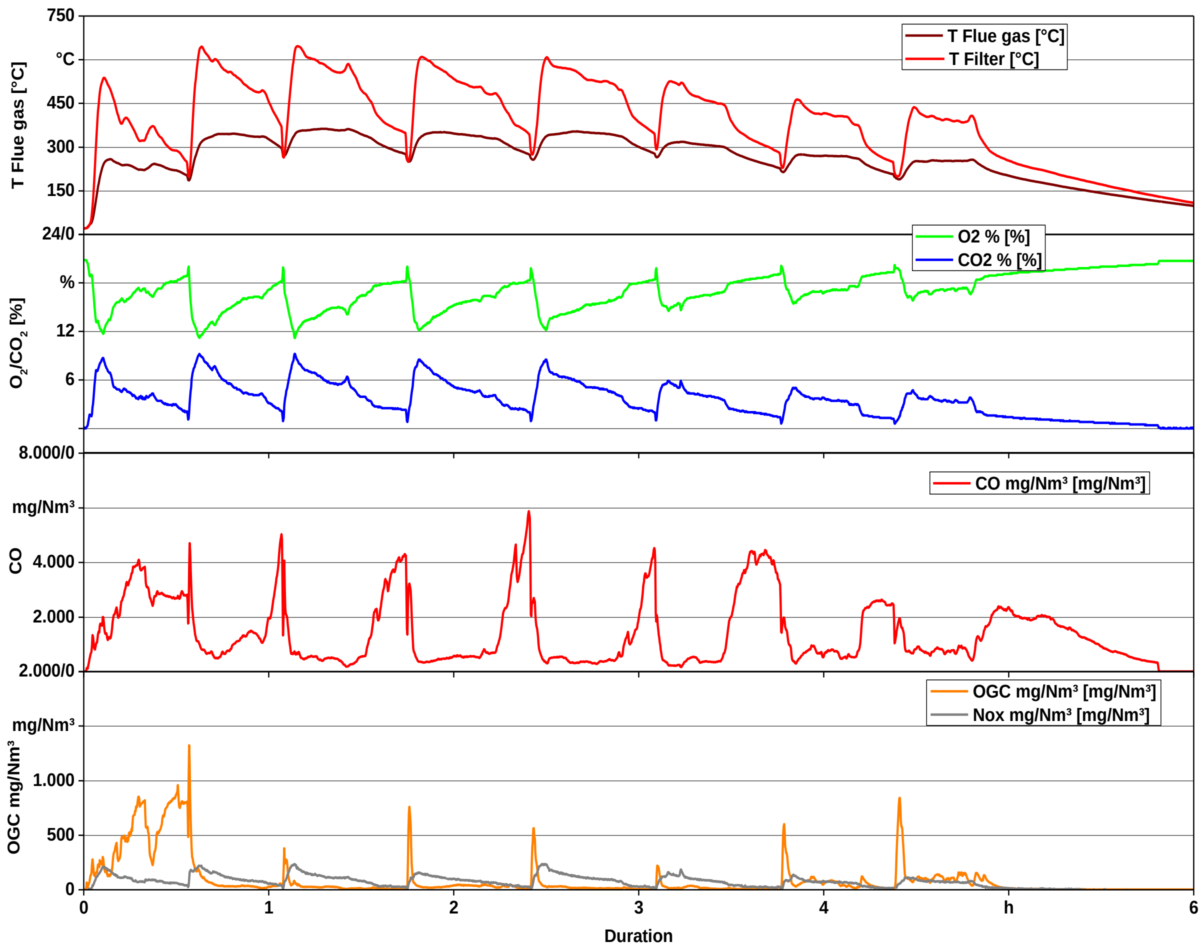
The pressure drop by the Dummy is very similar to the foam ceramic and the catalyst. This is very important when comparing results with and without catalyst, to ensure the same flow conditions in both cases. Reference measurements without using a Dummy are not very meaningful and therefore the use of a dummy is highly recommended.



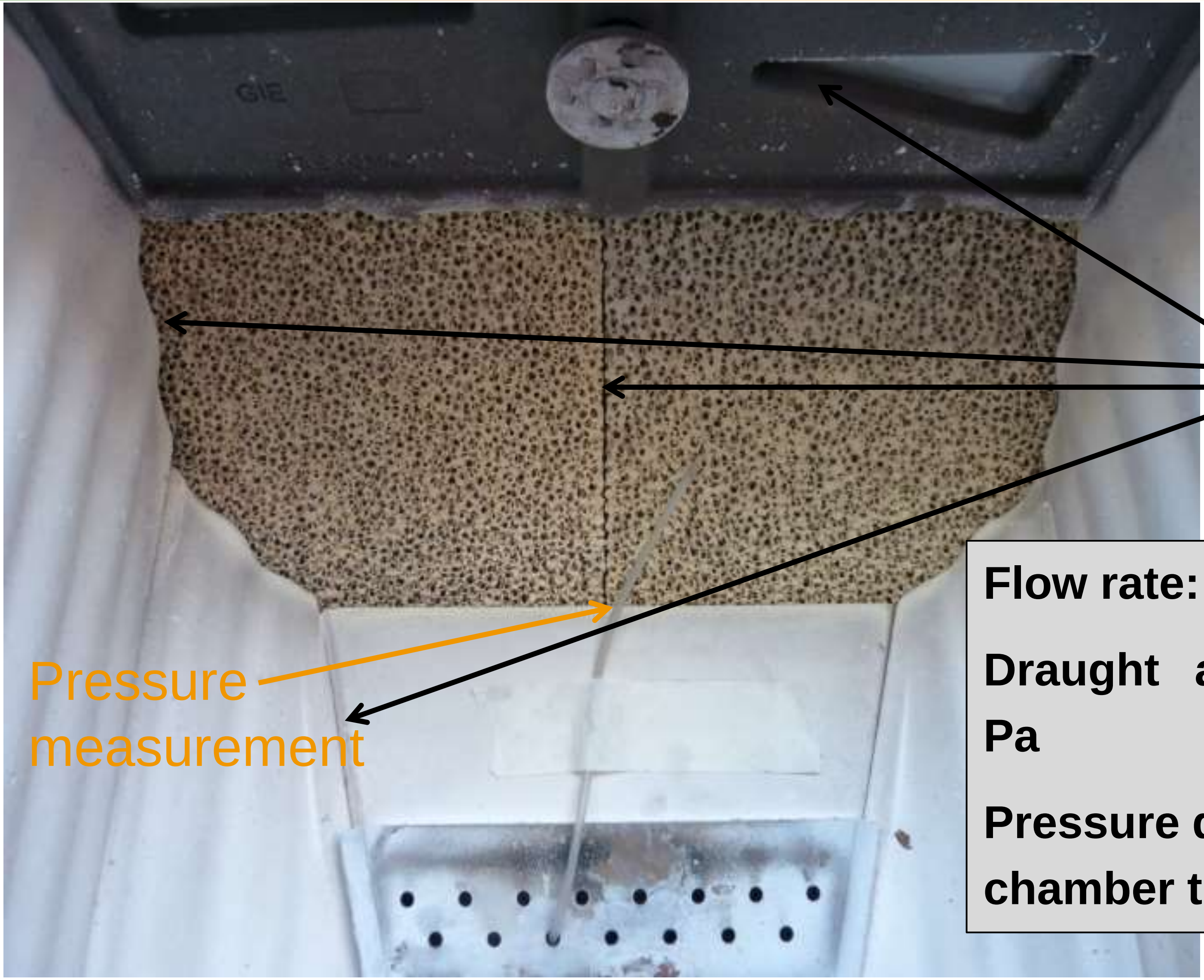
Construction of an equivalent flow reduction ("Dummy"-Filter)

- The pressure drop by the Dummy has to be very similar to the foam ceramic and the catalyst. This is very important when comparing results with and without catalyst, to ensure the same flow conditions in both cases.
- Reference measurements without using a Dummy are not very meaningful and therefore the use of a dummy is highly recommended.

Measurement of filter temperature



Determination of the actual flue gas flow path



Flow rate: 35.4 Nm³/h

Draught at socket: -11.8 Pa

Pressure drop, burning chamber to socket: 3.2 Pa

Determination of the actual flue gas flow path (2)

1. Masking the filter plates with air tight tape

Flow rate: 33.9 Nm³/h

Draught at socket: -11.9 Pa

Pressure drop, burning chamber to socket: 3.8 Pa

Determination of the actual flue gas flow path (3)

2. Masking all suspected leakages with air tight tape

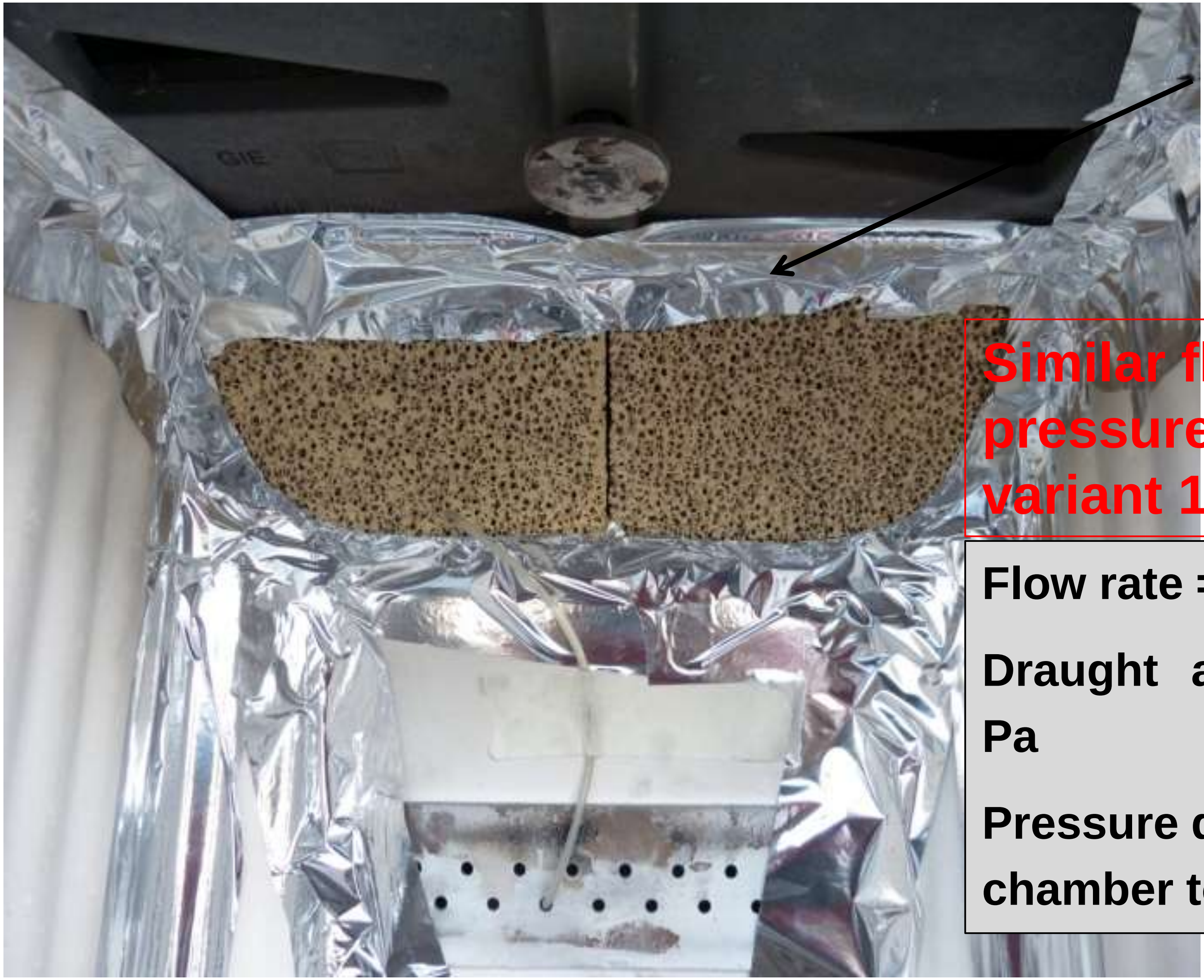
Flow rate ↓pressure drop ↑

Flow rate = 21.2 Nm³/h

Draught at socket = -11,8 Pa

Pressure drop, burning chamber to socket: 9.1 Pa

Determination of the actual flue gas flow path (4)



3. Cutting the air tight tape from the filter plates

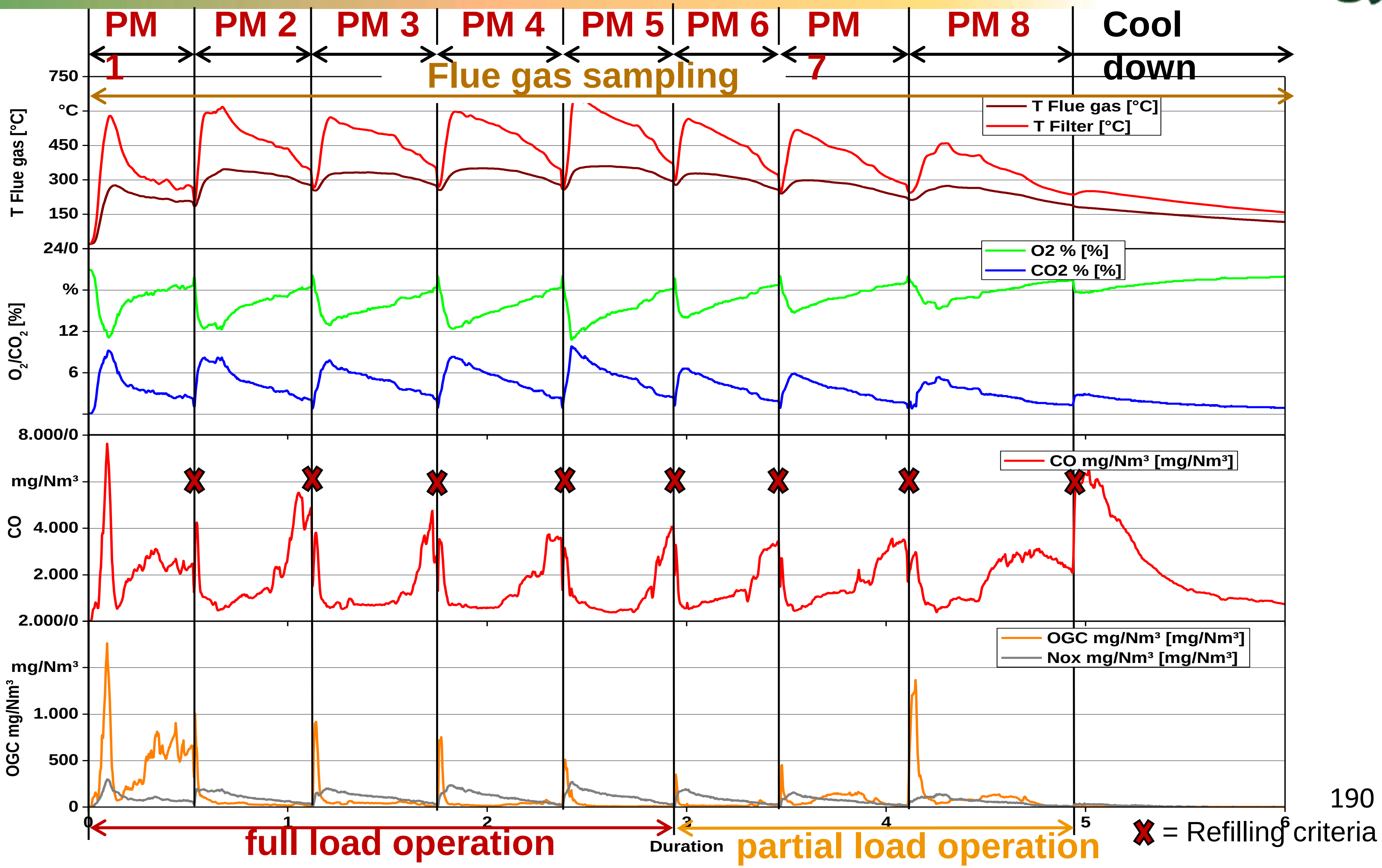
Similar flow rate and pressure drop to variant 1.

Flow rate = 33.9 Nm³/h

Draught at socket: -12.0 Pa

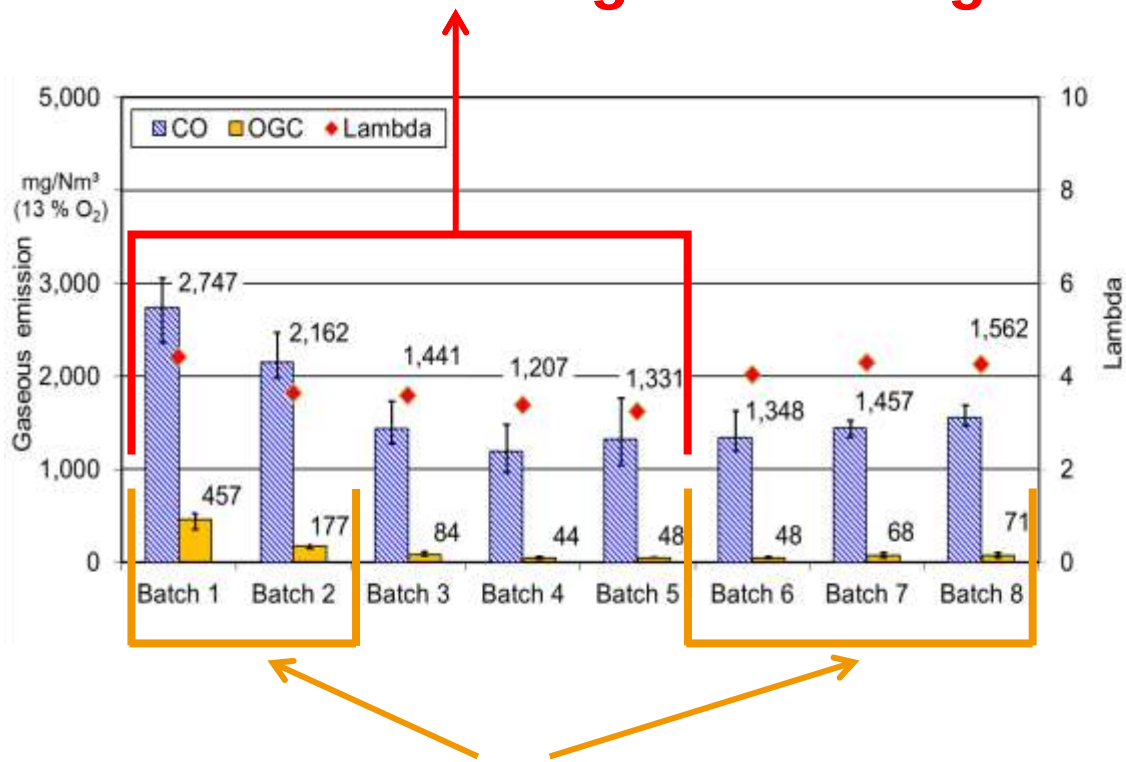
Pressure drop, burning chamber to socket: 3,9 Pa

Flowchart of the testing procedure used



Evaluation of measuring cycle (full load and part load)

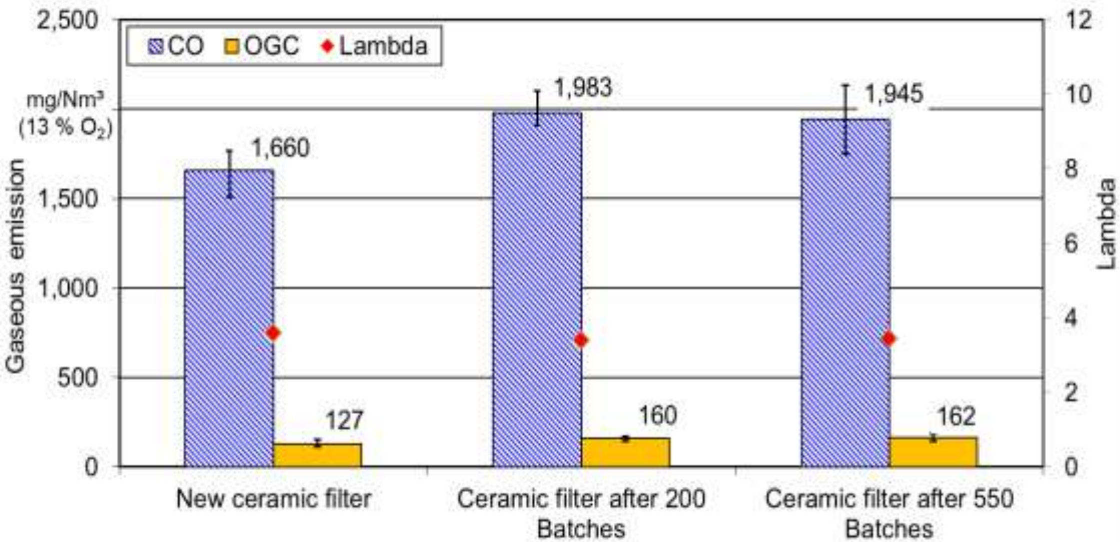
Full load: time weighted average value of batch 1-5



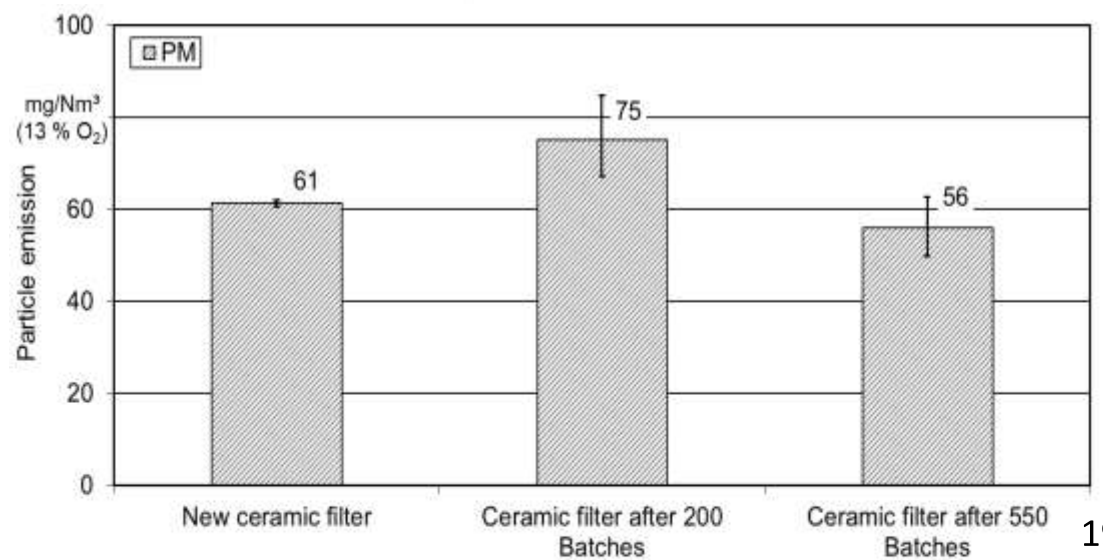
Each testing cycle existing of 8 successive batches (5 full load, 3 part load) including the ignition batch. Gaseous emissions will be measured continuously over the complete cycle. Particle measurement over each complete batch. Evaluation in mg/Nm³ at 13 % O_2.

Part load: time weighted average value of batch 1,2,6,7,8

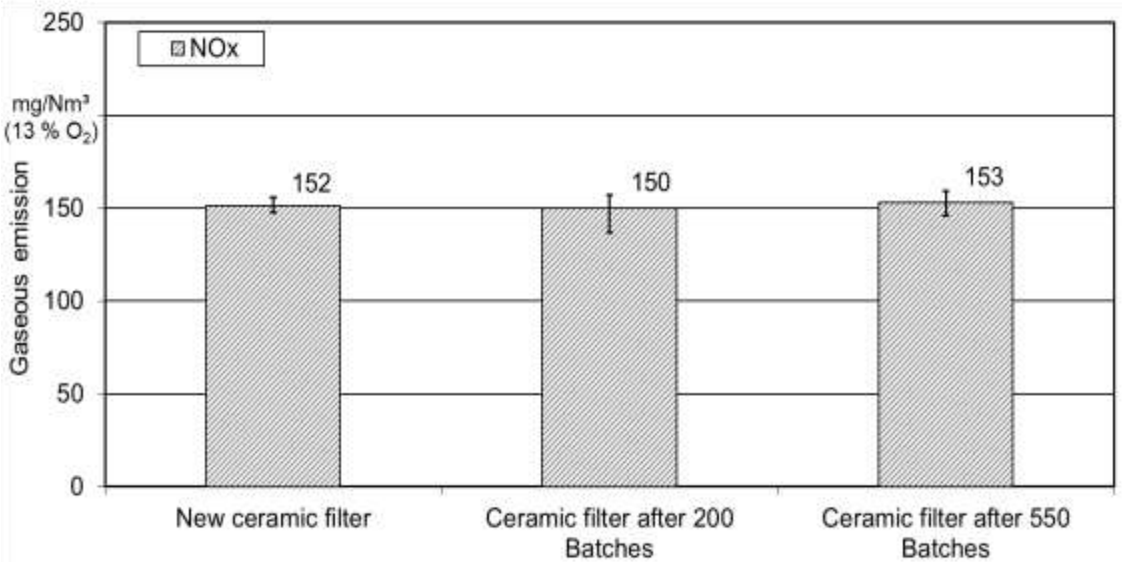
Comparison of foam ceramic filters: Full load cycle (1)

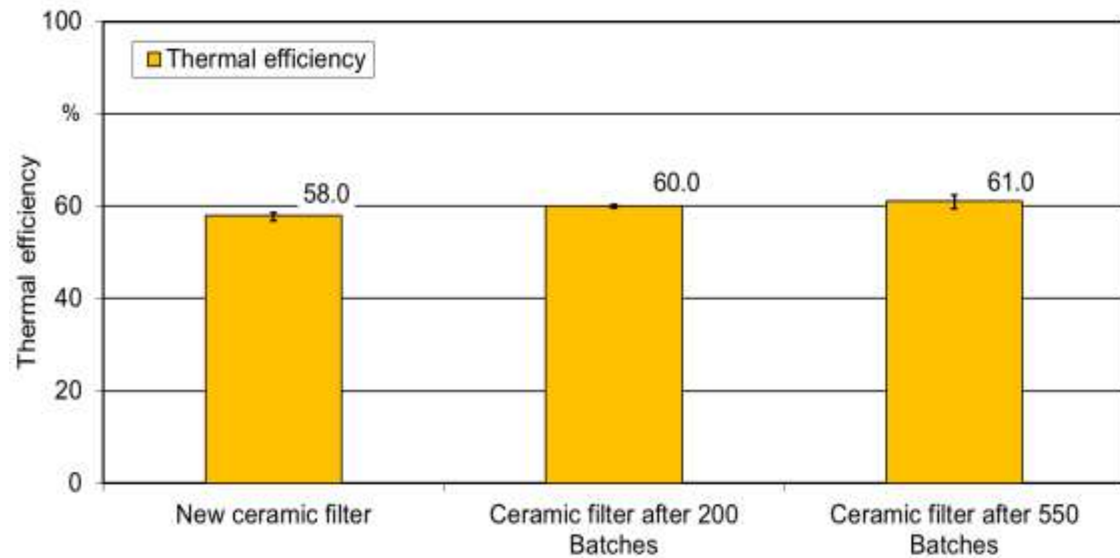


- 3 testing days per filter
- All tests at natural draught
- One weighted average value of batch 1-5
- Same damper settings for all tests
- Test fuel: Beech with bark
- PM sampling starts before refilling and ends before next refilling

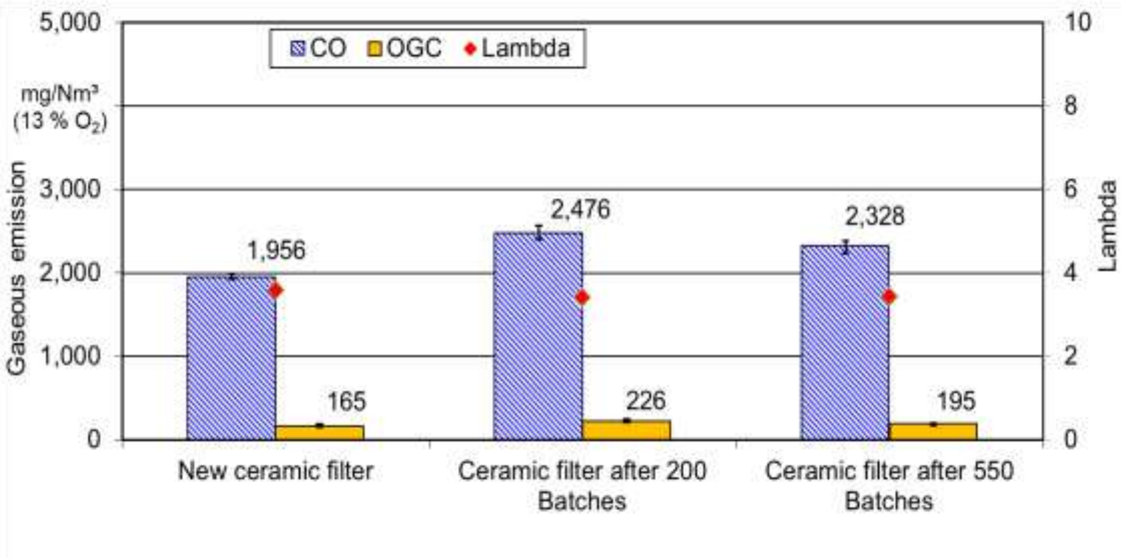


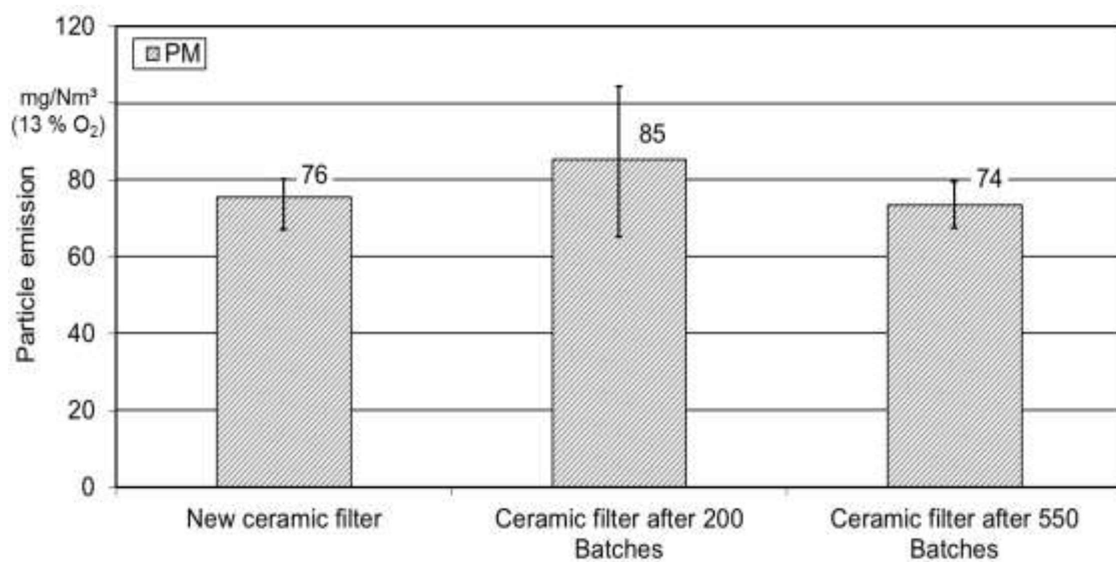
Comparison of foam ceramic filters: Full load cycle (2)





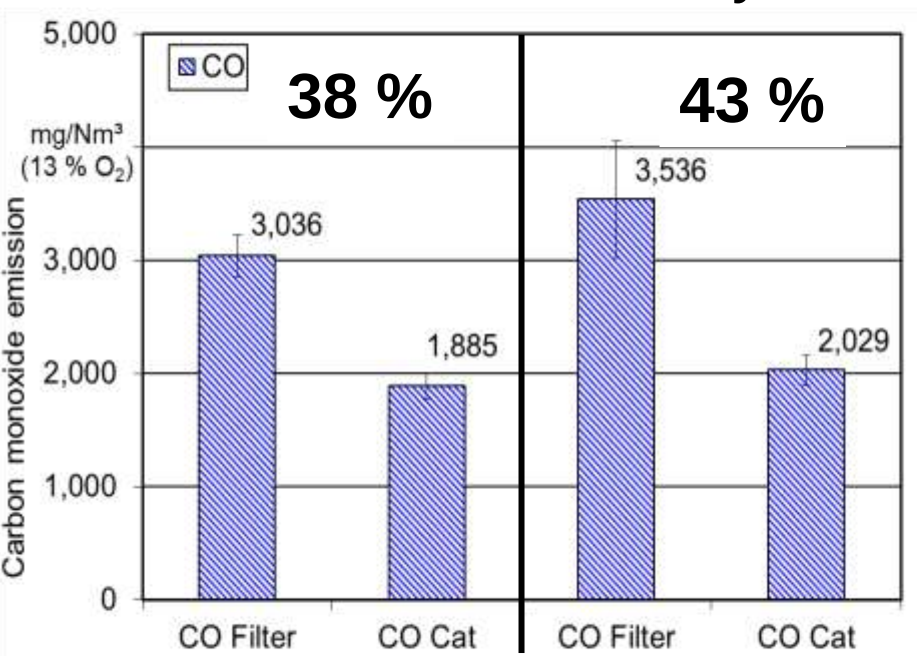
Comparison of foam ceramic filters: Part load cycle (1)





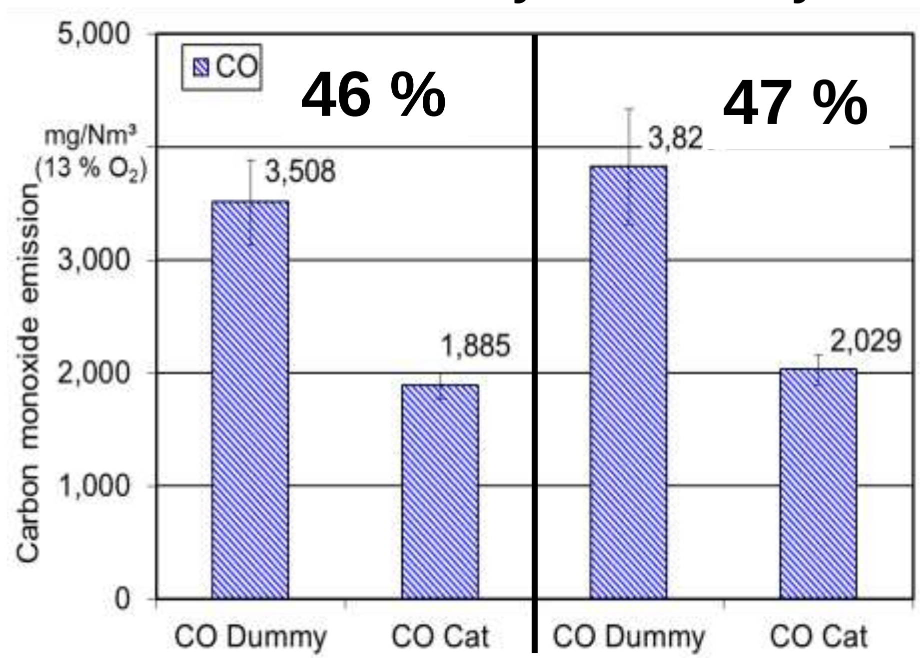
Catalytically coated foam ceramic: CO conversion

Filter → Catalyst



Nominal load Partial load

Dummy → Catalyst

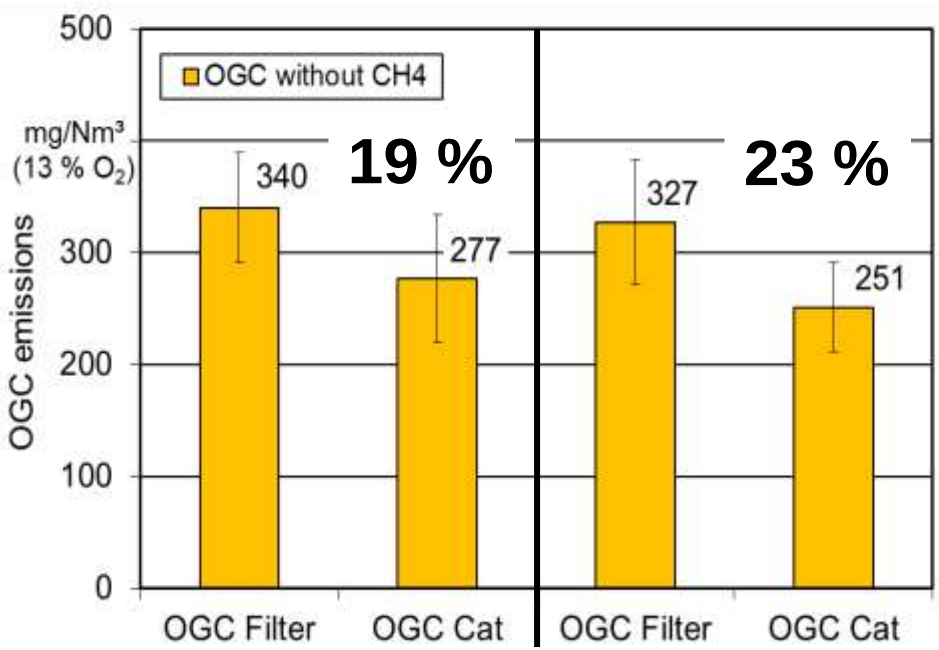


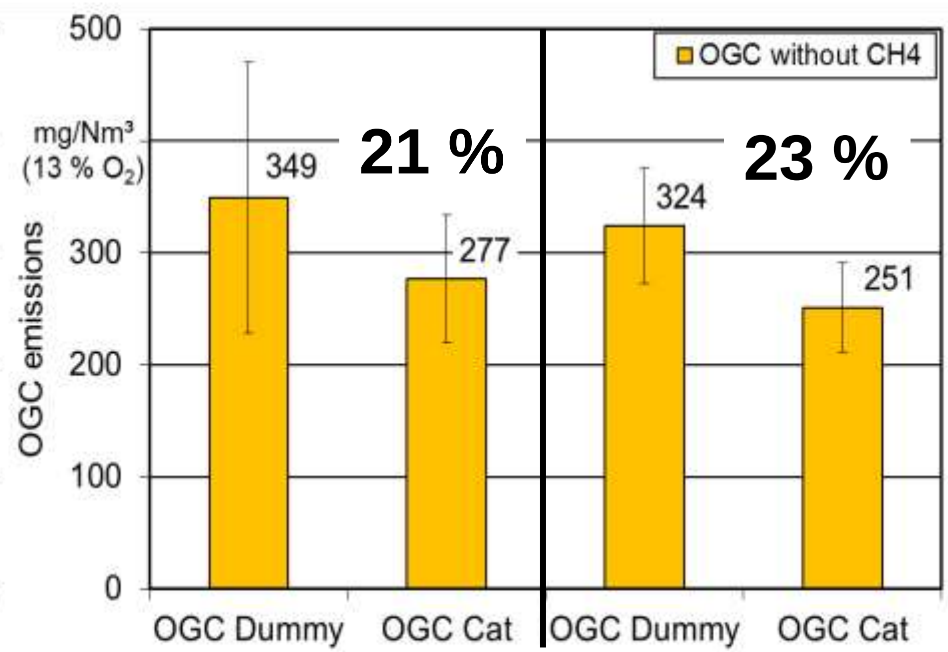
Nominal load Partial load

Catalytically coated foam ceramic: : Non-Methane-OGC conversion

Filter → Catalyst

Dummy → Catalyst

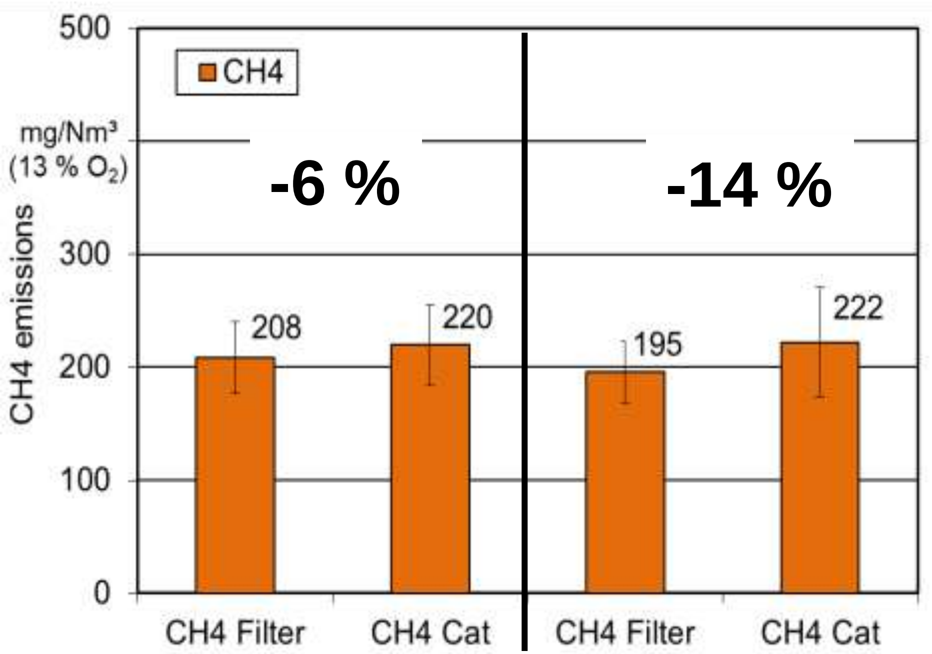




Nominal load Partial load Nominal load Partial load

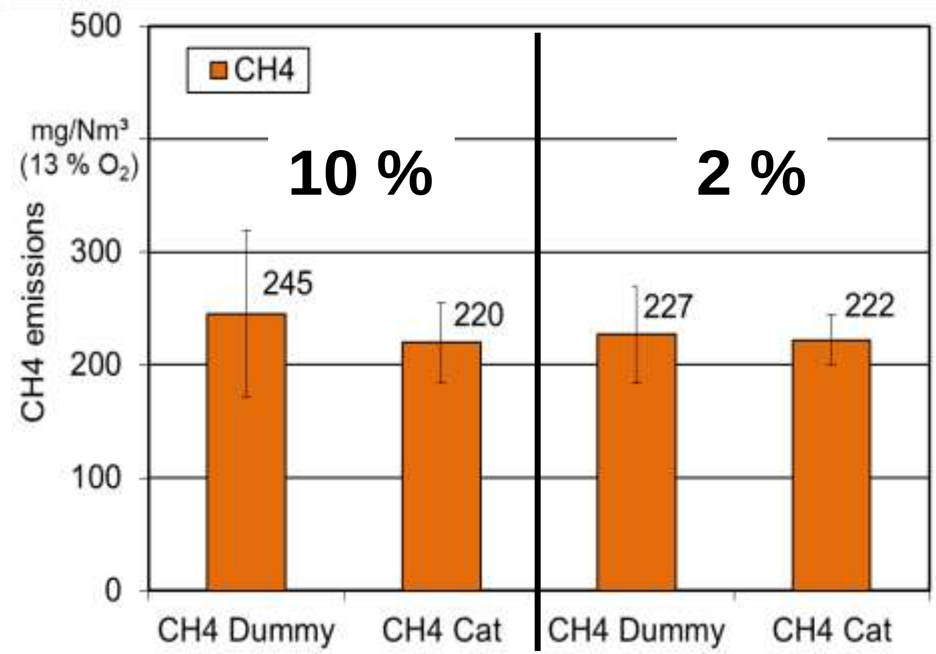
Catalytically coated foam ceramic: Methane conversion

Filter → Catalyst



Nominal load Partial load

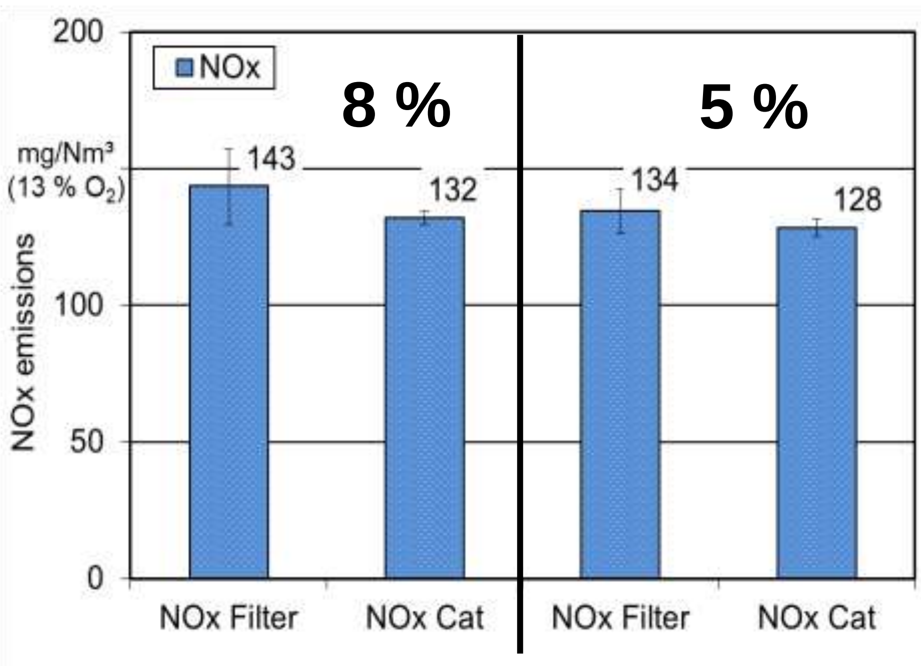
Dummy → Catalyst



Nominal load Partial load

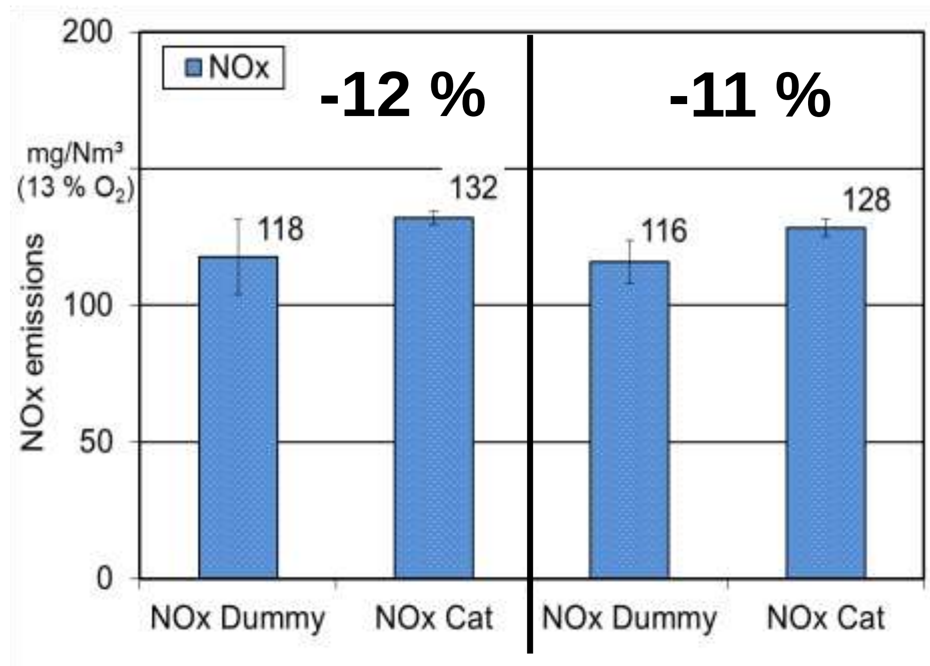
Catalytically coated foam ceramic: NO_x conversion

Filter → Catalyst



Nominal load Partial load

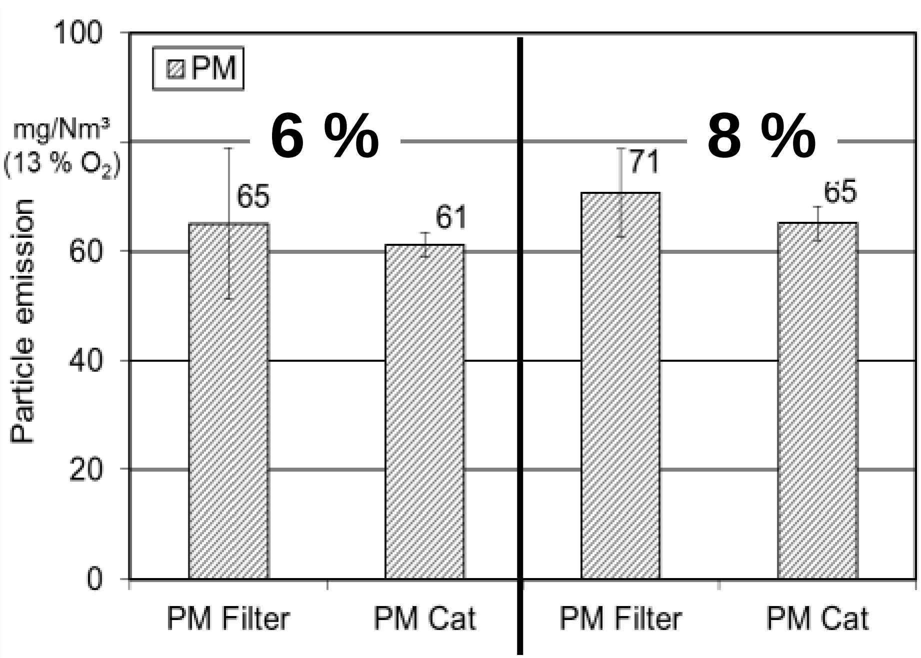
Dummy → Catalyst



Nominal load Partial load

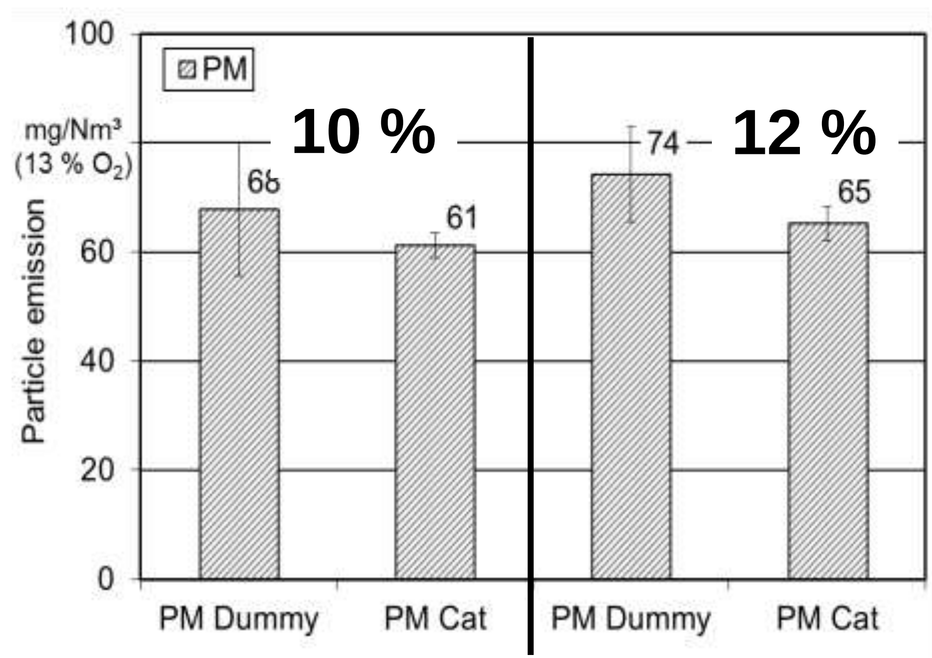
Catalytically coated foam ceramic: PM reduction

Filter → Catalyst



Nominal load Partial load

Dummy → Catalyst

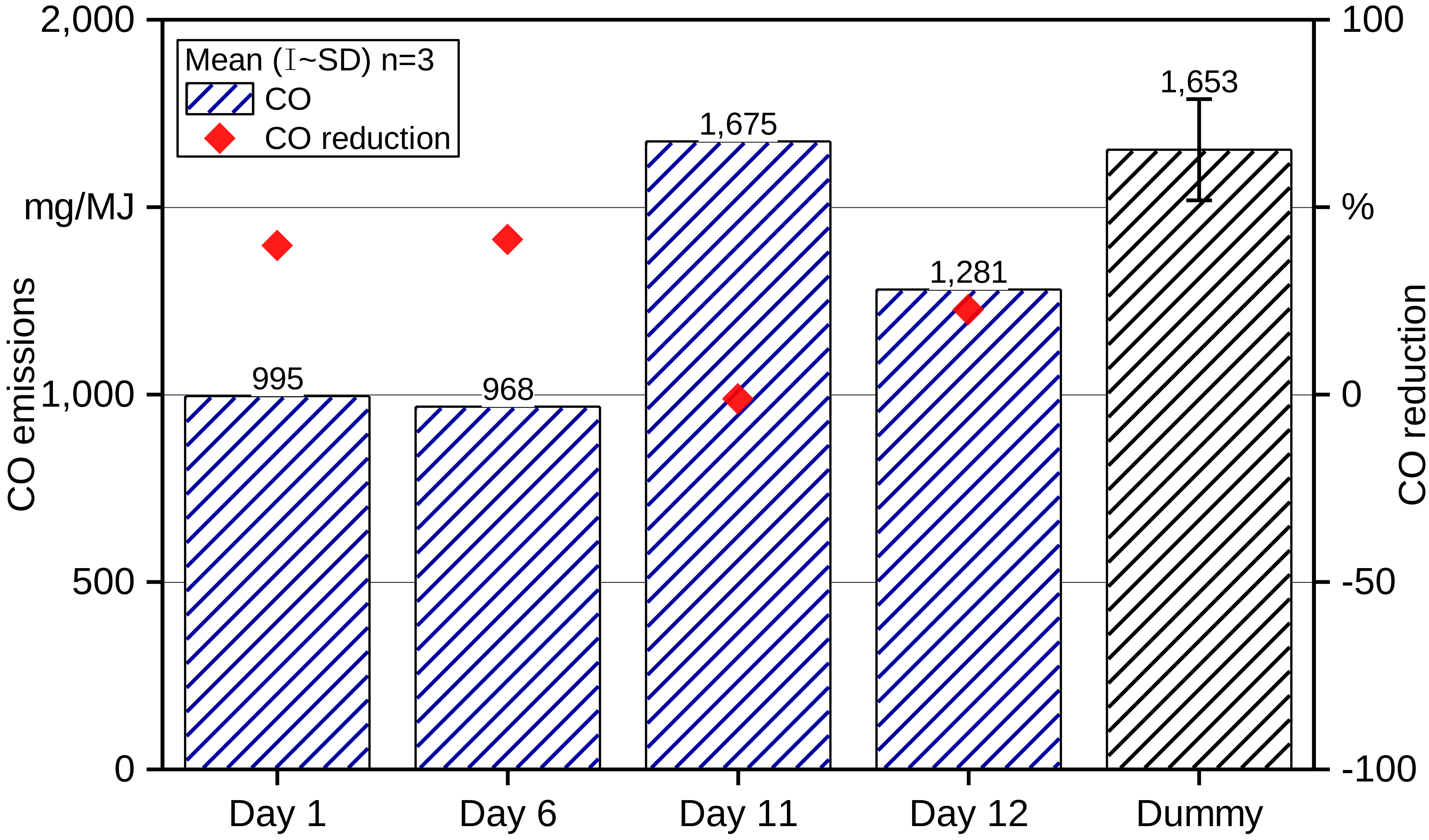


Nominal load Partial load

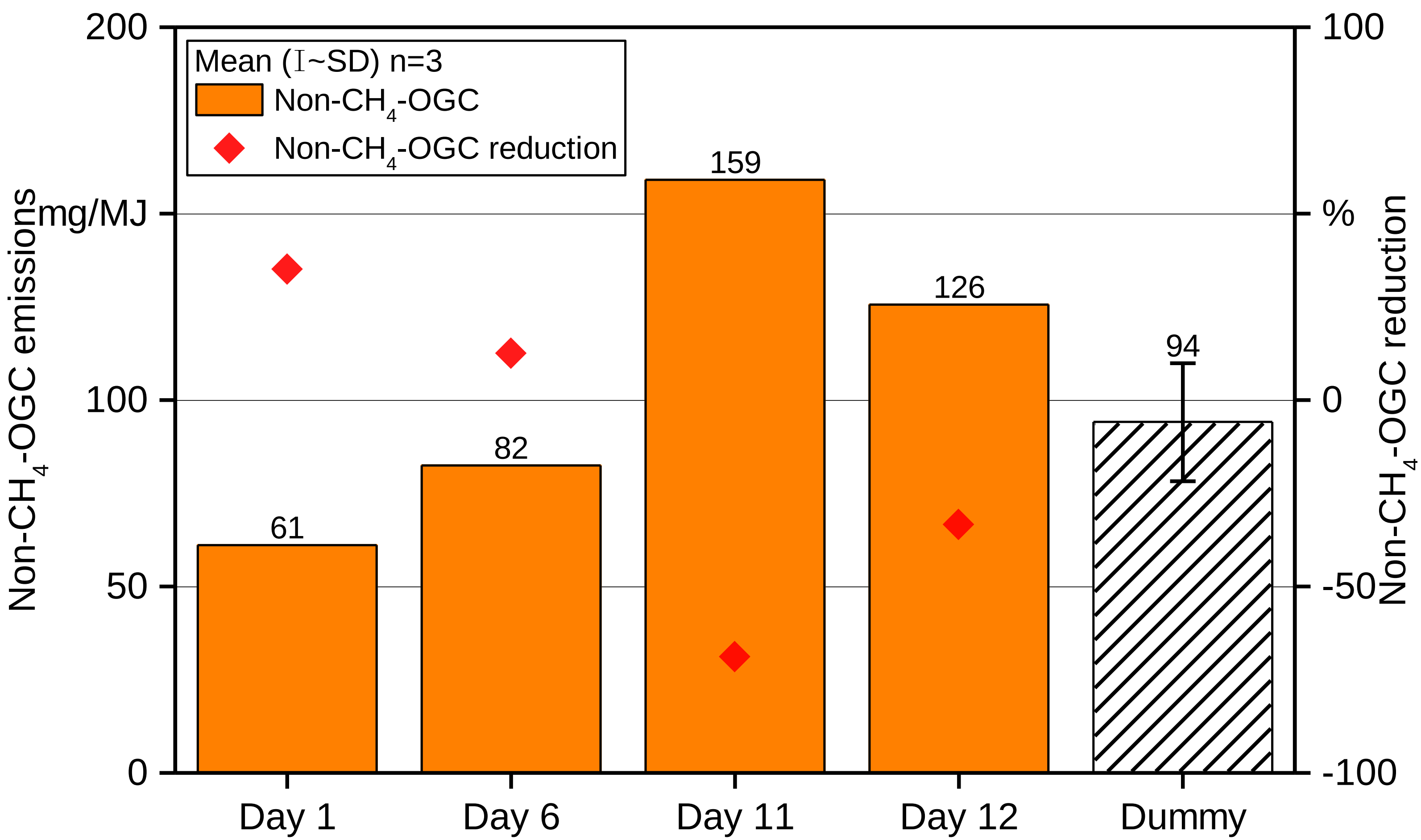
Estimation of long-term behavior by using a 2 weeks test cycle

- For a first estimation of long term behavior the catalyst has been tested by using a 2 week testing cycle.
  - 1st day of operation (day 1 with catalyst + 1 test with dummy)
  - after one week of operation (day 6 with catalyst + 1 test with dummy)
  - after two weeks of operation (day 11 with catalyst + 1 test with dummy)
  - after manual cleaning of the catalyst after 2 weeks operation (day 12 with catalyst + 1 test with dummy)
- Between and while the testing days the stove has been operated according the method described in slide “flowchart of the testing method” which means 8 successive batches (5 full load, 3 part load) including the ignition batch.
- For the “long term” test runs the emissions have been evaluated in mg/MJ based on volume flow and converted fuel mass.

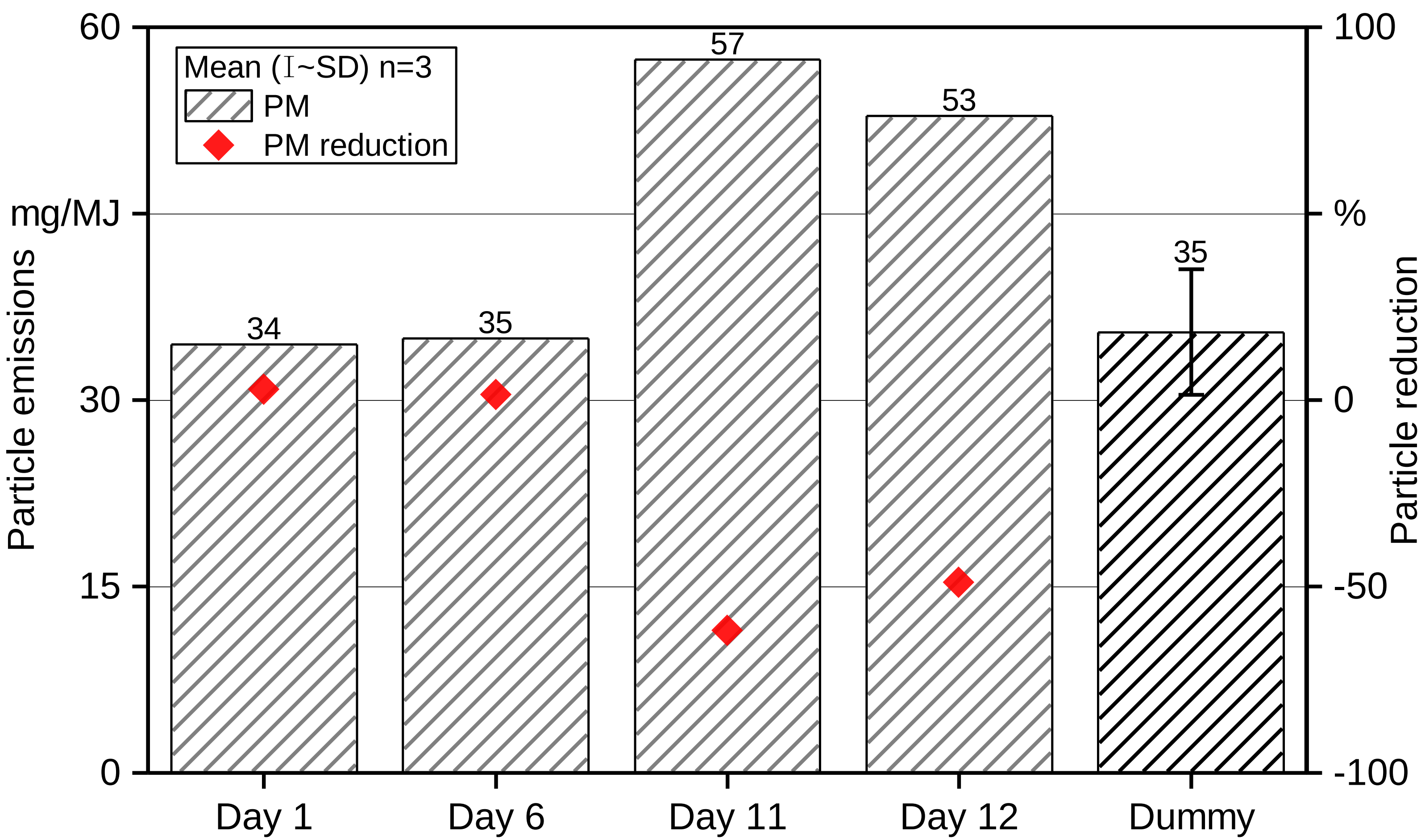
Aging effects within a 2 weeks test cycle: CO reduction



Aging effects within a 2 weeks test cycle: Non-methane OGC reduction



Aging effects within a 2 weeks test cycle: Methane reduction



Final conclusions (I)

- Expectations for PM reductions by foam ceramic elements were not met (particularly for non-catalytic elements).
- Catalytic foam ceramic elements can reduce gaseous flue gas emissions (CO, OGC).
- The first results on long-term testing have shown a significant decrease of the reduction rates.
- This could not be completely regenerated by manual cleaning of the catalyst.
- Long-term monitoring of this effect is required (field tests).
- Regarding the flue gas flow through the foam ceramics there is still some potential for optimization.

Final conclusions (II)

- It is desirable to achieve higher surface temperatures (> 700 °C) on catalytic elements in order to improve reduction efficiencies
- Retrofitting of catalytic foam ceramic elements may be an interesting option if long-term tests at higher temperatures are successful

Selection and testing of medium temperature metal based mesh catalysts and different honeycomb catalysts for stoves

Prepared by: Ingmar Schüßler (RISE Research Institutes of Sweden AB)

Catalyst evaluation at RISE
Content

- **Background & Motivation**
- **Evaluation in catalyst test rig**
  - **Initial testing**
  - **Prolonged testing**
  - **Tests with reduced area**
  - **Tests with different catalyst models**
- **Evaluation of stove integrated catalyst**
- **Conclusion & Recommendations**

Catalyst evaluation at RISE
Background/Motivation

Why looking at secondary measures?

- Emissions of unburned components from stove operation, especially at start & end of single batches, cannot totally be avoided by primary measures, even with best designs
- Further particle reduction at low levels is hard to achieve only by applying primary measures
- User induced errors in operation (for example wrong wood amount or wood condition) can result in significant increase in emissions
- Aiming for a fast & affordable solution for improving existing stoves and stove models without the possibility for design changes

Commonly mentioned secondary measures

- Particle filters, as for example ceramic filters, have been introduced in some commercially available stoves
- Catalysts are integrated in several stoves available on the North American market

Catalyst evaluation at RISE
Background/Motivation – Ceramic Filters

Literature study

- **Contradictory statements; some reports claim noticeable particle reduction, others did not observe an improvement with implementing ceramic filters**

Pretest

- **Comparative test run with vs. without ceramic filter**
  - Same stove, same test procedure (wood mass, moisture, dampers, etc.); 1st test day with filter; 2nd test day with vermiculite plate, designed to achieve same conditions in combustion chamber as with filter (same air flow, same flow resistance)
- **No indication for a noticeable improvement regarding particle emissions (measured with Pegasor online instrument) → Path not further considered**

	Batch		7	8	9	10	11	Ø
Filter	Flue gas temperature	°C	269	269	270	283	279	274
	CO_2	%	7.7	7.7	7.8	7.0	6.4	7.3
	CO at 13% O_2	mg/m^3_N	993	1137	1038	679	1054	985
	OGC at 13% O_2	mg/m^3_N	130	181	128	66	112	125
	PM at 13% O_2	mg/m^3_N	70	62	59	55	40	57
No Filter	Flue gas temperature	°C	270	270	274	288	288	278
	CO_2	%	7.0	7.6	7.6	7.1	7.2	7.3
	CO at 13% O_2	mg/m^3_N	941	570	520	689	695	688
	OGC at 13% O_2	mg/m^3_N	97	42	56	51	67	67
	PM at 13% O_2	mg/m^3_N	48	61	37	58	56	52

Catalyst evaluation at RISE
Background/Motivation – Catalyst

Literature study

- **Long term experience with catalysts on American market; commonly used for reducing particles (American standard method with dilution tunnel)**
- **Catalysts have been evaluated in several projects identifying advantages and challenges (reduction capacity, long-term durability, flow resistance)**

Pretest

- **Comparative test run with vs. without catalyst (simple mesh in baffle plate)**
  - Same stove, same test procedure (wood mass, moisture, dampers, etc.); 1st test day with catalyst; 2nd test day with same baffle plate but without catalyst
- **Noticeable improvement regarding CO, but no clear statement regarding HC**
- **Noticeable particle reduction at Norwegian standard test (dilution tunnel)**

Batch			2	3	4	5	Ø
Catalyst	Flue gas temperature	°C	257	247	231	229	241
	CO_2	%	9.7	9.0	7.9	7.9	8.7
	CO at 13% O_2	mg/m^3_N	1456	1409	1817	1995	1667
	OGC at 13% O_2	mg/m^3_N	151	201	256	282	222
No Catalyst	Flue gas temperature	°C	259	236	229	232	239
	CO_2	%	8.9	7.9	8.0	8.0	8.2
	CO at 13% O_2	mg/m^3_N	2953	2829	2743	3173	2925
	OGC at 13% O_2	mg/m^3_N	190	402	191	321	276

Catalyst evaluation at RISE
Overall evaluation procedure

- **Choice of catalyst**
  - **Metal based mesh catalyst**
- **Evaluation in catalyst test rig**
  - **Control check of test rig with empty catalyst box & non-catalytic insert**
  - **Initial catalyst tests (temperature variation, light-off conditions)**
  - **Catalyst aging and control tests with aged & cleaned catalyst**
  - **Comparison tests with reduced catalyst area & other catalyst models**
- **Evaluation of stove integrated catalyst**
  - **Modified traditional stove with catalyst integrated into stove socket**
  - **Evaluation according to project's "close to real life" testing cycle**
    - Reference cycle without catalyst
    - Impact of catalyst (different sizes) on stove performance

Catalyst evaluation at RISE
Catalyst

- **Manufacturer**
  - Catator AB
- **Type & Size**
  - Metal based mesh catalyst
  - Wire opening & diameter: about 1.24 & 0.5 mm
  - Total cross section about 0.2 m^2, split into 8 pieces at ø 180mm
- **Catalytic properties**
  - Base material: High temperature steel (AISI 330)
  - Active material: Stabilized Ce-Oxide / stabilized Platinum
- **Cost estimation**
  - 100-200 Euro (depending on order volume)

Note: Catalyst size & properties chosen after consultation with manufacturer on expected flue gas conditions (volume, emissions, etc.)

RISE NIBE

Catalyst evaluation at RISE
Catalyst test rig (CTR)

ERA-NET Bioenergy

- **Setup**
  - **Traditional stove (emission source)**
  - **Heated flue (to adjust gas temperature at catalyst)**
  - **Two measuring sections up- and downstream catalyst box (layout according to prEN 16510)**
  - **Catalyst box dimension: L 180 x W 180 x H 100 mm**
- **Measurement equipment**
  - **2 sampling trains for gaseous components**
    - M&C PMA 10 (paramagnetic oxygen analyzer)
    - Emerson NDIR analyzer X-Stream XEGC (CO, CO_2)
    - JUM FID 3-300A & JUM FID VE5 (hydrocarbons)
  - **2 sampling trains for particles (gravimetric)**
    - Nozzle ø10 mm, Sampling volume about 0.5-0.6 m^3/h
    - Plane filter, Filter temperature at sampling 160°C
    - Sampling over whole batch (open door till open door)
  - **Thermocouples & pressure transmitters**

Catalyst evaluation at RISE
Test fuel properties

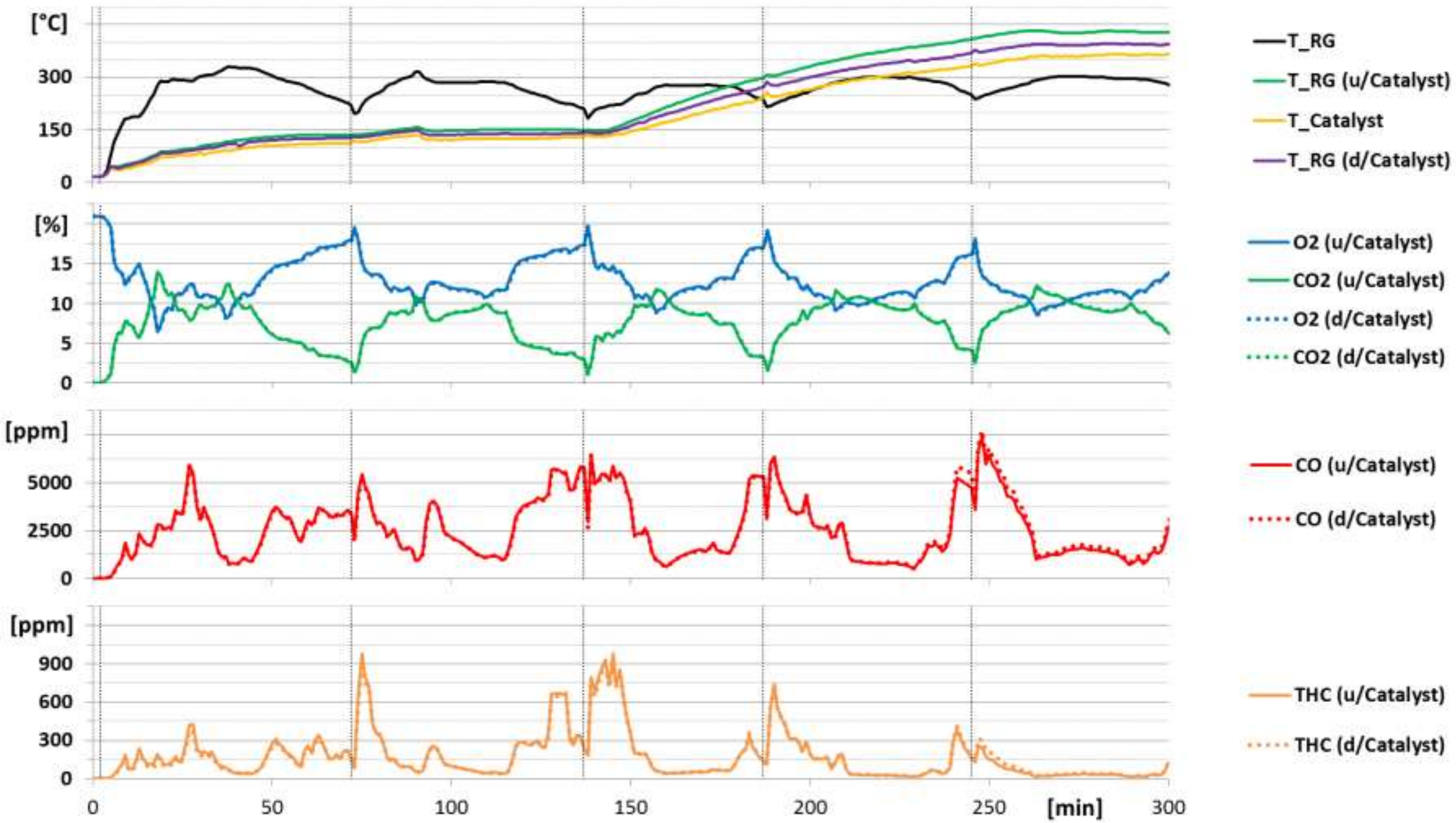
- **Test fuel**
  - **Birch wood logs**
  - **Bark free (in main part) & with bark**
  - **Triangle shape, length between 25-30 cm**
  - **Moisture content 13 - 20% (wet basis)**
- **Charge arrangement**
  - **2-3 logs (except ignition batches)**
  - **Mass in general between 1.2 - 1.8 kg**
  - **Generally crosswise placement (with variation)**

Wood properties (dry basis)		
C	wt-%	49.9
H	wt-%	6.1
N	wt-%	0.14
S	wt-%	< 0.2
Ash	wt-%	0.4
HHV	MJ/kg	19.99
LHV	MJ/kg	18.67

Catalyst evaluation at RISE
CTR control check with empty catalyst box (I)

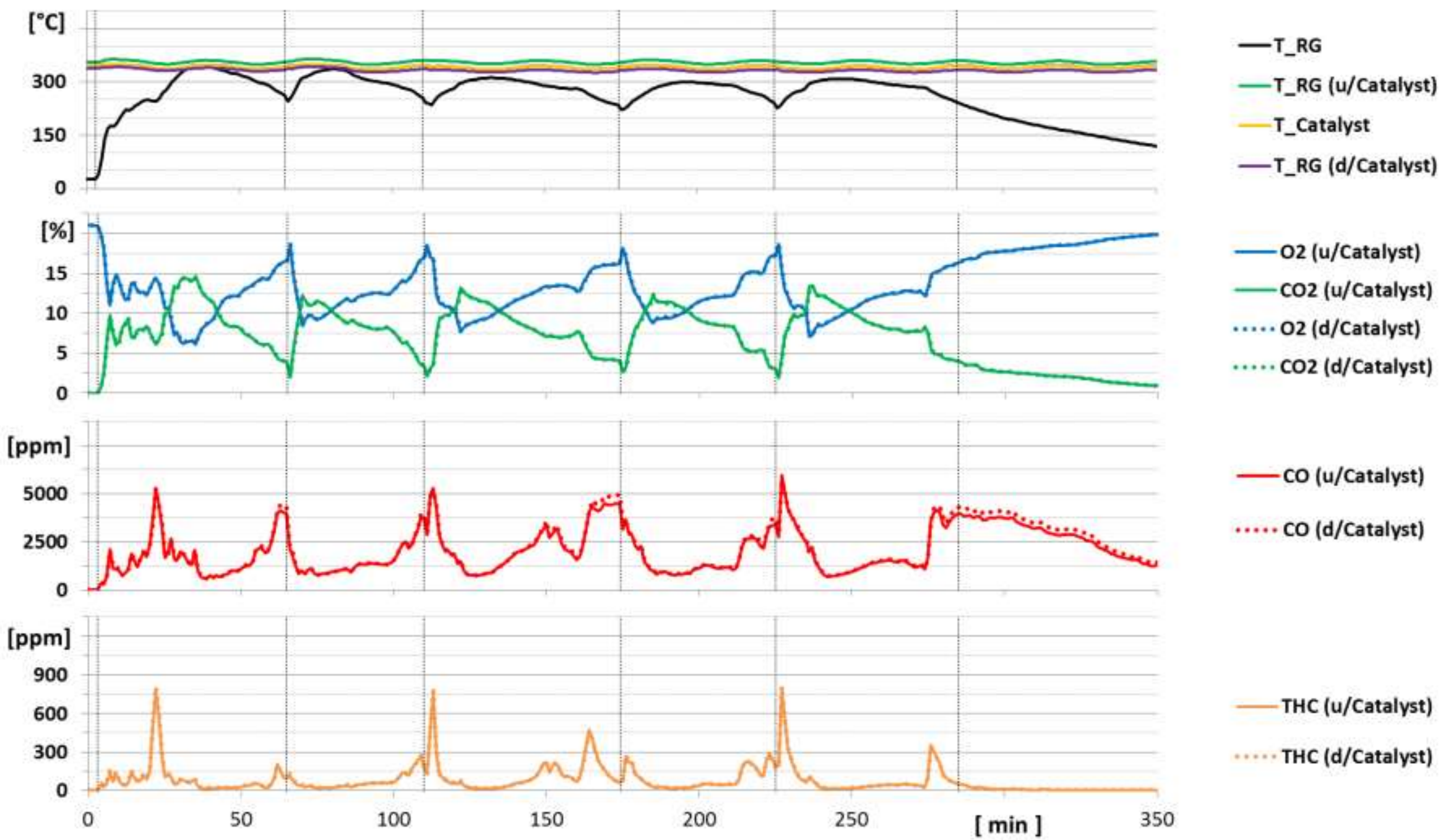
- **Empty catalyst box**
  - **Two test days, 1st with varying temperatures & 2nd with stable "catalyst" temperature**
- **Results**
  - **Gaseous components from two sampling trains (O_2, CO_2, CO, HC) highly comparable**
  - **Slight deviation for CO & HC values when running at higher "catalyst" temperatures**
    - Mainly at end of batches during char coal burnout
    - Most likely some layer formation based on outside heating and low flue gas velocity
  - **Coinciding result from particle measurements up- and downstream catalyst box**
  - **At higher temperatures CO & HC conversion in test rig prior sampling; results in lower peak and average values**

Catalyst evaluation at RISE
CTR control check with empty catalyst box (II)



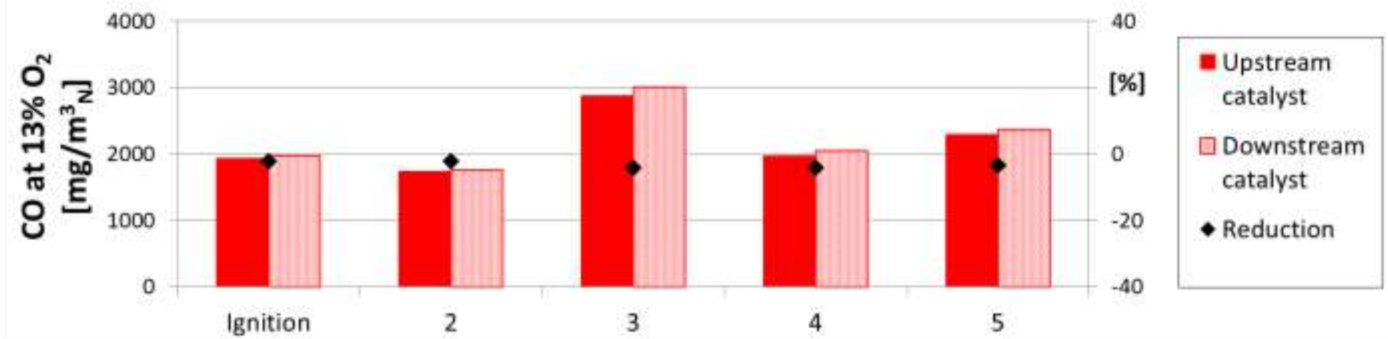
Note: Chart from test with empty catalyst box at varying temperatures

Catalyst evaluation at RISE
CTR control check with empty catalyst box (III)

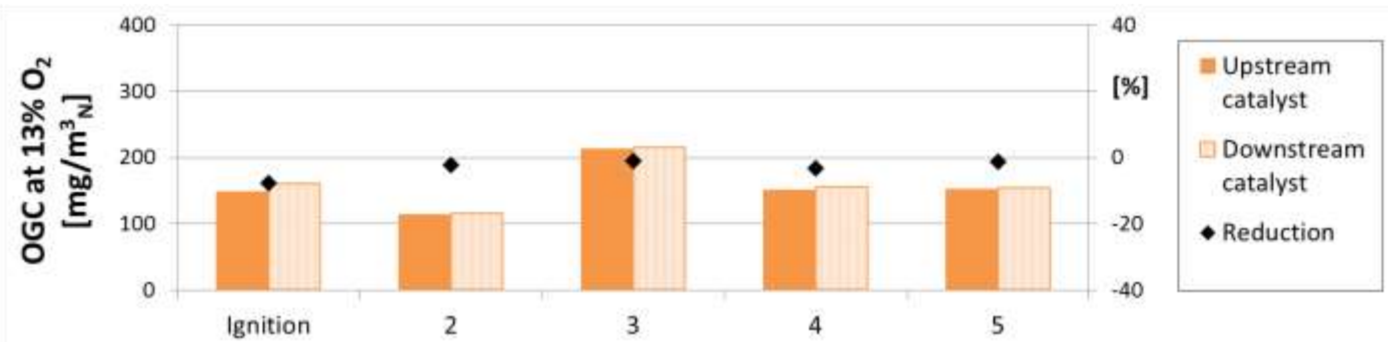


Note: Chart from test with empty catalyst box at stable temperature of about 350°C

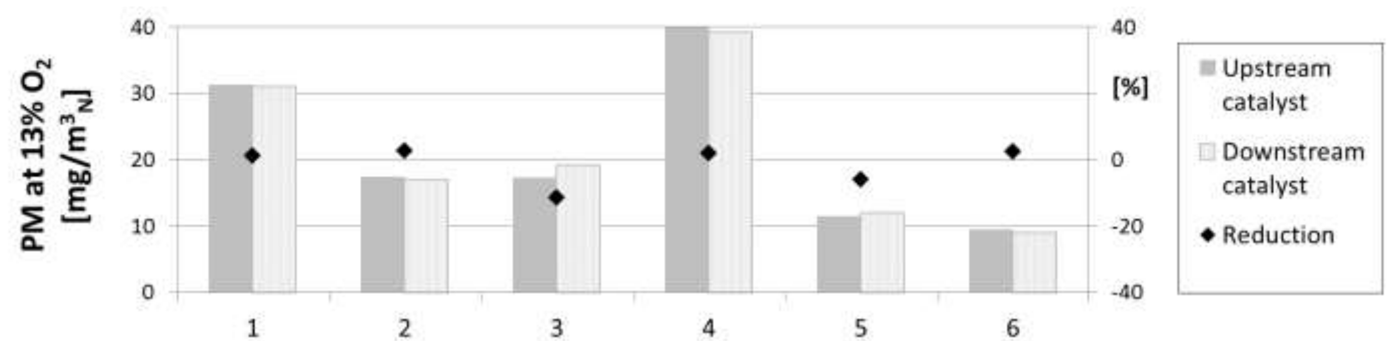
Catalyst evaluation at RISE
CTR control check with empty catalyst box (IV)



Test run with empty catalyst box at 350°C



Test run with empty catalyst box at 350°C



Test runs with empty catalyst box at varying temperatures

Catalyst evaluation at RISE
CTR control check with non-catalytic insert (I)

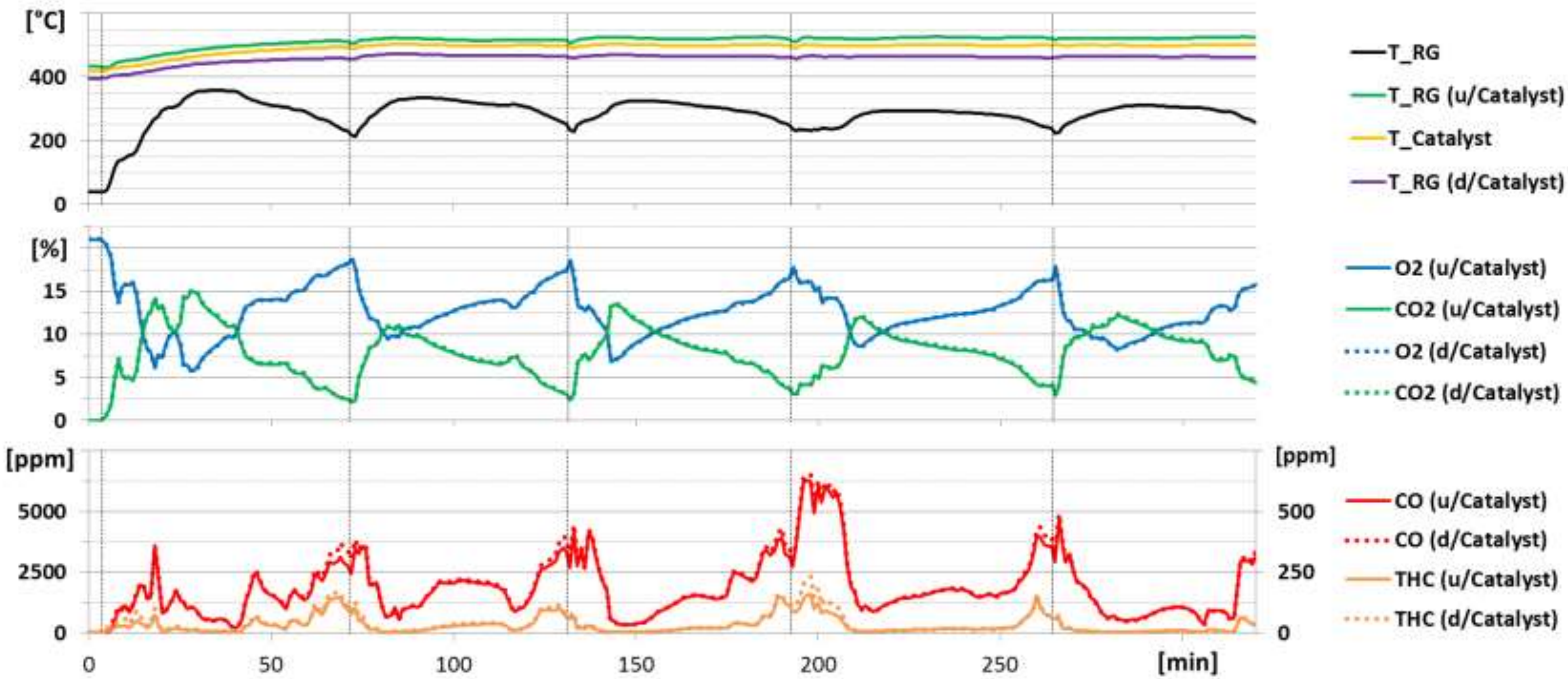
Non-catalytic insert

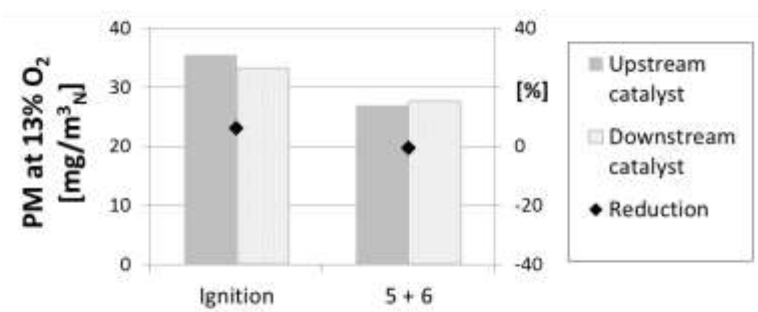
- **Two test days with uncoated mesh (same base material as mesh catalyst)**
- **Total cross section about 0.1 m², split into 4 pieces at ø 180mm**
- **Mesh pieces stacked directly above each other in catalyst box**

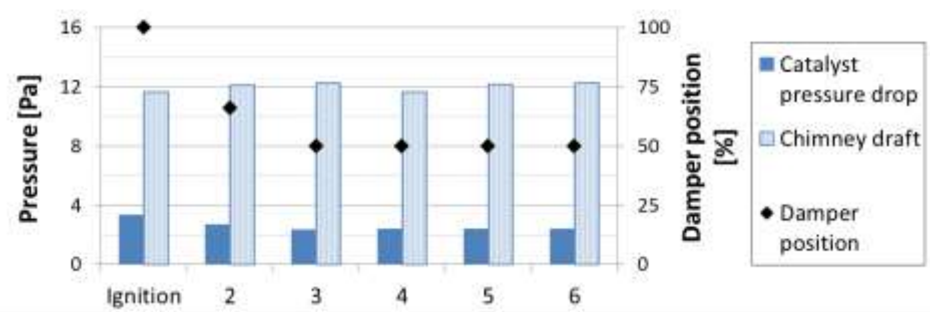
Results

- **No observable conversion of CO or HC**
  - CO & HC only with slight deviation, corresponding to results from runs with empty catalyst box
  - No effect on temperature downstream catalyst
  - No effect on O_2 or CO_2 (coinciding values)
- **No observable particle reduction (based on only two samples)**
- **Pressure drop across insert between 2-3 Pa**

Catalyst evaluation at RISE
CTR control check with non-catalytic insert (II)







Catalyst test rig

Initial testing with mesh catalyst

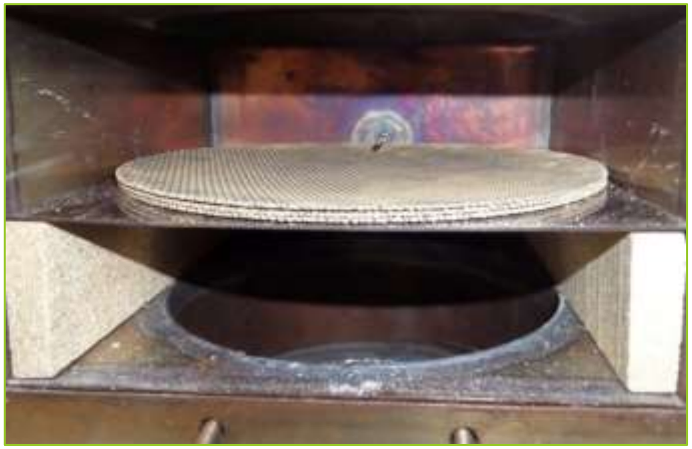
Catalyst evaluation at RISE
Initial catalyst tests – Placement & scheme

Catalyst placement

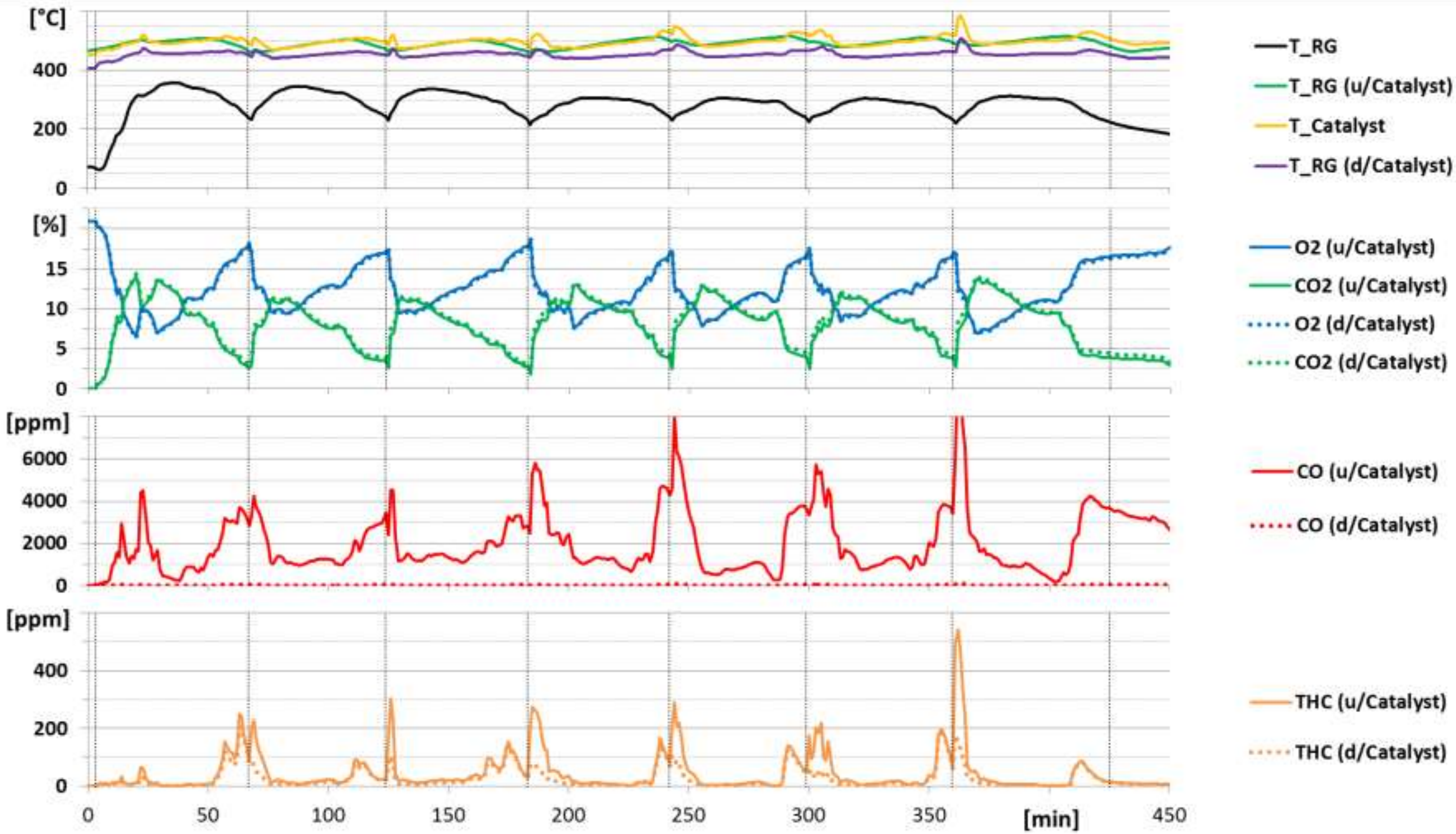
- In middle of catalyst box (matching thermocouple location)
- All 8 mesh pieces stacked directly above each other

Test scheme

- Initial test at temperatures 300°C, 400°C & 500°C (regulating with thermocouple at catalyst location)
- Initial test for catalyst impact on particles at 400°C (regulating with thermocouple upstream catalyst)
- Check for light-off temperatures for carbon monoxide & hydrocarbon conversion



Catalyst evaluation at RISE
Initial catalyst tests – Temperature at 500°C (I)

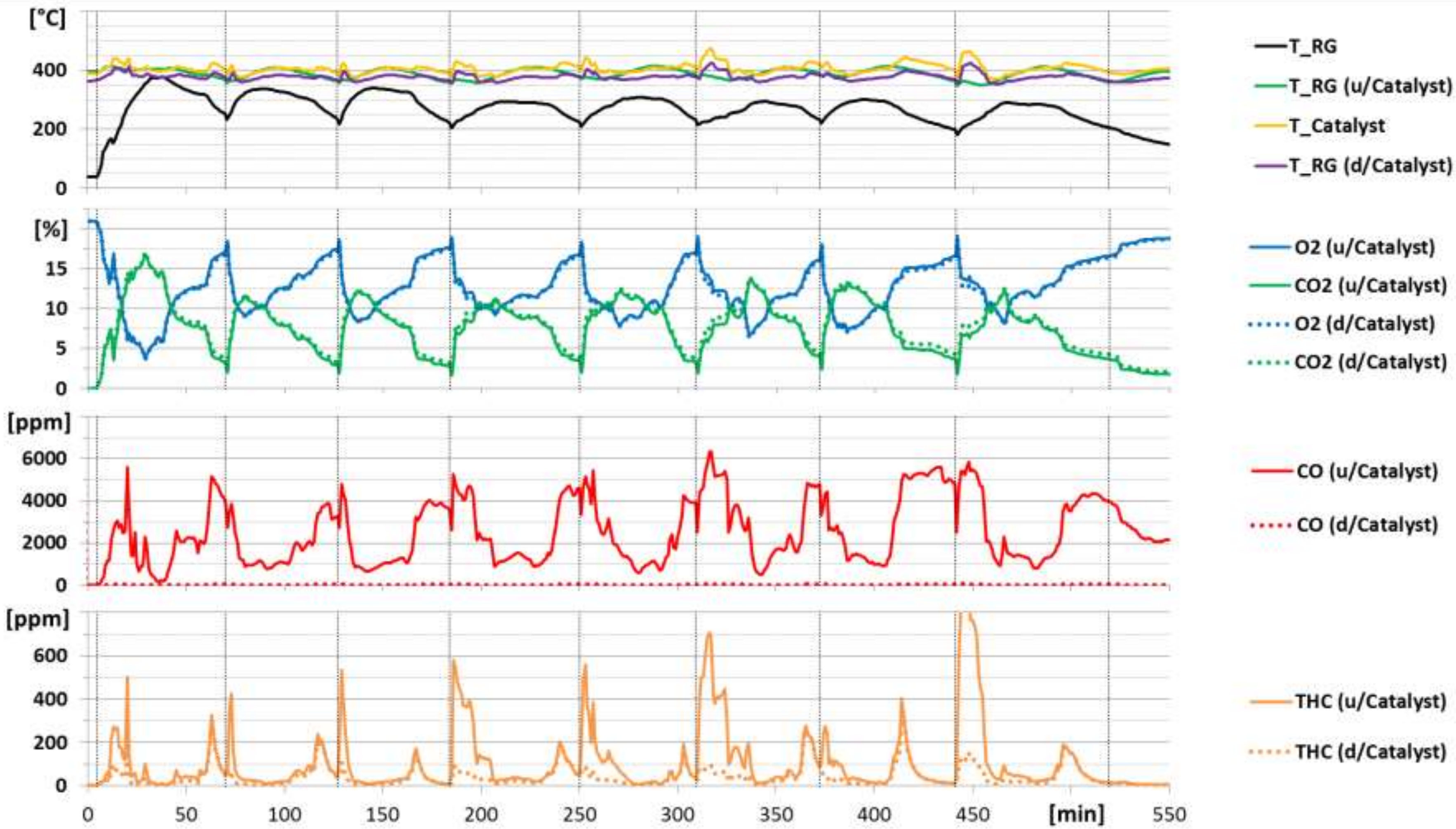


Catalyst evaluation at RISE
Initial catalyst tests – Temperature at 500°C (II)

	Batch		Ignition	2	3	4	5	6	7
Temperatures	Flue Gas	°C	283	309	305	284	284	280	284
	u/Catalyst	°C	495	486	486	489	501	496	501
	Catalyst	°C	496	493	495	495	504	502	508
	d/Catalyst	°C	455	454	456	451	458	456	461
Upstream catalyst	CO_2	%	8.4	7.5	7.5	9.0	8.8	8.3	8.9
	O_2	%	12.2	13.0	13.1	11.6	11.7	12.2	11.6
	CO at 13% O_2	%	0.14	0.18	0.19	0.18	0.17	0.19	0.19
		mg/m^3_N	1756	2235	2386	2303	2143	2398	2375
	OGC at 13% O_2	mg/m^3_N	60	72	94	81	72	85	81
Downstream catalyst	CO_2	%	8.7	7.8	7.8	9.3	9.2	8.6	9.2
	O_2	%	12.0	12.8	12.9	11.3	11.5	12.0	11.4
	CO at 13% O_2	%	0.002	0.002	0.002	0.002	0.002	0.002	0.002
		mg/m^3_N	25	29	29	26	23	26	26
	OGC at 13% O_2	mg/m^3_N	45	43	64	38	42	47	38
Reduction	CO	%	99	99	99	99	99	99	99
	OGC	%	25	40	32	53	42	44	53

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Initial catalyst tests – Temperature at 400°C (I)

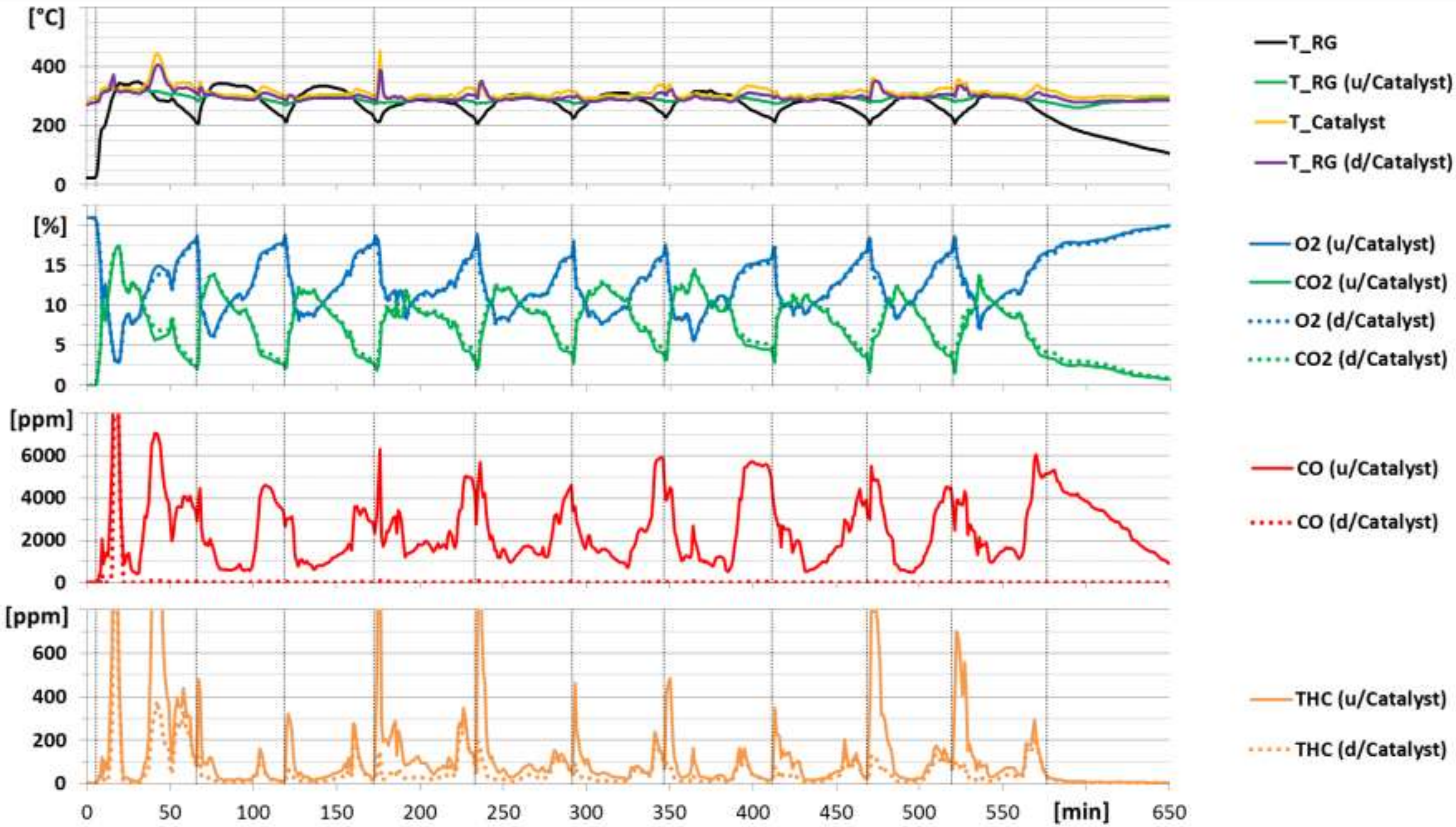


Catalyst evaluation at RISE
Initial catalyst tests – Temperature at 400°C (II)

	Batch		Ignition	2	3	4	5	6	7	8
Temperatures	Flue Gas	°C	290	304	299	269	280	263	260	253
	u/Catalyst	°C	398	387	386	387	393	389	392	381
	Catalyst	°C	409	399	400	404	407	414	412	408
	d/Catalyst	°C	383	376	376	376	378	382	379	379
Upstream catalyst	CO_2	%	9.3	7.3	7.3	7.8	8.6	8.4	8.0	7.0
	O_2	%	11.1	13.1	13.1	12.6	11.7	11.9	12.3	13.3
	CO at 13% O_2	%	0.17	0.20	0.22	0.24	0.20	0.28	0.30	0.30
		mg/m^3_N	2073	2451	2745	3038	2473	3438	3796	3796
	OGC at 13% O_2	mg/m^3_N	118	128	103	215	147	292	119	312
Downstream catalyst	CO_2	%	9.6	7.6	7.6	8.2	9.0	8.9	8.4	7.5
	O_2	%	11.0	12.9	12.9	12.3	11.5	11.6	12.1	13.0
	CO at 13% O_2	%	0.002	0.002	0.003	0.003	0.002	0.003	0.003	0.003
		mg/m^3_N	28	30	33	34	28	38	37	39
	OGC at 13% O_2	mg/m^3_N	64	76	50	78	50	93	72	94
Reduction	CO	%	99	99	99	99	99	99	99	99
	OGC	%	46	40	51	64	66	68	39	70

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Initial catalyst tests – Temperature at 300°C (I)



RISE NIBE

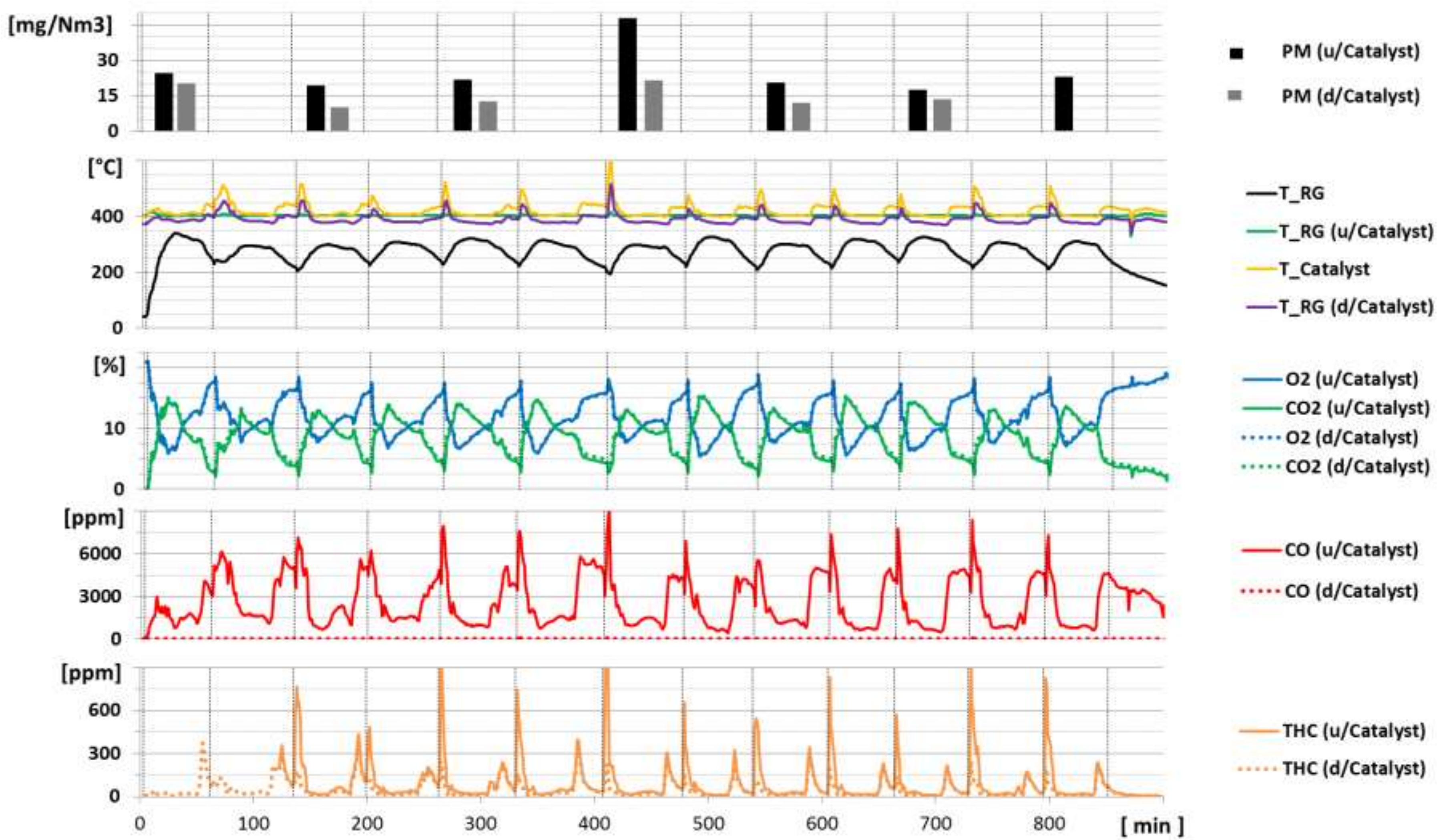
Catalyst evaluation at RISE
Initial catalyst tests – Temperature at 300°C (II)

ERA-NET Bioenergy

	Batch		Ignition	2	3	4	5	6	7	8	9	10
Temperatures	Flue Gas	°C	284	302	298	268	278	285	282	269	268	275
	u/Catalyst	°C	314	295	292	285	290	292	293	294	297	295
	Catalyst	°C	346	312	306	309	307	307	313	306	319	318
	d/Catalyst	°C	330	300	294	295	295	292	297	292	305	302
Upstream catalyst	CO_2	%	8.5	7.9	7.7	7.7	8.5	9.0	8.6	8.1	7.7	7.9
	O_2	%	12.0	12.3	12.8	12.6	11.8	11.4	11.6	12.2	12.8	12.5
	CO at 13% O_2	%	0.32	0.20	0.17	0.25	0.20	0.19	0.24	0.19	0.24	0.25
		mg/m^3_N	3968	2444	2185	3076	2477	2401	3006	2327	2959	3133
	OGC at 13% O_2	mg/m^3_N	579	98	130	317	212	127	115	132	313	263
Downstream catalyst	CO_2	%	8.9	8.3	8.0	8.1	8.9	9.3	9.0	8.4	8.1	8.3
	O_2	%	11.7	12.2	12.6	12.4	11.6	11.2	11.4	12.0	12.5	12.2
	CO at 13% O_2	%	0.067	0.003	0.002	0.003	0.002	0.002	0.002	0.001	0.002	0.001
		mg/m^3_N	838	32	26	32	24	19	22	18	19	18
	OGC at 13% O_2	mg/m^3_N	293	42	64	110	76	66	50	62	92	97
Reduction	CO	%	79	99	99	99	99	99	99	99	99	99
	OGC	%	49	57	50	65	64	47	56	53	70	63

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Initial catalyst tests – Impact on particles (I)

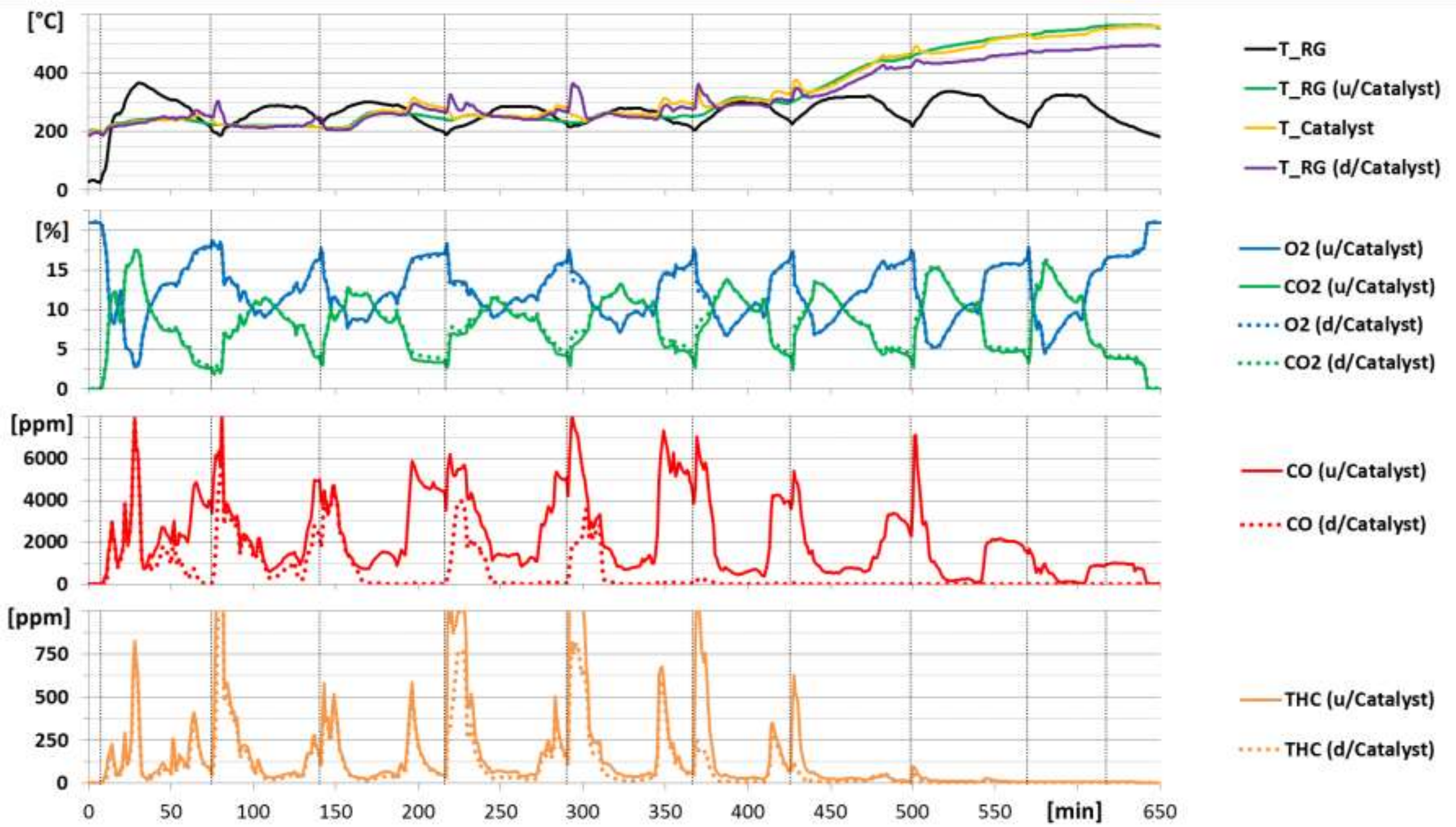


Catalyst evaluation at RISE
Initial catalyst tests – Impact on particles (II)

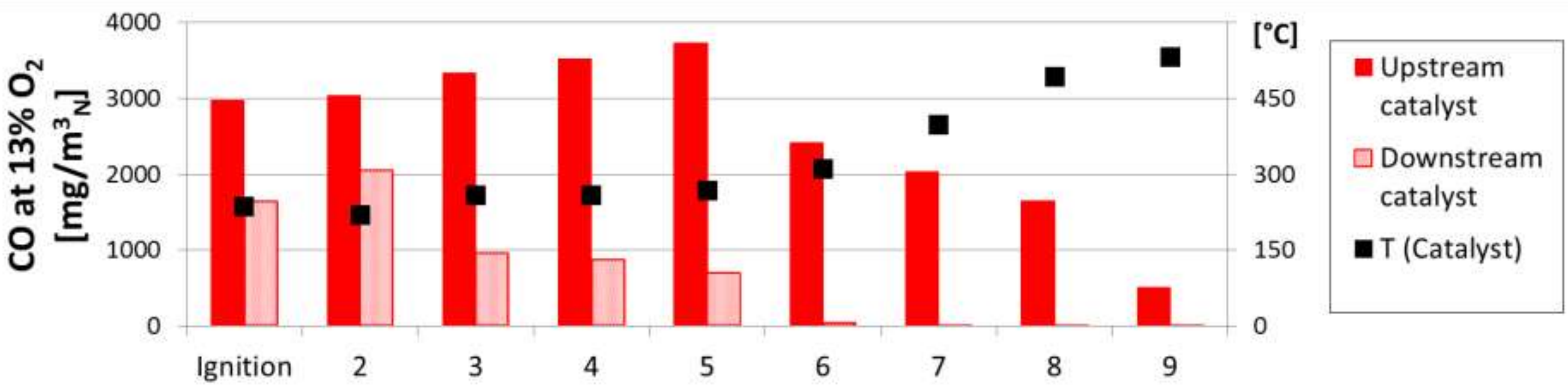
	Batch		Ignition	2	3	4	5	6	7	8	9	10	11	12	13
Temperatures	Flue Gas	°C	277	267	272	283	290	276	271	289	274	290	290	275	281
	u/Catalyst	°C	405	405	405	405	405	404	405	404	405	405	404	404	405
	Catalyst	°C	417	435	425	421	421	426	426	419	423	419	418	424	420
	d/Catalyst	°C	390	400	393	390	389	392	393	389	390	389	386	392	389
Upstream catalyst	CO_2	%	8.8	7.9	8.7	9.1	9.3	8.7	8.7	9.3	8.6	9.6	9.3	8.4	9.1
	O_2	%	11.8	12.5	11.7	11.2	11.0	11.6	11.7	11.1	11.7	10.7	11.0	12.0	11.4
	CO at 13% O_2	%	0.16	0.32	0.23	0.21	0.20	0.27	0.22	0.19	0.23	0.18	0.20	0.23	0.18
		mg/m^3_N	1971	4020	2899	2679	2481	3318	2697	2421	2890	2238	2535	2874	2243
	OGC at 13% O_2	mg/m^3_N	N/A	N/A	208	138	151	158	190	117	142	125	91	164	150
	PME at 13% O_2	mg/m^3_N	25		20		22		48		21		18		23
Downstream catalyst	CO_2	%	9.1	8.3	9.0	9.5	9.6	9.1	9.0	9.6	9.0	9.9	9.6	8.5	9.2
	O_2	%	11.7	12.4	11.7	11.2	11.1	11.6	11.7	11.1	11.8	10.8	11.2	12.2	11.6
	CO at 13% O_2	%	0.001	0.002	0.002	0.001	0.001	0.002	0.001	0.001	0.001	0.001	0.001	0.001	0.001
		mg/m^3_N	17	26	20	18	16	20	17	14	15	13	14	16	13
	OGC at 13% O_2	mg/m^3_N	79	131	105	76	79	88	80	64	73	63	52	73	70
	PME at 13% O_2	mg/m^3_N	20		10		13		22		12		14		N/A
Reduction	CO	%	99	99	99	99	99	99	99	99	99	99	99	99	99
	OGC	%	N/A	N/A	50	46	48	45	58	46	49	50	43	56	54
	PME	%	18		47		43		55		43		24		N/A

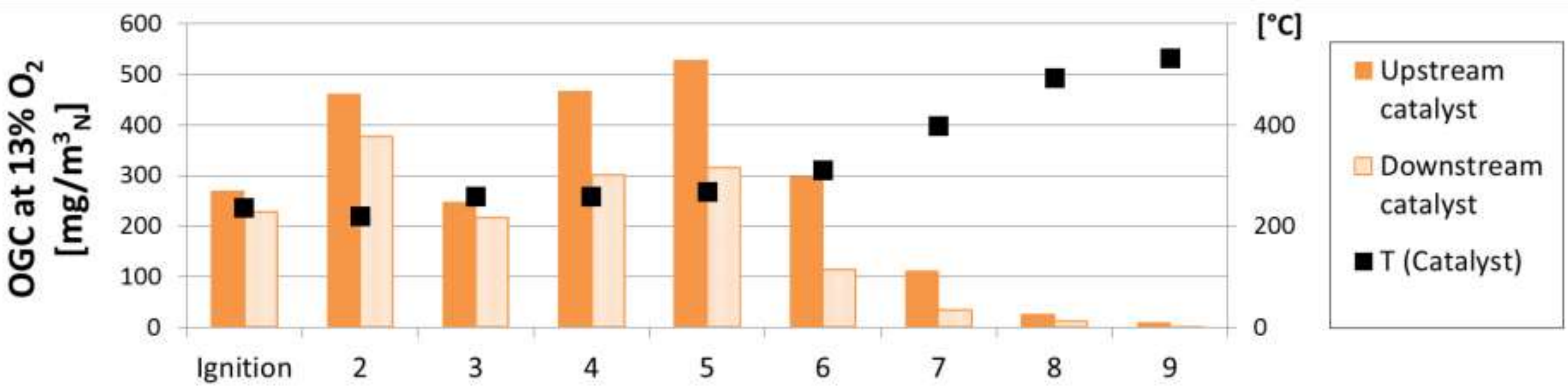
Note:
- Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)
- No hydrocarbon measurement upstream catalyst during first two batches, last particle sampling downstream catalyst failed

Catalyst evaluation at RISE
Initial catalyst tests – Light-off conditions (I)



Catalyst evaluation at RISE
Initial catalyst tests – Light-off conditions (II)





Catalyst evaluation at RISE
Initial catalyst tests – Results (I)

General

- **Noticeable pressure drop across catalyst (stacked 8 mesh pieces)**
  - Initial range of 8-12 Pa is significantly higher than for uncoated stacked 4 mesh pcs. (2-3 Pa)
- **Catalyst temperature increase through conversion of unburnt components**
  - Especially extensive increase (up to 100/200K) for times with high hydrocarbon conversion
- **O_2 and CO_2 trends & differentials confirm conversion of unburnt components**

Conversion of carbon monoxide

- **Nearly complete CO reduction at temperatures above 300°C**
- **Light-off temperature for CO conversion around 250°C**
- **Reduction rate at temperatures above 300°C not affected by CO amount or other boundary conditions**
- **Reduction rate at temperatures below 300°C**
  - Existence of hydrocarbons seems to reduce/prevent CO conversion
  - Turn-off temperature (point when conversion drops again) seems lower than 250°C

Catalyst evaluation at RISE
Initial catalyst tests – Results (II)

Conversion of hydrocarbons

- **Hydrocarbon reduction at initial tests in range 25-75%**
- **Reduction rate strongly affected by composition & amount of hydrocarbons**
  - Strong reduction during first phase of a batch, when there is a larger share of long-chain hydrocarbons
  - None resp. negligible reduction of hydrocarbons during end phase of batch, when there is mainly methane present (valid for entire evaluated catalyst temperature range of 300-500°C)
- **Light-off temperatures for hydrocarbon conversion hard to specify**
  - Significant reduction already at temperatures above 300°C
  - Reduction rate should typically further increase at higher temperatures
  - Light-off temperature for methane conversion could not be determined due to hydrocarbon reduction in test rig prior sampling when trying to reach high catalyst temperatures

Impact on particles

- **Significant particle reduction at initial tests in range 20-50%**
- **Reduction in large part based on reduction of particle forming hydrocarbons, since reduction seems higher when there also is large hydrocarbon reduction**

Catalyst test rig

Prolonged testing with mesh catalyst

Catalyst evaluation at RISE
Prolonged testing – Placement & scheme

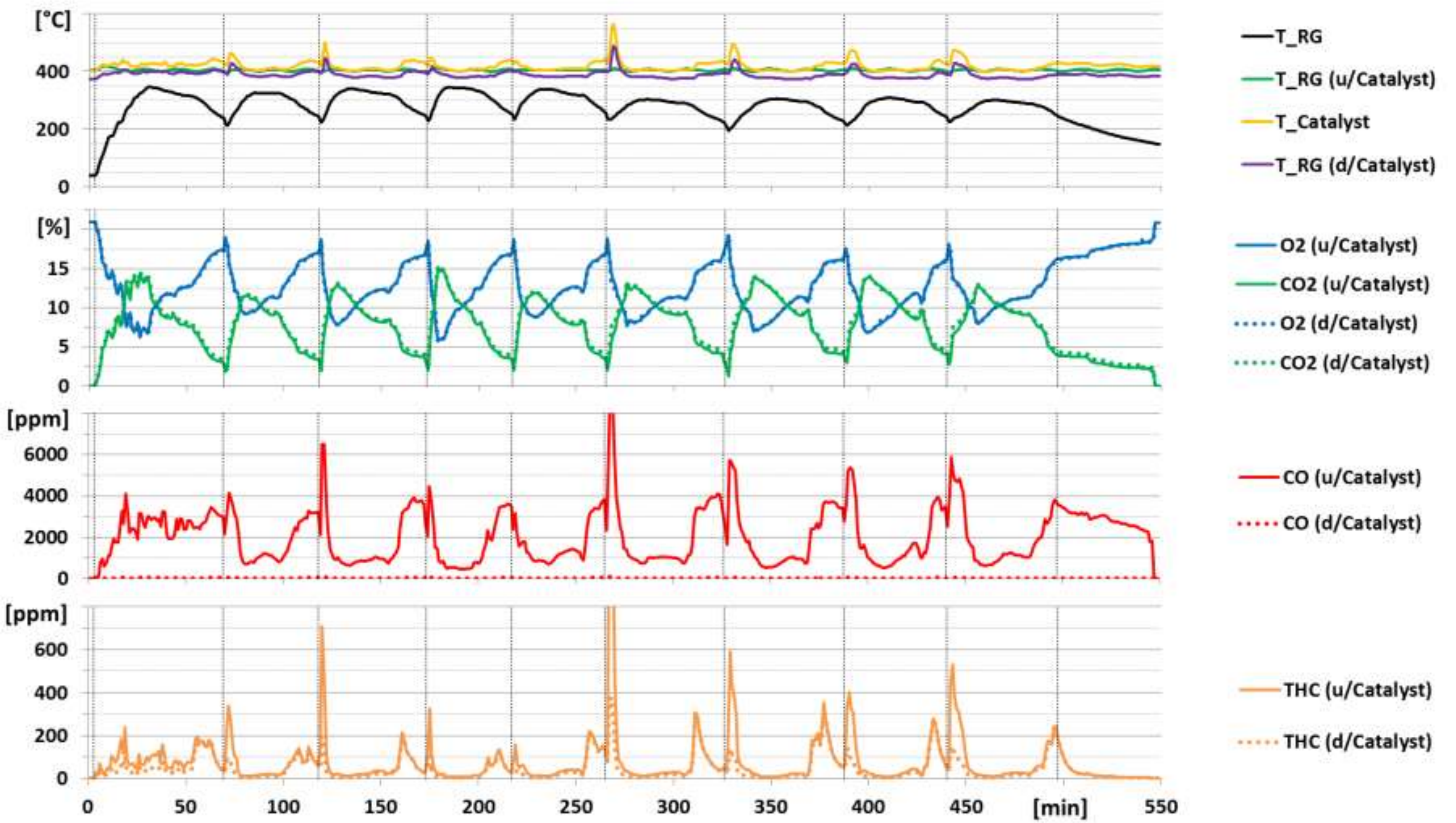
Catalyst placement

- Catalyst untouched during aging
- Same placement after cleaning

Test scheme

- Catalyst aging for about 120 hours with operation at temperatures between 300°C and 500°C
- Control test with aged catalyst at temperatures 300°C, 400°C & 500°C (regulating with thermocouple upstream catalyst)
- Catalyst removal and cleaning
- Control test with cleaned catalyst at temperatures 300°C, 400°C & 500°C (regulating with thermocouple upstream catalyst)

Catalyst evaluation at RISE
Prolonged testing – Aged catalyst at 400°C (I)

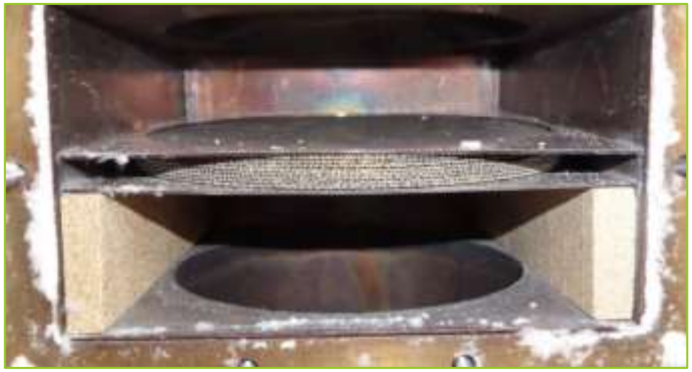


Catalyst evaluation at RISE
Prolonged testing – Aged catalyst at 400°C (II)

	Batch		Ignition	2	3	4	5	6	7	8	9
Temperatures	Flue Gas	°C	274	292	304	311	309	275	272	280	278
	u/Catalyst	°C	406	404	404	405	404	405	405	405	405
	Catalyst	°C	426	420	419	416	415	422	418	417	417
	d/Catalyst	°C	396	392	390	389	388	390	386	386	386
Upstream catalyst	CO_2	%	8.0	7.4	8.0	8.4	8.1	8.3	8.7	9.2	8.7
	O_2	%	12.6	13.1	12.5	12.1	12.4	12.1	11.8	11.2	11.7
	CO at 13% O_2	%	0.23	0.19	0.18	0.15	0.16	0.21	0.18	0.16	0.17
		mg/m^3_N	2870	2409	2200	1829	1981	2566	2197	1986	2138
	OGC at 13% O_2	mg/m^3_N	157	121	113	74	104	187	142	120	142
	PME at 13% O_2	mg/m^3_N	26		25		22		18		22
Downstream catalyst	CO_2	%	8.4	7.7	8.3	8.6	8.4	8.7	9.0	9.4	9.0
	O_2	%	12.5	13.0	12.4	12.1	12.4	12.0	11.7	11.2	11.7
	CO at 13% O_2	%	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.002
		mg/m^3_N	35	30	26	20	21	24	20	19	19
	OGC at 13% O_2	mg/m^3_N	97	75	69	50	79	99	90	77	76
	PME at 13% O_2	mg/m^3_N	19		15		15		11		14
Reduction	CO	%	99	99	99	99	99	99	99	99	99
	OGC	%	39	38	40	33	25	48	37	37	47
	PME	%	27		40		33		40		37

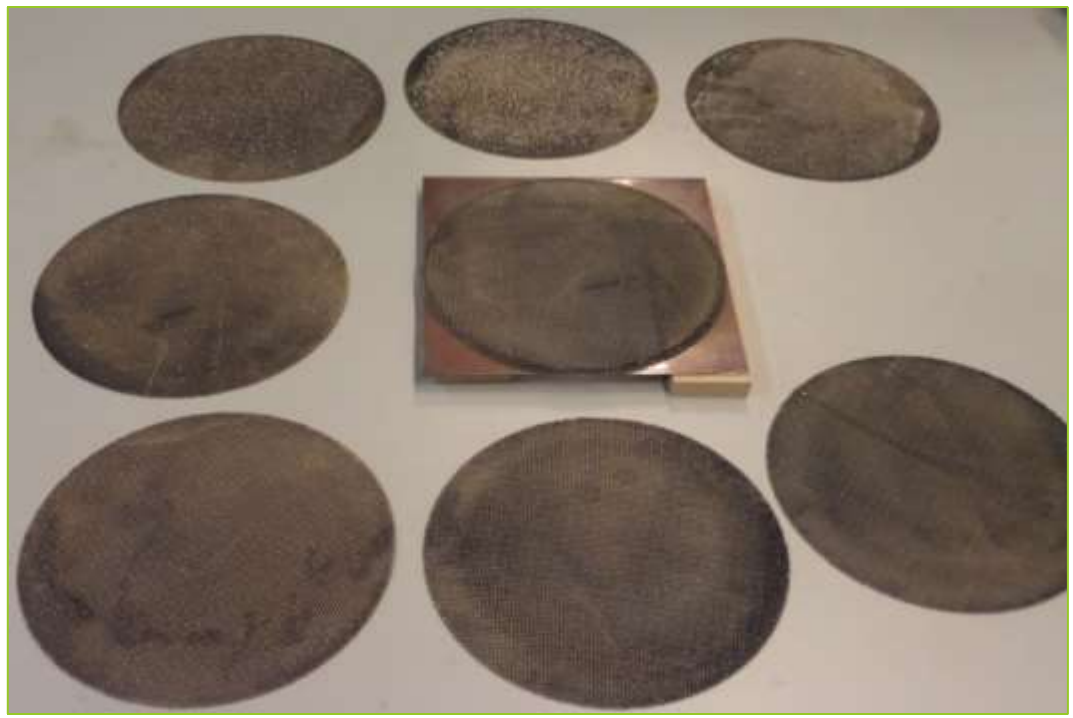
Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Prolonged testing – Catalyst aged

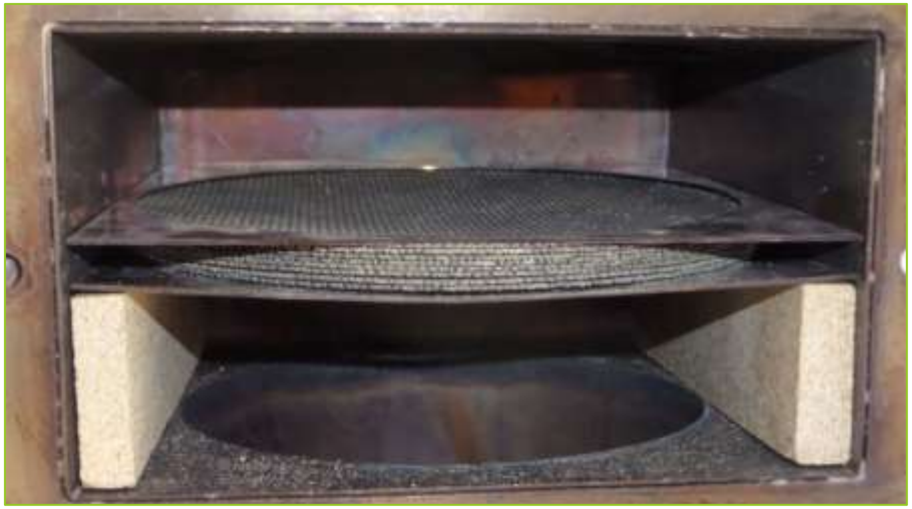


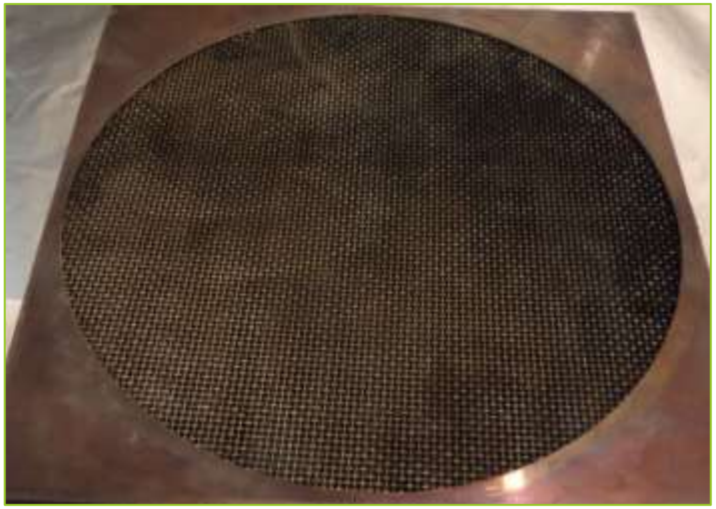
Cleaning procedure

- **Step I: Deposit removed with brush**
- **Step II: Mesh rinsed under water**

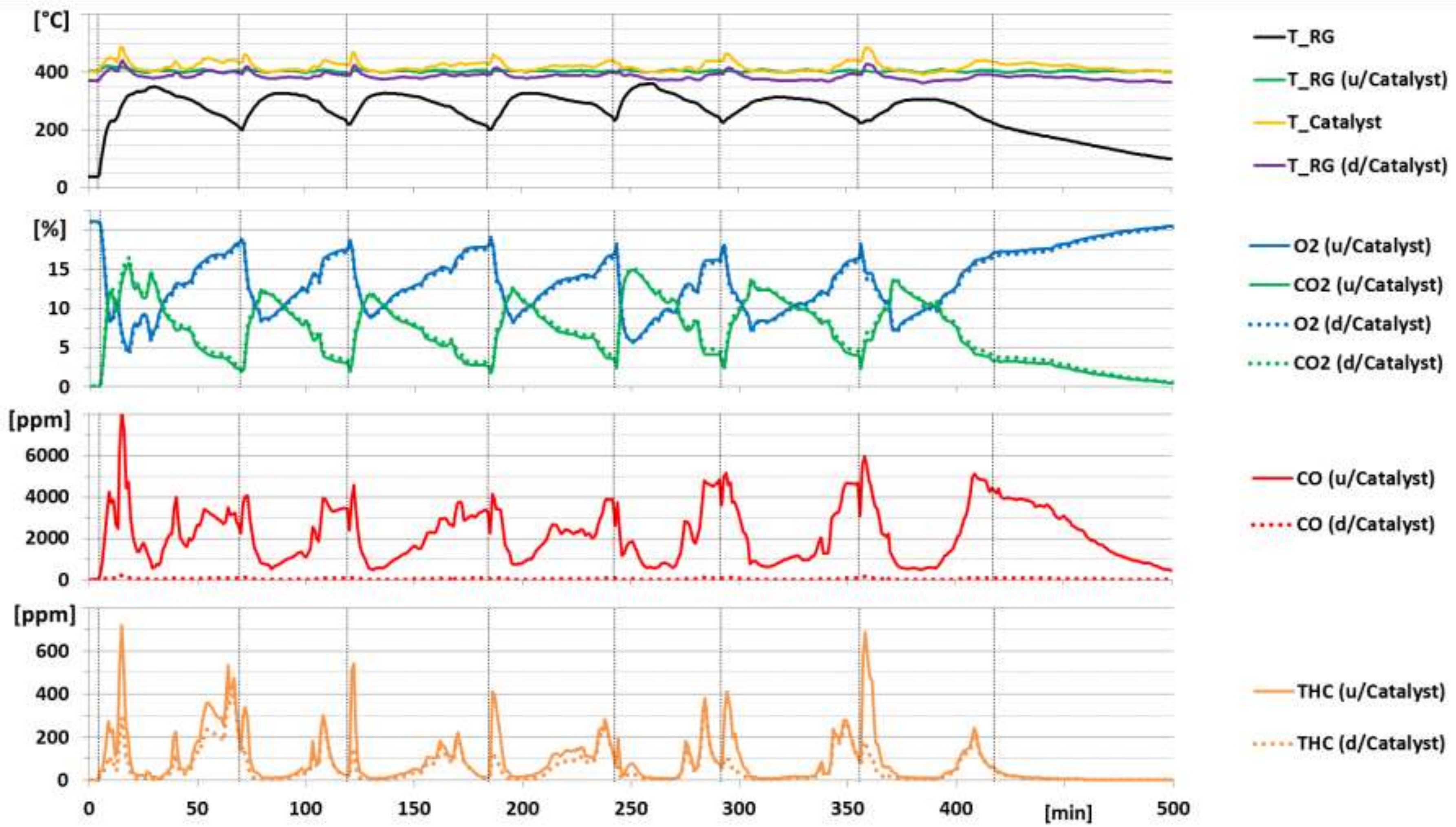


Catalyst evaluation at RISE
Prolonged testing – Catalyst cleaned





Catalyst evaluation at RISE
Prolonged testing – Cleaned catalyst 400°C (I)

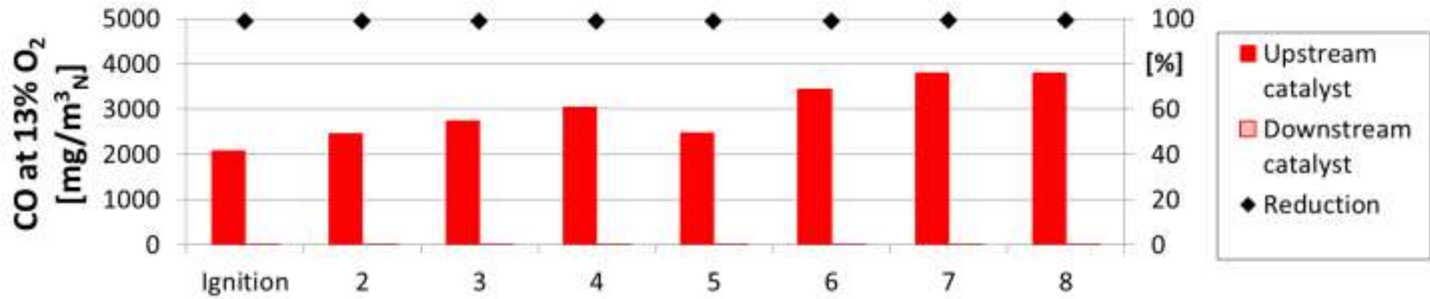


Catalyst evaluation at RISE
Prolonged testing – Cleaned catalyst 400°C (II)

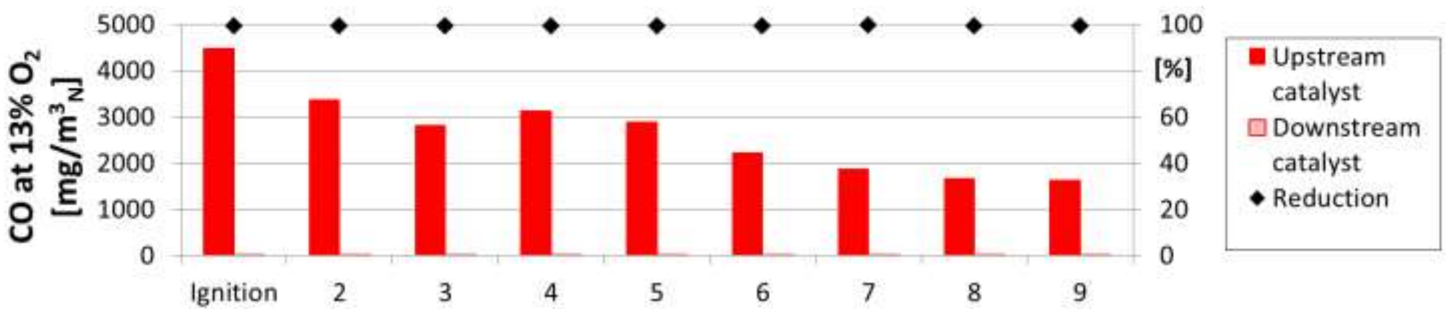
Batch			Ignition	2	3	4	5	6	7
Temperatures	Flue Gas	°C	283	290	287	294	311	286	276
	u/Catalyst	°C	407	405	405	404	405	405	404
	Catalyst	°C	430	420	420	422	415	416	420
	d/Catalyst	°C	396	389	388	390	383	381	383
Upstream catalyst	CO_2	%	8.2	7.5	6.7	7.5	9.6	8.9	8.3
	O_2	%	12.3	13.0	13.9	13.0	11.0	11.6	12.2
	CO at 13% O_2	%	0.24	0.20	0.24	0.22	0.16	0.18	0.21
	CO at 13% O_2	mg/m^3_N	3038	2525	2950	2788	2006	2292	2680
	OGC at 13% O_2	mg/m^3_N	302	139	157	210	109	139	175
	PME at 13% O_2	mg/m^3_N	36		19			19	
Downstream catalyst	CO_2	%	8.6	7.8	7.0	7.9	9.9	9.2	8.6
	O_2	%	12.1	12.8	13.6	12.8	10.7	11.3	12.0
	CO at 13% O_2	%	0.006	0.005	0.005	0.005	0.004	0.004	0.005
	CO at 13% O_2	mg/m^3_N	76	60	68	64	44	49	57
	OGC at 13% O_2	mg/m^3_N	183	95	100	127	83	85	88
	PME at 13% O_2	mg/m^3_N	22		11			13	
Reduction	CO	%	97	98	98	98	98	98	98
	OGC	%	38	31	35	39	23	38	49
	PME	%	38		39			34	

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

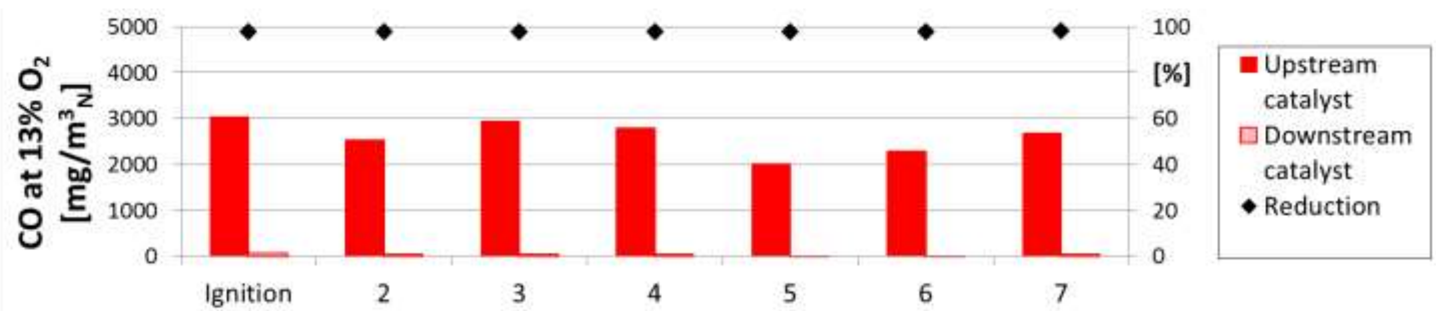
Catalyst evaluation at RISE
Prolonged testing – Comparison CO



Test run with fresh catalyst at 400°C

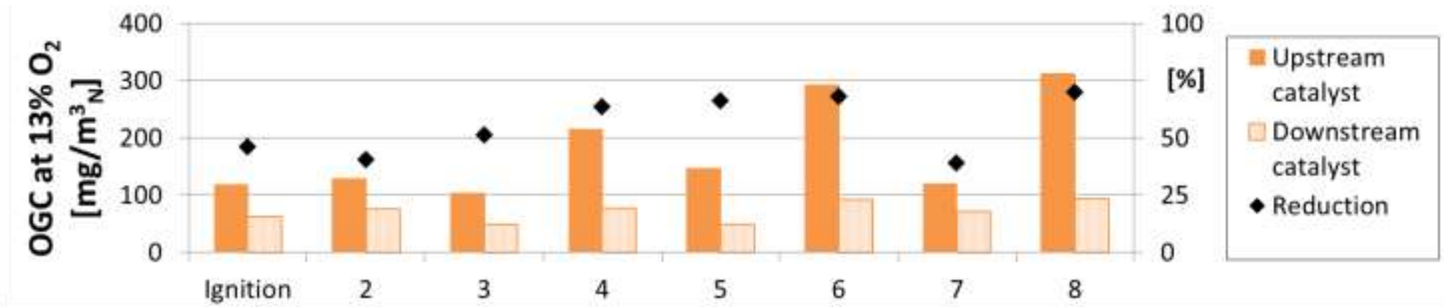


Test run with aged catalyst at 300-500°C

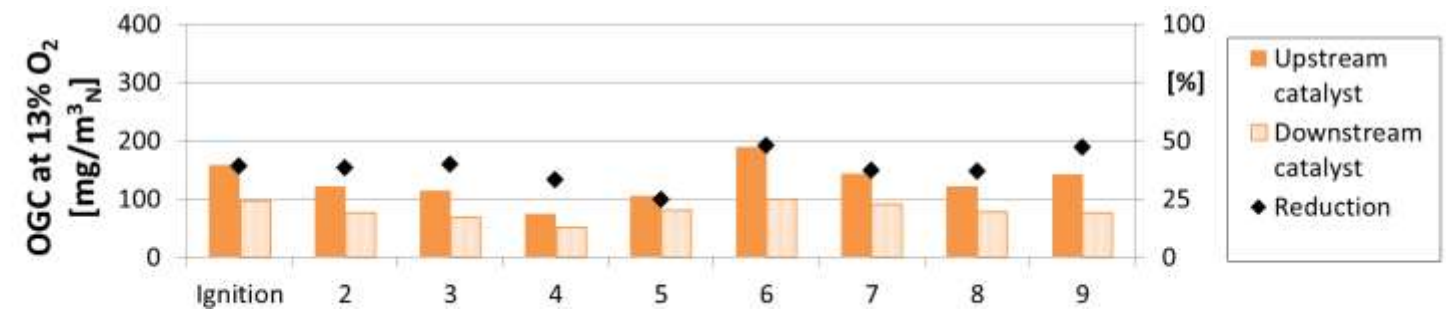


Test run with cleaned catalyst at 400°C

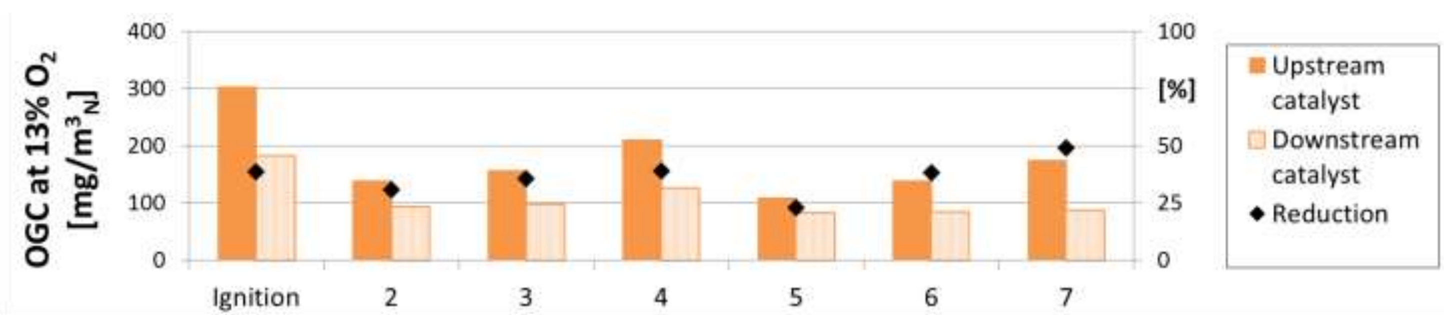
Catalyst evaluation at RISE
Prolonged testing – Comparison HC



Test run with fresh catalyst at 400°C

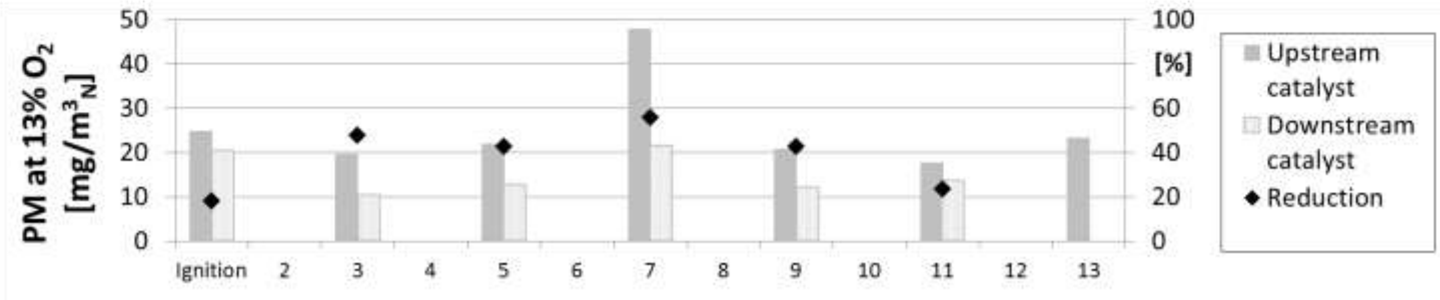


Test run with aged catalyst at 400°C

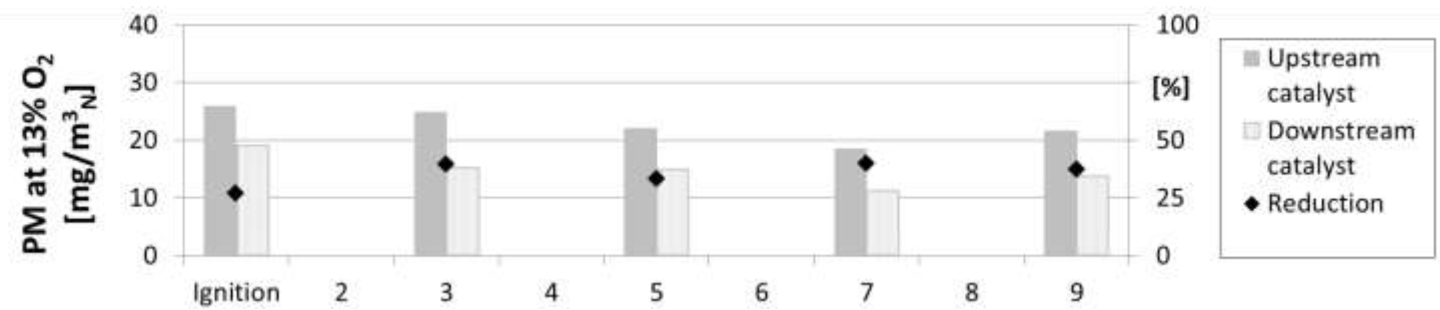


Test run with cleaned catalyst at 400°C

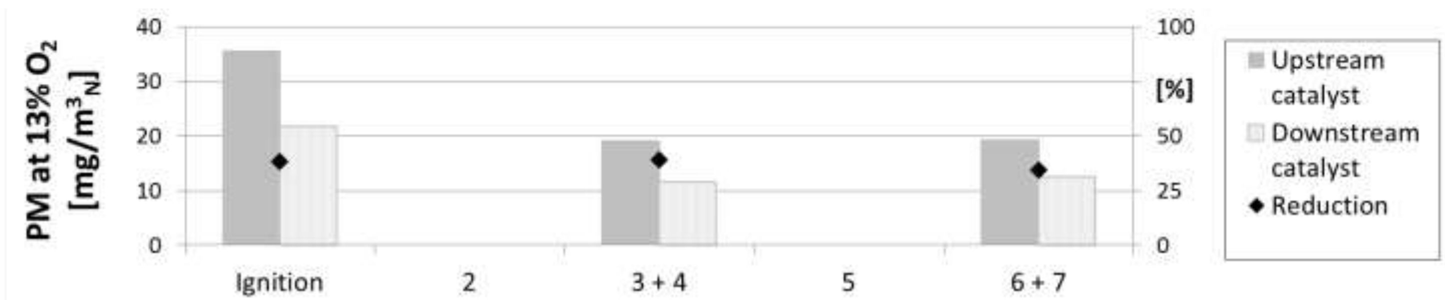
Catalyst evaluation at RISE
Prolonged testing – Comparison PM



Test run with fresh catalyst at 400°C

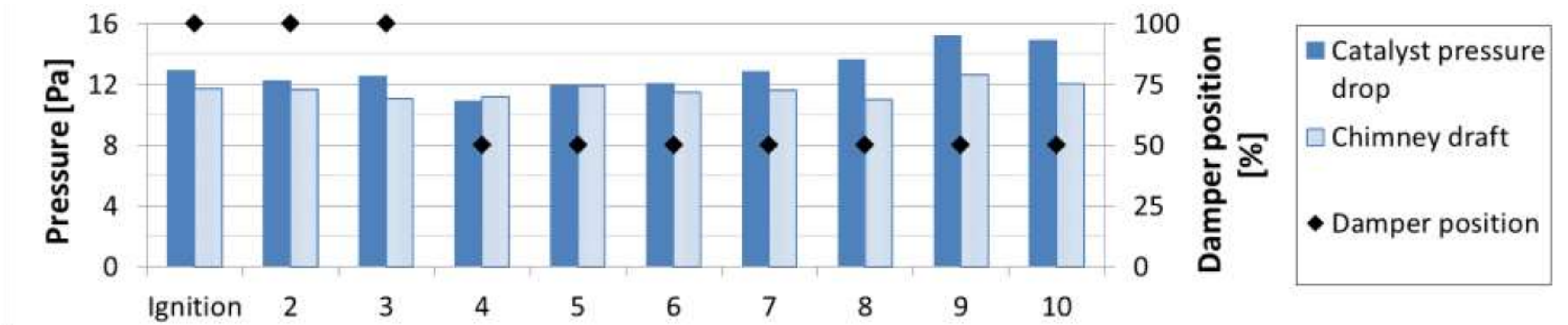


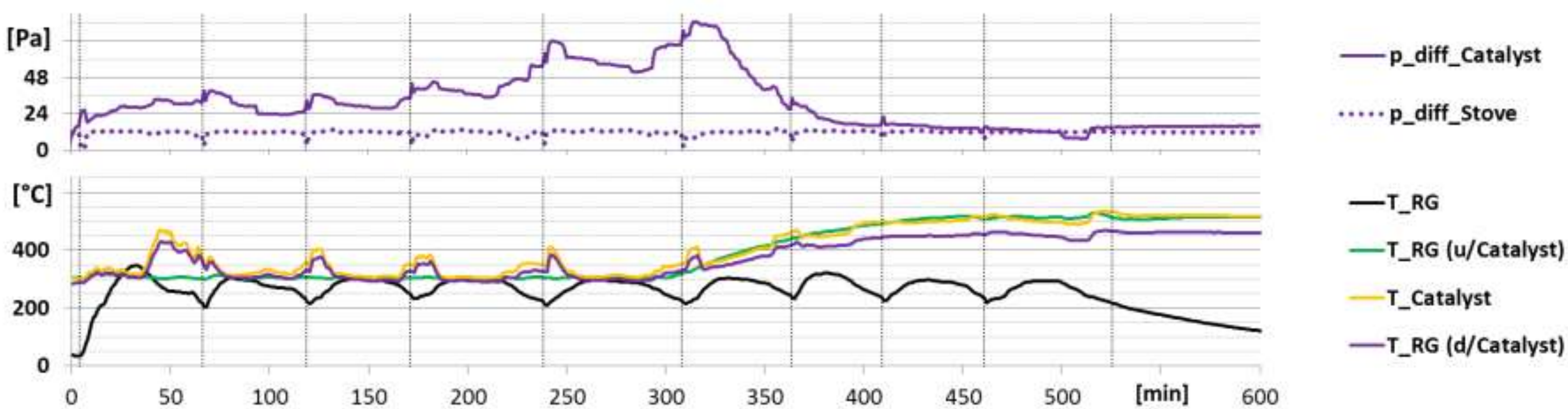
Test run with aged catalyst at 400°C



Test run with cleaned catalyst at 400°C

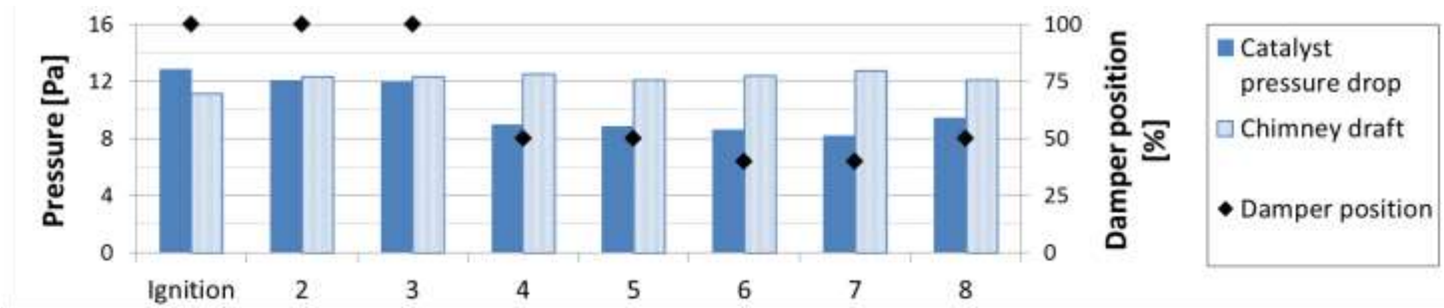
Catalyst evaluation at RISE
Prolonged testing – Flow resistance (I)



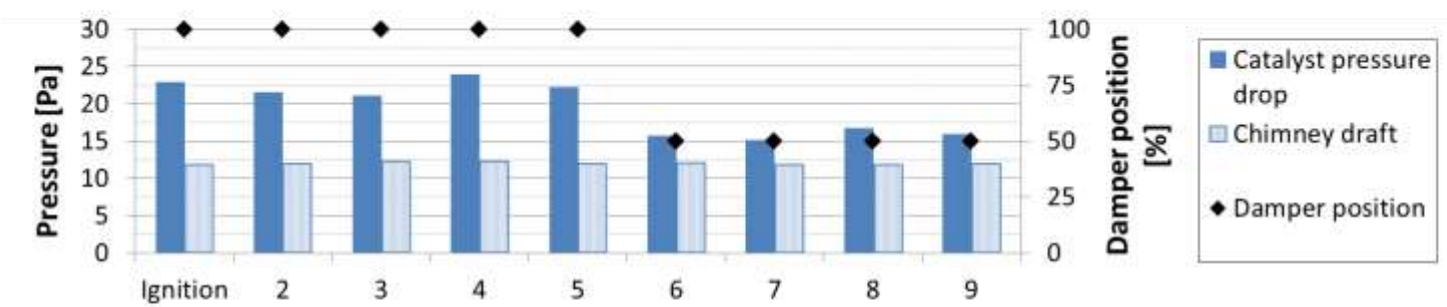


Examples for pressure drop increase when operating at low temperatures

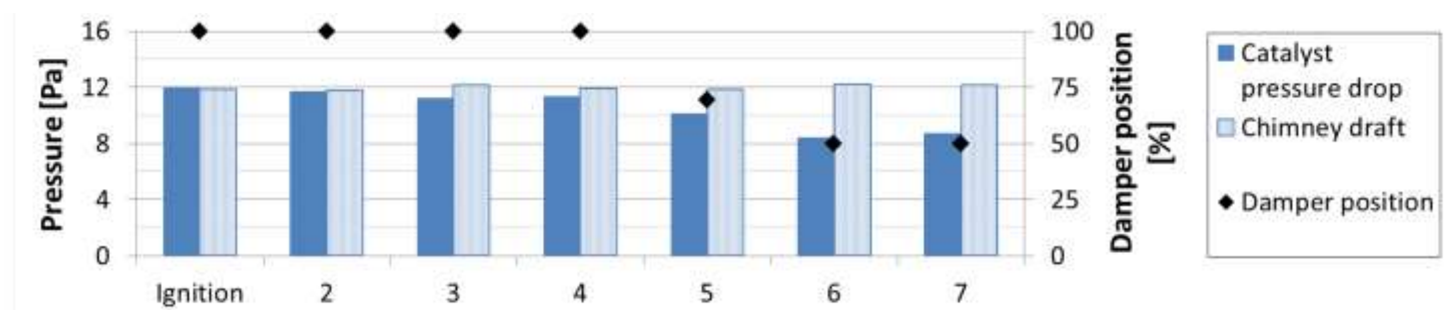
Catalyst evaluation at RISE
Prolonged testing – Flow resistance (II)



Test run with fresh catalyst at 400°C



Test run with aged catalyst at 400°C



Test run with cleaned catalyst at 400°C

Catalyst evaluation at RISE
Prolonged testing – Results (I)

Impact of catalyst aging and cleaning on reduction capacity

- **No clear change in conversion rates during evaluation period observed**
- **Still nearly complete conversion of CO**
  - Reason for tiny decrease in first test after cleaning (97-98% reduction) unknown, since reduction rate reached 99% again in later tests (possible caused by positioning in catalyst box)
- **Still significant hydrocarbon conversion**
  - Mainly in range 25-50% for moderate hydrocarbon content, reaching up to 70/80% at high hydrocarbon levels (observed with fresh, aged & cleaned catalyst)
  - Indication for an eventual decrease in reduction rate hard to distinguish due to strong dependence of reduction rate on hydrocarbon level & composition
- **Still significant particle reduction**
  - Generally in range 20-50%, higher reduction rates have been observed during whole evaluation period at batches with large hydrocarbon reduction
  - Reduction partly due to solid deposit on catalyst surface, observed at cleaning and on the basis of pressure drop trend (especially at low catalyst temperatures)

Catalyst evaluation at RISE
Prolonged testing – Results (II)

Flow resistance (catalyst pressure drop)

- **Noticeable flow resistance based on positioning (8 mesh stacked above each other) and mesh properties (low free cross section)**
- **”Temporarily” increase in flow resistance**
  - Extensive pressure drop increase when running long time at low catalyst temperatures (around 300°C and lower)
  - Increase due to continued accumulation of particles on catalyst surface
  - Mostly reversible when reaching higher catalyst temperatures (around 400°C and above) due to start of carbon conversion in deposited particles
- **”Permanently” increase in flow resistance**
  - Pressure drop increased during evaluation period (about 120h) from initial 8-12 Pa (damper settings 50/100%) up to 16-24 Pa (same damper settings)
  - Increase conforms with visual observation of particle deposit on surface
  - Removal of deposit through cleaning restored initial flow resistance conditions

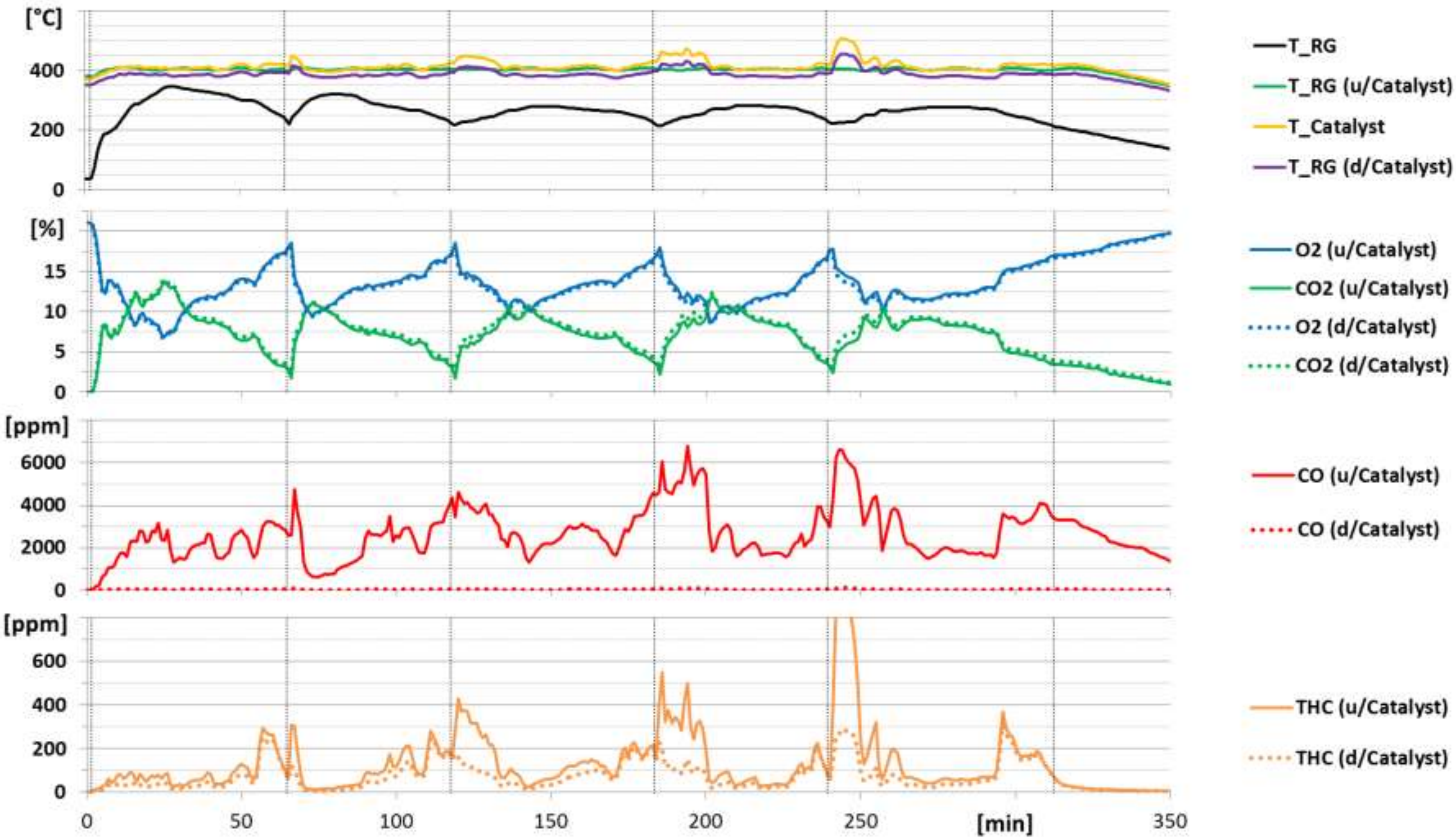
Catalyst test rig

Test runs with reduced area

Catalyst evaluation at RISE
Reduced catalyst area – Overview

- **Check for impact of reducing catalyst area on emission reduction capacity & flow resistance**
- **At least one test day each with**
  - **4 mesh (equals 50% of original area)**
  - **2 mesh (equals 25% of original area)**
  - **1 mesh (equals 12.5% of original area)**

Catalyst evaluation at RISE
Reduced catalyst area – 50% area (I)



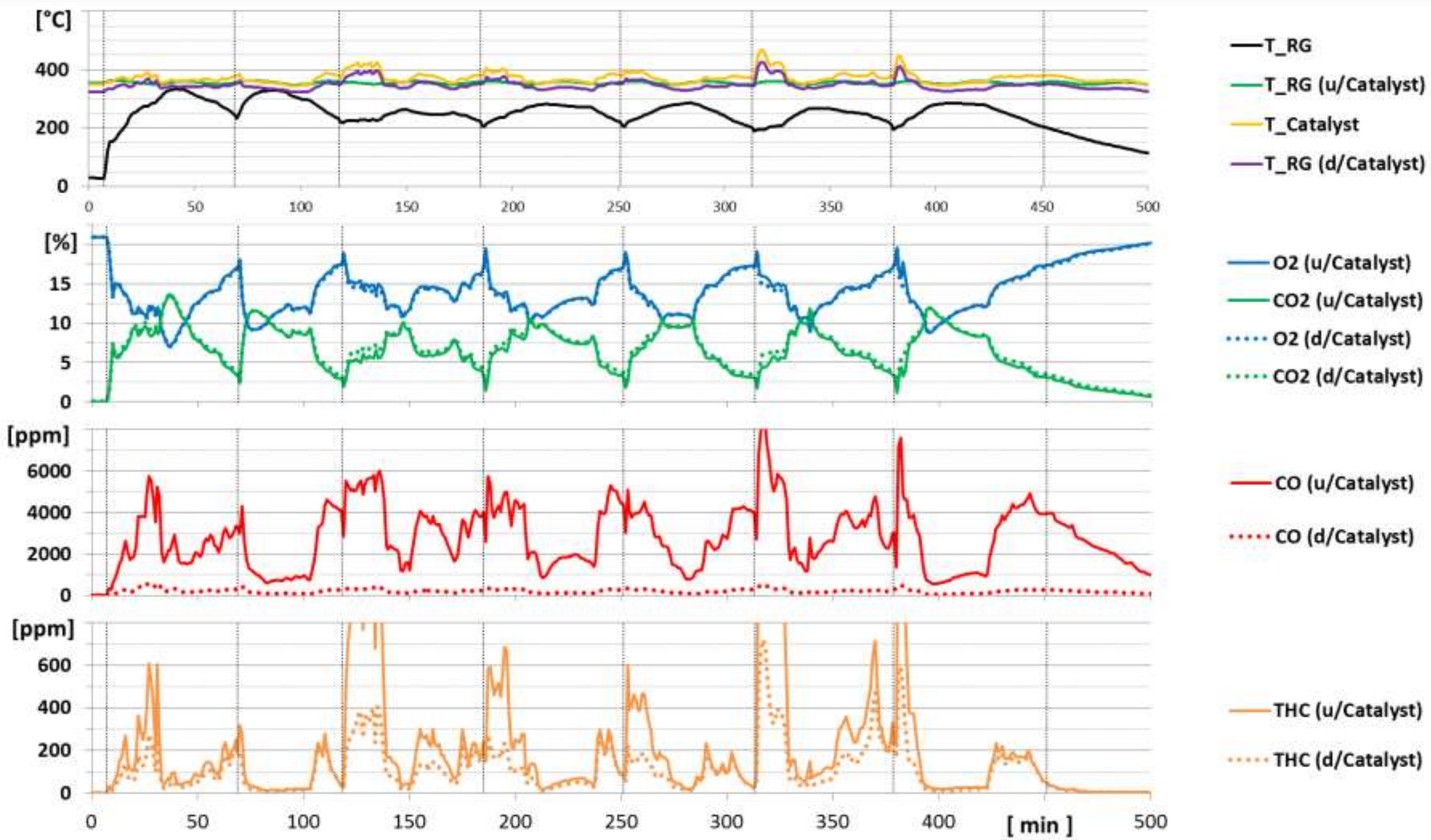
Catalyst evaluation at RISE
Reduced catalyst area – 50% area (II)

Batch			Ignition	2	3	4	5
Temperatures	Flue Gas	°C	285	283	258	261	256
	u/Catalyst	°C	404	405	405	404	404
	Catalyst	°C	408	410	417	422	423
	d/Catalyst	°C	385	386	390	394	394
Upstream catalyst	CO_2	%	8.3	7.2	7.1	7.9	7.0
	O_2	%	12.2	13.4	13.3	12.5	13.4
	CO at 13% O_2	%	0.19	0.22	0.30	0.30	0.32
		mg/m^3_N	2368	2808	3790	3776	4046
	OGC at 13% O_2	mg/m^3_N	136	193	280	256	369
	PME at 13% O_2	mg/m^3_N	26		27		37
Downstream catalyst	CO_2	%	8.6	7.5	7.6	8.4	7.5
	O_2	%	12.0	13.1	13.0	12.2	13.1
	CO at 13% O_2	%	0.004	0.003	0.004	0.004	0.004
		mg/m^3_N	50	43	47	47	51
	OGC at 13% O_2	mg/m^3_N	90	125	157	122	186
	PME at 13% O_2	mg/m^3_N	21		16		20
Reduction	CO	%	98	98	99	99	99
	OGC	%	33	34	43	52	49
	PME	%	16		38		45

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE

Reduced catalyst area – 25% area (I)

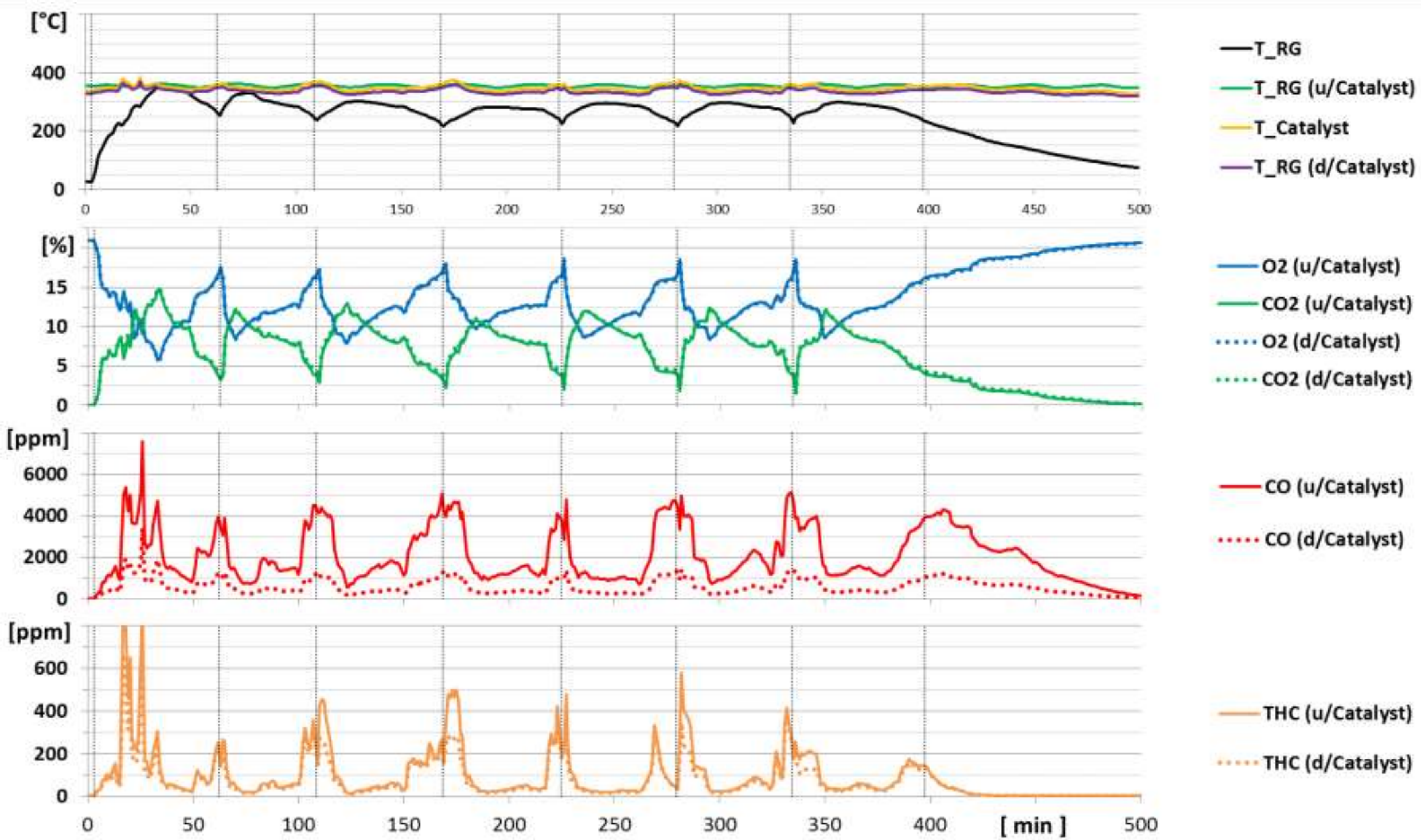


Catalyst evaluation at RISE
Reduced catalyst area – 25% area (II)

	Batch		Ignition	2	3	4	5	6	7
Temperatures	Flue Gas	°C	269	294	241	257	251	238	253
	u/Catalyst	°C	356	356	355	355	355	355	355
	Catalyst	°C	367	362	382	371	371	384	370
	d/Catalyst	°C	344	338	357	346	346	359	344
Upstream catalyst	CO_2	%	8.0	7.8	6.3	7.0	6.5	6.5	7.0
	O_2	%	12.6	12.7	14.2	13.4	14.0	14.0	13.5
	CO at 13% O_2	%	0.24	0.18	0.42	0.32	0.32	0.41	0.28
		mg/m^3_N	2977	2251	5269	3972	4026	5117	3481
	OGC at 13% O_2	mg/m^3_N	270	120	800	354	323	905	351
	PME at 13% O_2	mg/m^3_N	35		40			48	
Downstream catalyst	CO_2	%	8.3	8.0	6.8	7.4	6.8	7.0	7.3
	O_2	%	12.4	12.6	14.0	13.3	13.8	13.8	13.3
	CO at 13% O_2	%	0.025	0.015	0.025	0.020	0.023	0.026	0.018
		mg/m^3_N	310	184	317	256	287	324	230
	OGC at 13% O_2	mg/m^3_N	159	95	321	190	182	411	192
	PME at 13% O_2	mg/m^3_N	31		31			33	
Reduction	CO	%	90	92	94	94	93	94	93
	OGC	%	41	21	59	46	43	54	45
	PME	%	9		20			30	

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Reduced catalyst area – 12.5% area (I)

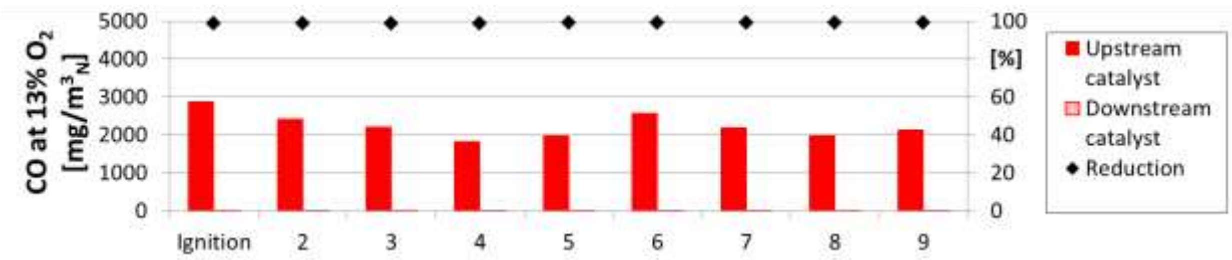


Catalyst evaluation at RISE
Reduced catalyst area – 12.5% area (II)

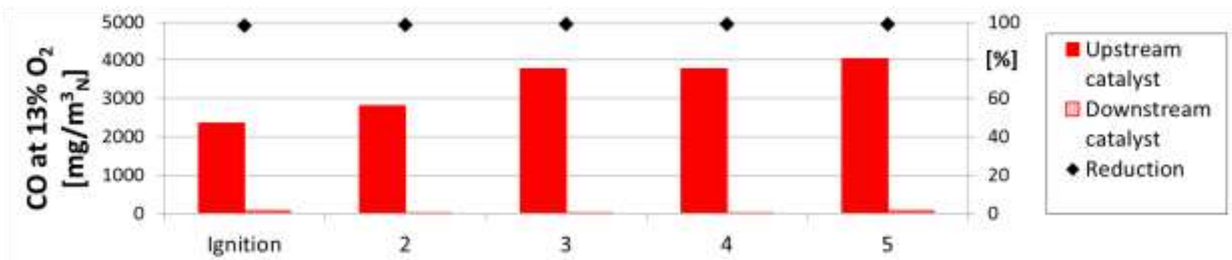
	Batch		Ignition	2	3	4	5	6	7
Temperatures	Flue Gas	°C	273	297	278	267	275	278	277
	u/Catalyst	°C	355	357	355	356	355	355	356
	Catalyst	°C	352	348	348	349	346	347	348
	d/Catalyst	°C	342	338	336	337	334	336	336
Upstream catalyst	CO_2	%	8.5	8.4	8.1	7.8	8.3	8.4	7.8
	O_2	%	12.0	12.1	12.4	12.7	12.2	12.1	12.7
	CO at 13% O_2	%	0.21	0.17	0.22	0.20	0.18	0.20	0.21
		mg/m^3_N	2608	2127	2700	2550	2243	2499	2663
	OGC at 13% O_2	mg/m^3_N	279	151	201	225	123	208	162
	PME at 13% O_2	mg/m^3_N	38		19			18	
Downstream catalyst	CO_2	%	8.7	8.5	8.3	8.0	8.4	8.5	7.9
	O_2	%	11.9	12.1	12.3	12.6	12.2	12.1	12.6
	CO at 13% O_2	%	0.072	0.049	0.055	0.053	0.050	0.054	0.057
		mg/m^3_N	901	615	688	665	627	678	718
	OGC at 13% O_2	mg/m^3_N	212	126	154	162	101	156	125
	PME at 13% O_2	mg/m^3_N	38		19			16	
Reduction	CO	%	65	71	74	74	72	73	73
	OGC	%	24	16	23	27	18	24	22
	PME	%	1		0			14	

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

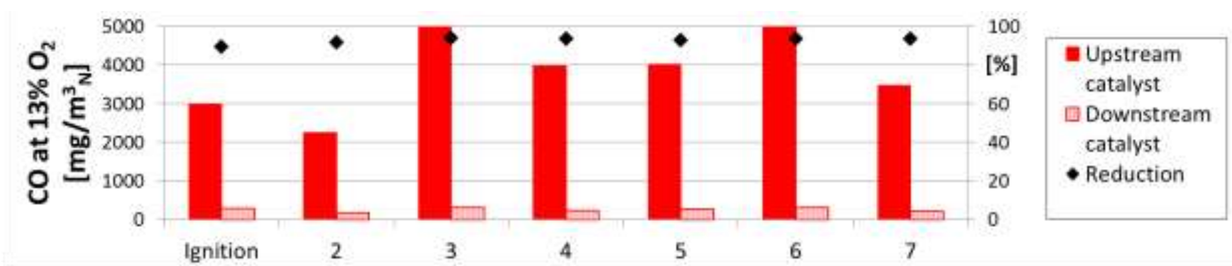
Catalyst evaluation at RISE
Reduced catalyst area – Comparison CO



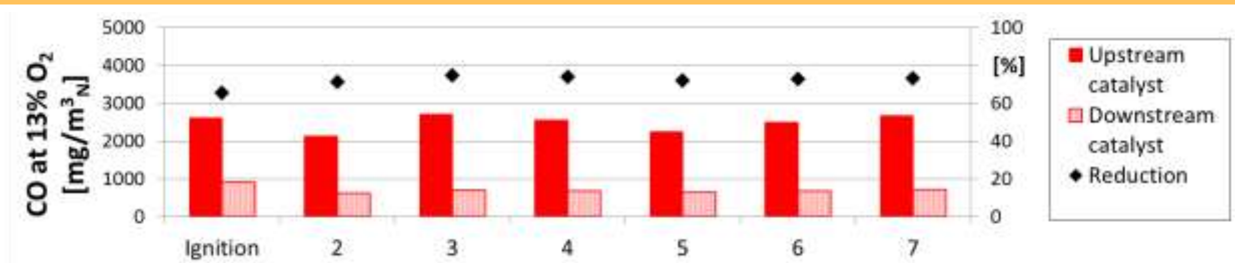
Catalyst 100% area (8 mesh) at 400°C



Catalyst 50% area (4 mesh) at 400°C

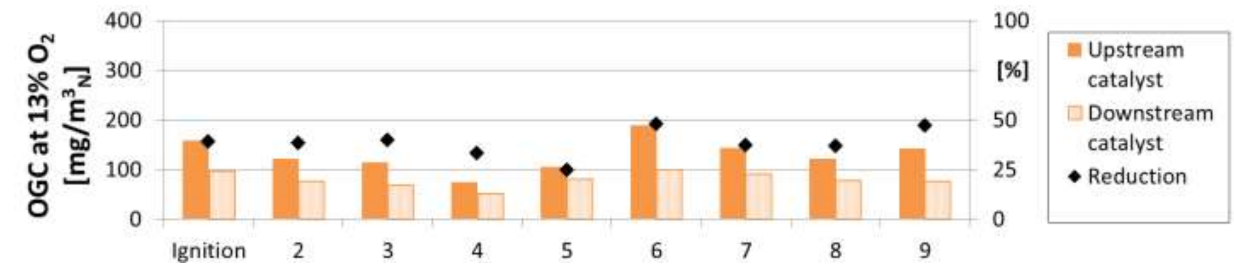


Catalyst 25% area (2 mesh) at 350°C

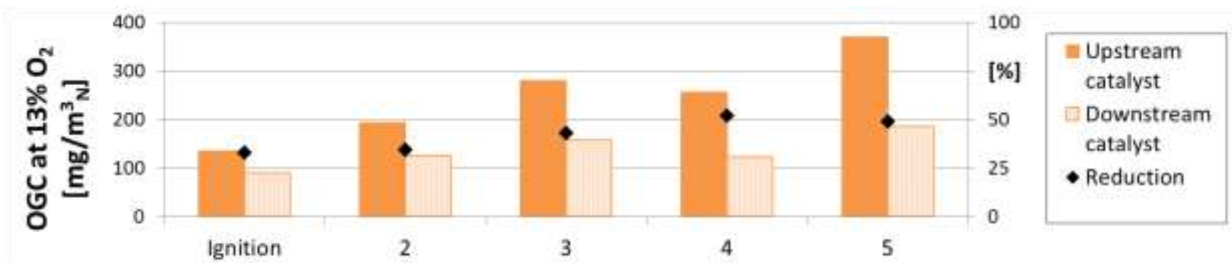


Catalyst 12.5% area (1 mesh) at 350°C

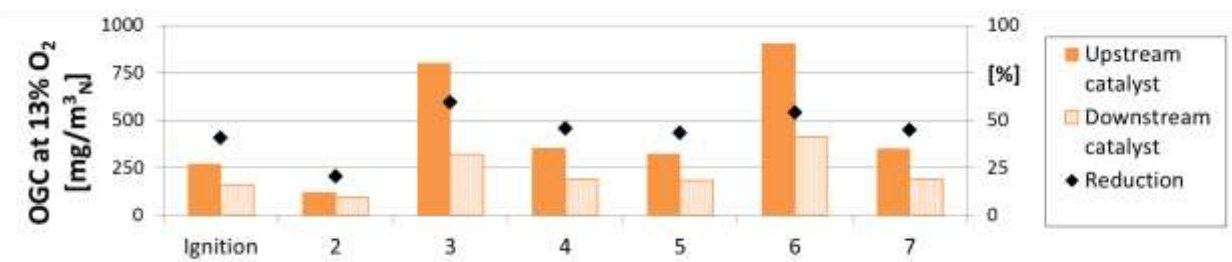
Catalyst evaluation at RISE
Reduced catalyst area – Comparison OGC



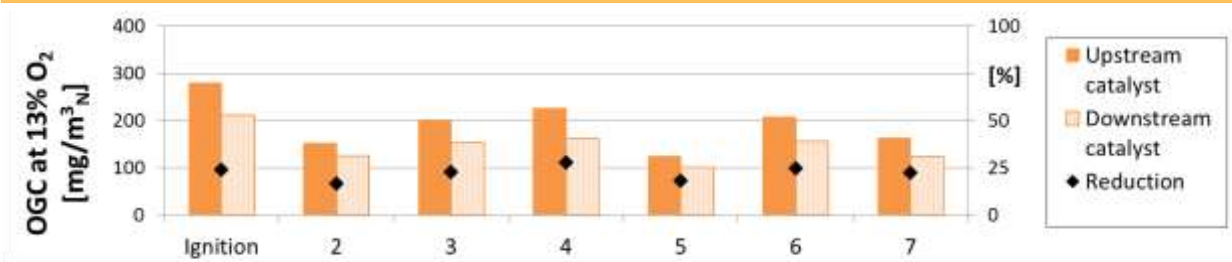
Catalyst 100% area (8 mesh) at 400°C



Catalyst 50% area (4 mesh) at 400°C

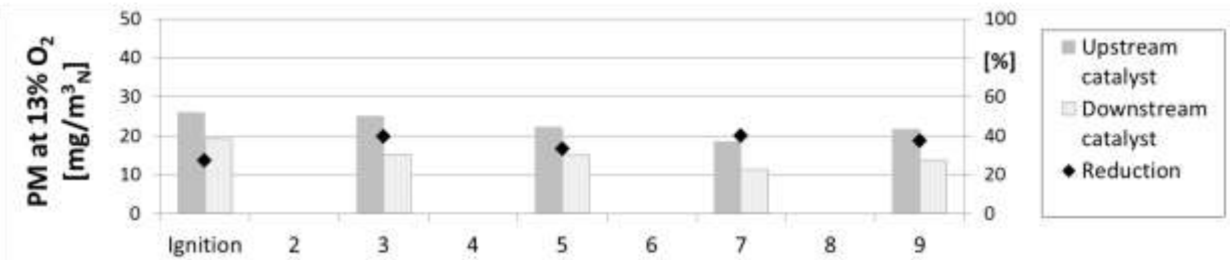


Catalyst 25% area (2 mesh) at 350°C

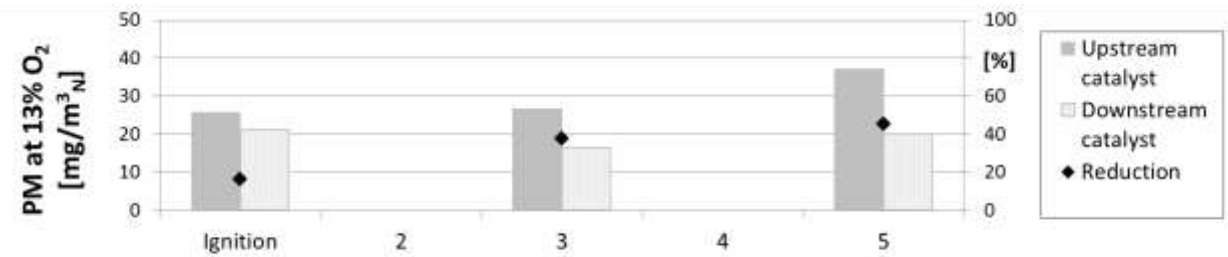


Catalyst 12.5% area (1 mesh) at 350°C

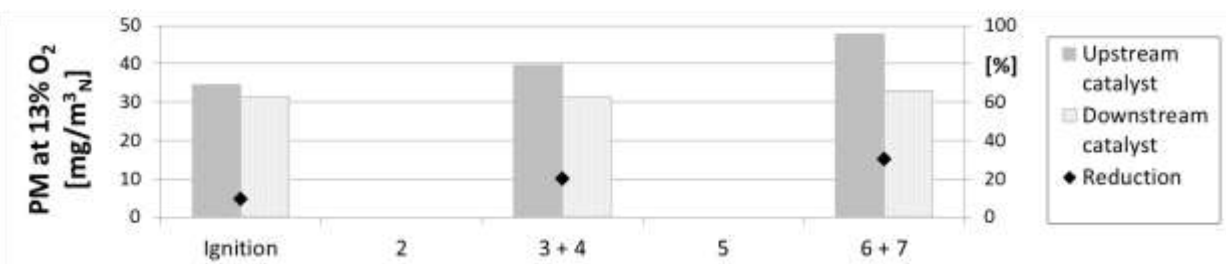
Catalyst evaluation at RISE
Reduced catalyst area – Comparison PM



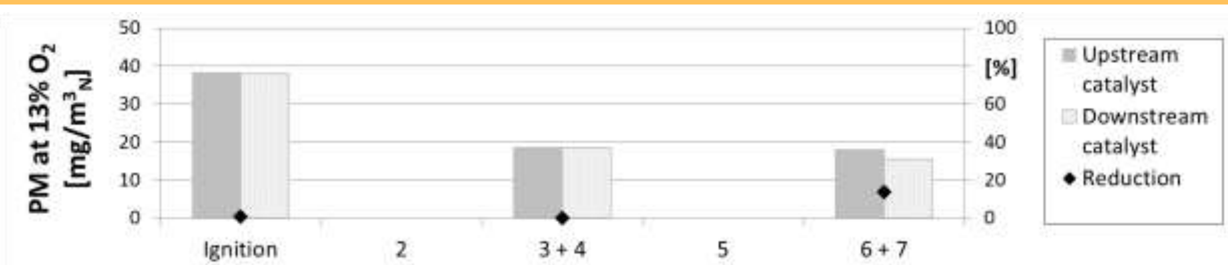
Catalyst 100% area (8 mesh) at 400°C



Catalyst 50% area (4 mesh) at 400°C

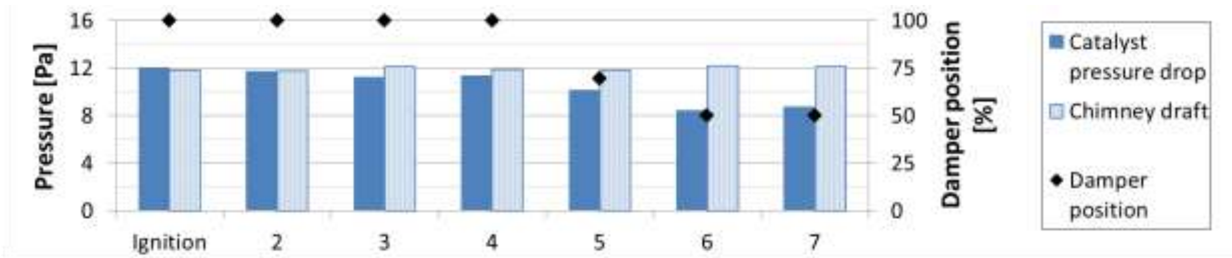


Catalyst 25% area (2 mesh) at 350°C

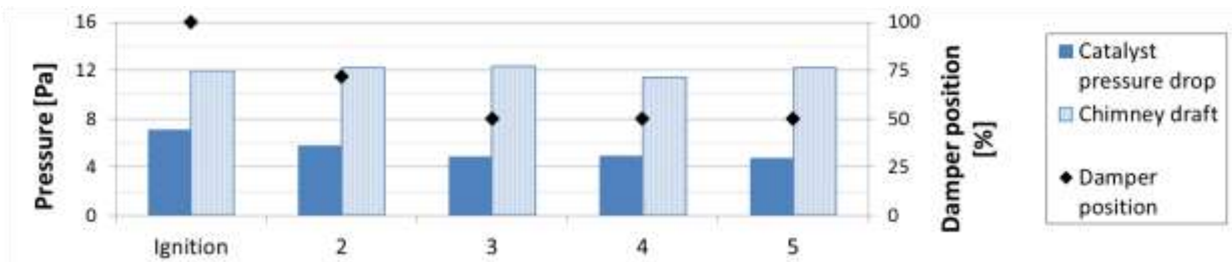


Catalyst 12.5% area (1 mesh) at 350°C

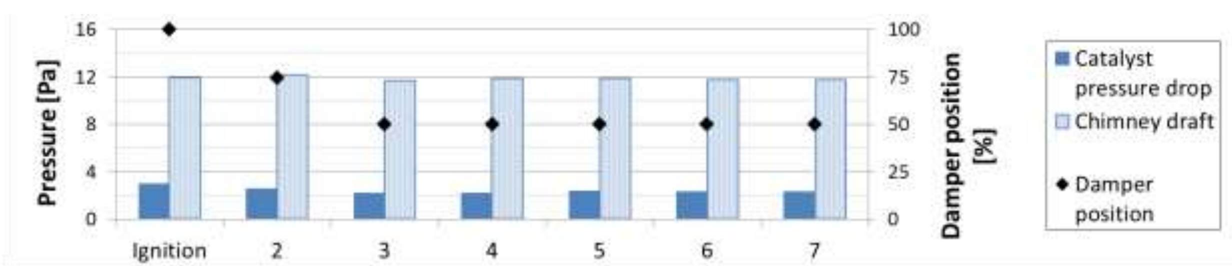
Catalyst evaluation at RISE
Reduced catalyst area – Flow resistance



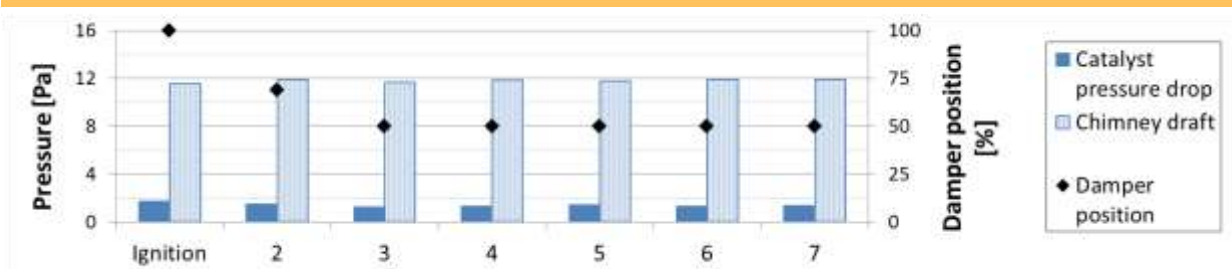
Catalyst 100% area (8 mesh) at 400°C



Catalyst 50% area (4 mesh) at 400°C



Catalyst 25% area (2 mesh) at 350°C



Catalyst 12.5% area (1 mesh) at 350°C

Catalyst evaluation at RISE
Reduced catalyst area – Results (I)

- **Still significant carbon monoxide reduction even with strongly reduced area**
  - **At 50% area still nearly complete reduction; indicates that catalyst is oversized for the purpose of CO conversion at given flue gas volume & carbon monoxide level**
  - **First noticeable drop in reduction capacity at 25% area and lower, with 90-95% CO reduction for 25% catalyst area and around 65-75% for 12.5% area**
- **Still significant hydrocarbon reduction, but seems more effected by area decrease**
  - **Capacity decrease is more clear when comparing the absolute achieved OGC values downstream catalyst during tests with reduced catalyst areas**
  - **But even with large area decrease (25% and lower) noticeable conversion of hydrocarbon, rising to even higher numbers during bad combustion conditions with high hydrocarbon content**

Catalyst evaluation at RISE
Reduced catalyst area – Results (II)

- **Particle reduction capacity most affected by area decrease**
  - **Particle reduction noticeably lower with reduced area (more clear at tests with less than 50% area)**
  - **Decrease in reduction capacity seems to be based on both, reduced hydrocarbon reduction and less particle deposit due to fewer meshes stacked above each other**
  - **At 25% area particle reduction seems exclusively based on reduction of particlse forming hydrocarbons, while at 12.5% area no clear particle reduction could be observed**
- **Significant improvement in flow resistance when decreasing stacked mesh**
  - **Relative pressure drop decrease correlates with reduction in mesh pieces**
  - **Therefore larger cross section, thus resulting in less stacked mesh, could be advantageous for stove integration (but possible negative effect on particle reduction capacity)**

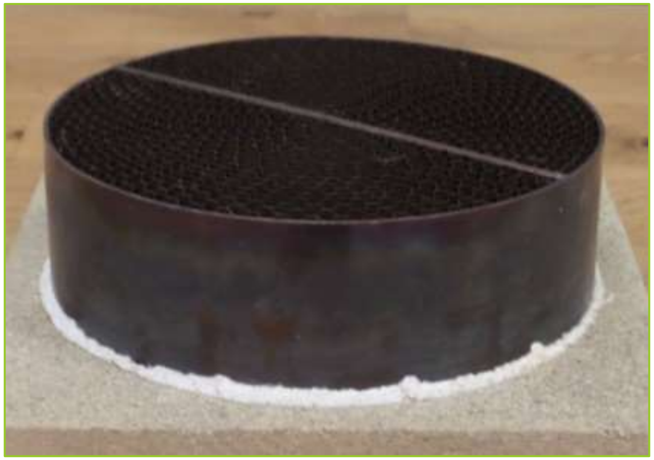
Catalyst test rig

Test runs with other catalyst models

Catalyst evaluation at RISE
Testing other catalysts – Overview

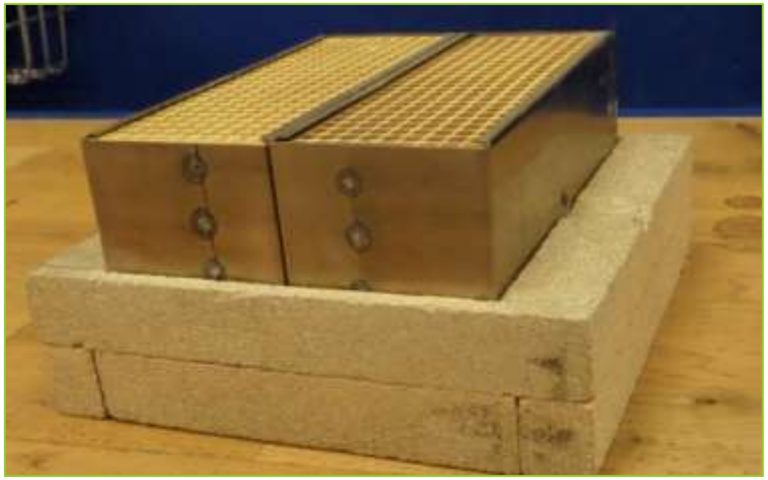
- Check with commercially available catalysts for comparison of reduction capacity & flow resistance

- At least one test day each with the different models (set point catalyst temperature 350°C)
  - 2 ceramic based honeycomb catalysts
  - 1 metal based honeycomb catalyst
  - 1 metal based packed bed catalyst

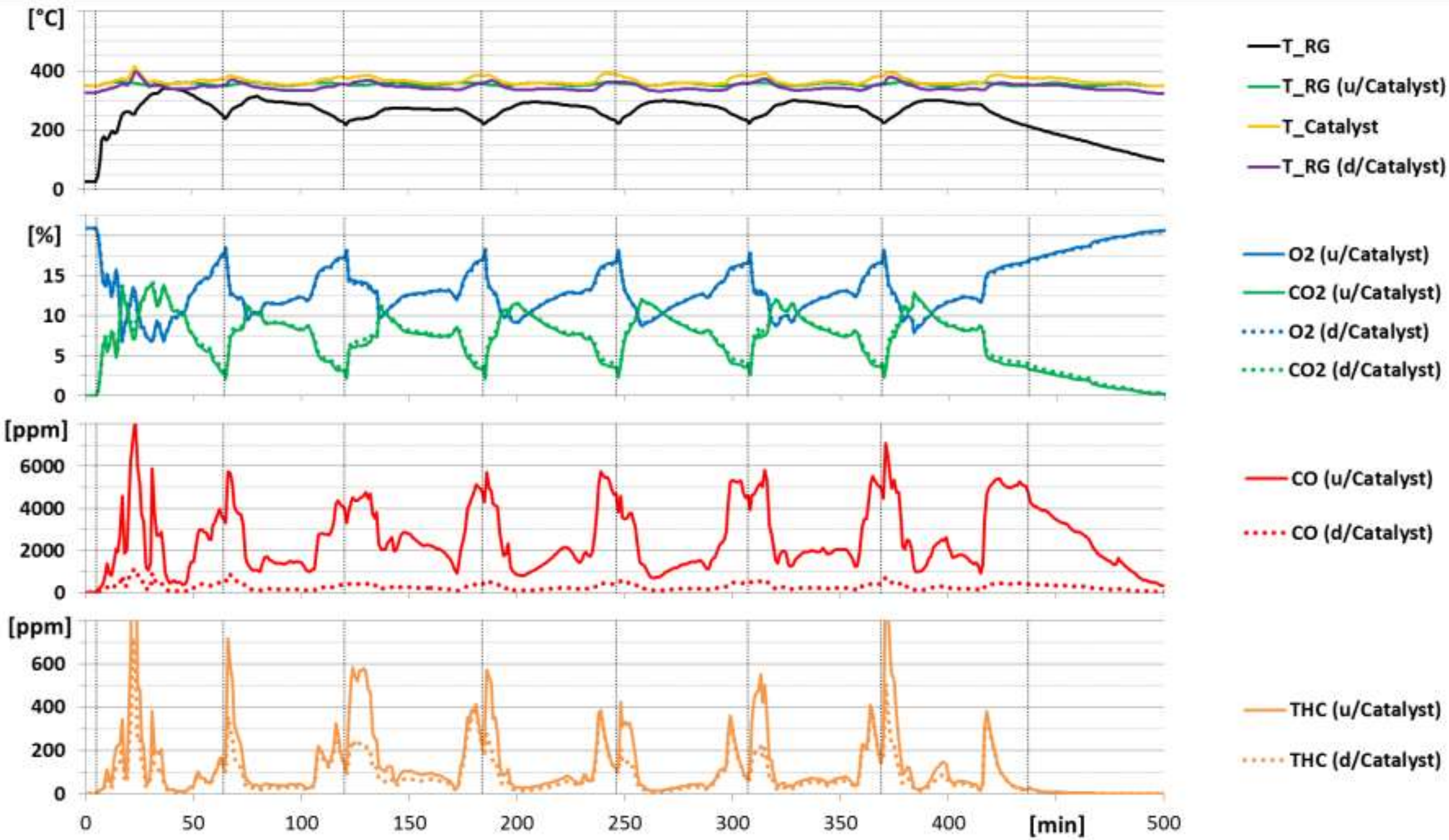


Catalyst evaluation at RISE
Testing other catalysts – Model 1 (I)

- **Manufacturer**
  - Condar
- **Type & Size**
  - Honeycomb catalyst
  - Outside dimension: L 165 x H 63 x H 50 mm (per piece)
- **Catalytic properties**
  - Base material: ceramic
  - Active material: platinum and palladium
- **Cost estimation**
  - N/A
- **Further information**
  - Life time around 12.000 hours, Light-off temperature around 260°C, with best results between 320°C and 800°C (stated)
  - Cell Density: 25 cpsi (square cell), free cross section per cell ca. 5x5mm



Catalyst evaluation at RISE
Testing other catalysts – Model 1 (II)



Catalyst evaluation at RISE
Testing other catalysts – Model 1 (III)

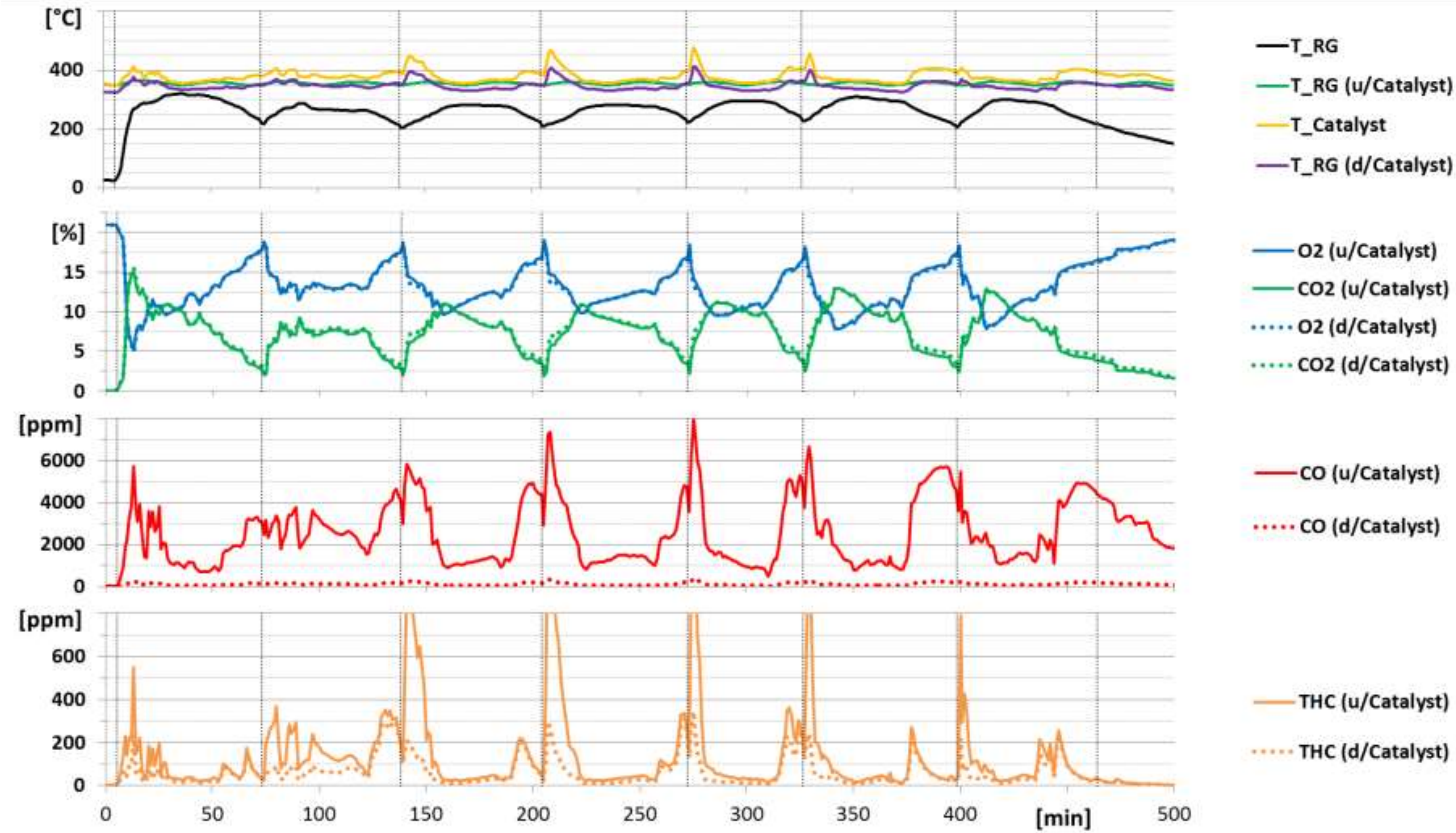
Batch			Ignition	2	3	4	5	6	7
Temperatures	Flue Gas	°C	276	281	260	273	276	276	270
	u/Catalyst	°C	356	356	355	355	355	355	355
	Catalyst	°C	367	366	369	365	364	366	371
	d/Catalyst	°C	349	345	349	344	343	346	349
Upstream catalyst	CO_2	%	8.6	7.5	7.2	7.9	7.9	8.0	7.5
	O_2	%	12.0	13.0	13.4	12.6	12.6	12.5	12.9
	CO at 13% O_2	%	0.21	0.23	0.31	0.24	0.22	0.26	0.32
	CO at 13% O_2	mg/m^3_N	2669	2881	3891	2967	2738	3220	3960
	OGC at 13% O_2	mg/m^3_N	267	234	382	217	175	243	252
	PME at 13% O_2	mg/m^3_N	42	22				21	
Downstream catalyst	CO_2	%	8.8	7.7	7.5	8.1	8.1	8.3	7.8
	O_2	%	11.9	13.0	13.3	12.6	12.6	12.4	12.8
	CO at 13% O_2	%	0.032	0.027	0.030	0.024	0.026	0.028	0.031
	CO at 13% O_2	mg/m^3_N	401	337	369	305	320	345	386
	OGC at 13% O_2	mg/m^3_N	163	163	230	148	125	162	160
	PME at 13% O_2	mg/m^3_N	35	16				16	
Reduction	CO	%	85	88	90	90	88	89	90
	OGC	%	39	30	40	31	28	33	36
	PME	%	18	25				24	

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Testing other catalysts – Model 2 (I)

- **Manufacturer**
  - Applied Ceramics
- **Type & Size**
  - Honeycomb catalyst
  - Dimension: ø 148mm, H 50 mm
- **Catalytic properties**
  - Base material: metal
  - Active material: Platinum/Palladium
- **Cost estimation**
  - About 40-60 Euro
- **Further information**
  - Wavelike cell shape, free cross section per cell about 5mm wide & 3.5mm high

Catalyst evaluation at RISE
Testing other catalysts – Model 2 (II)



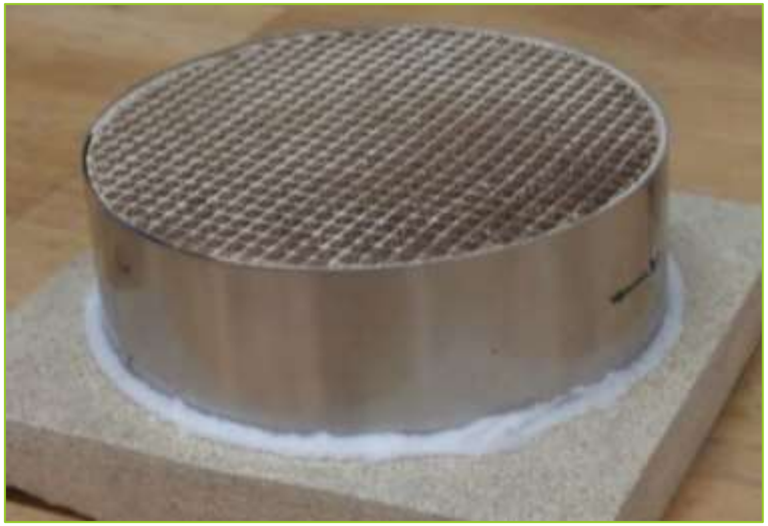
Catalyst evaluation at RISE
Testing other catalysts – Model 2 (III)

	Batch		Ignition	2	3	4	5	6	7
Temperatures	Flue Gas	°C	275	258	259	262	275	274	268
	u/Catalyst	°C	356	356	355	355	356	355	356
	Catalyst	°C	373	384	381	379	381	380	379
	d/Catalyst	°C	344	351	348	347	348	346	345
Upstream catalyst	CO_2	%	8.0	6.5	7.5	7.6	8.3	8.2	7.8
	O_2	%	12.5	14.1	12.9	12.9	12.1	12.2	12.6
	CO at 13% O_2	%	0.18	0.33	0.26	0.24	0.23	0.26	0.26
		mg/m^3_N	2264	4130	3209	2966	2835	3291	3252
	OGC at 13% O_2	mg/m^3_N	138	367	296	311	284	173	172
	PME at 13% O_2	mg/m^3_N	24	30				15	
Downstream catalyst	CO_2	%	8.2	6.8	7.8	7.9	8.6	8.4	8.0
	O_2	%	12.5	14.0	12.9	12.8	12.0	12.2	12.6
	CO at 13% O_2	%	0.008	0.014	0.011	0.010	0.010	0.011	0.011
		mg/m^3_N	106	177	135	127	126	137	137
	OGC at 13% O_2	mg/m^3_N	77	201	113	116	117	80	95
	PME at 13% O_2	mg/m^3_N	17	17				14	
Reduction	CO	%	95	96	96	96	96	96	96
	OGC	%	44	45	61	62	59	53	44
	PME	%	27	44				8	

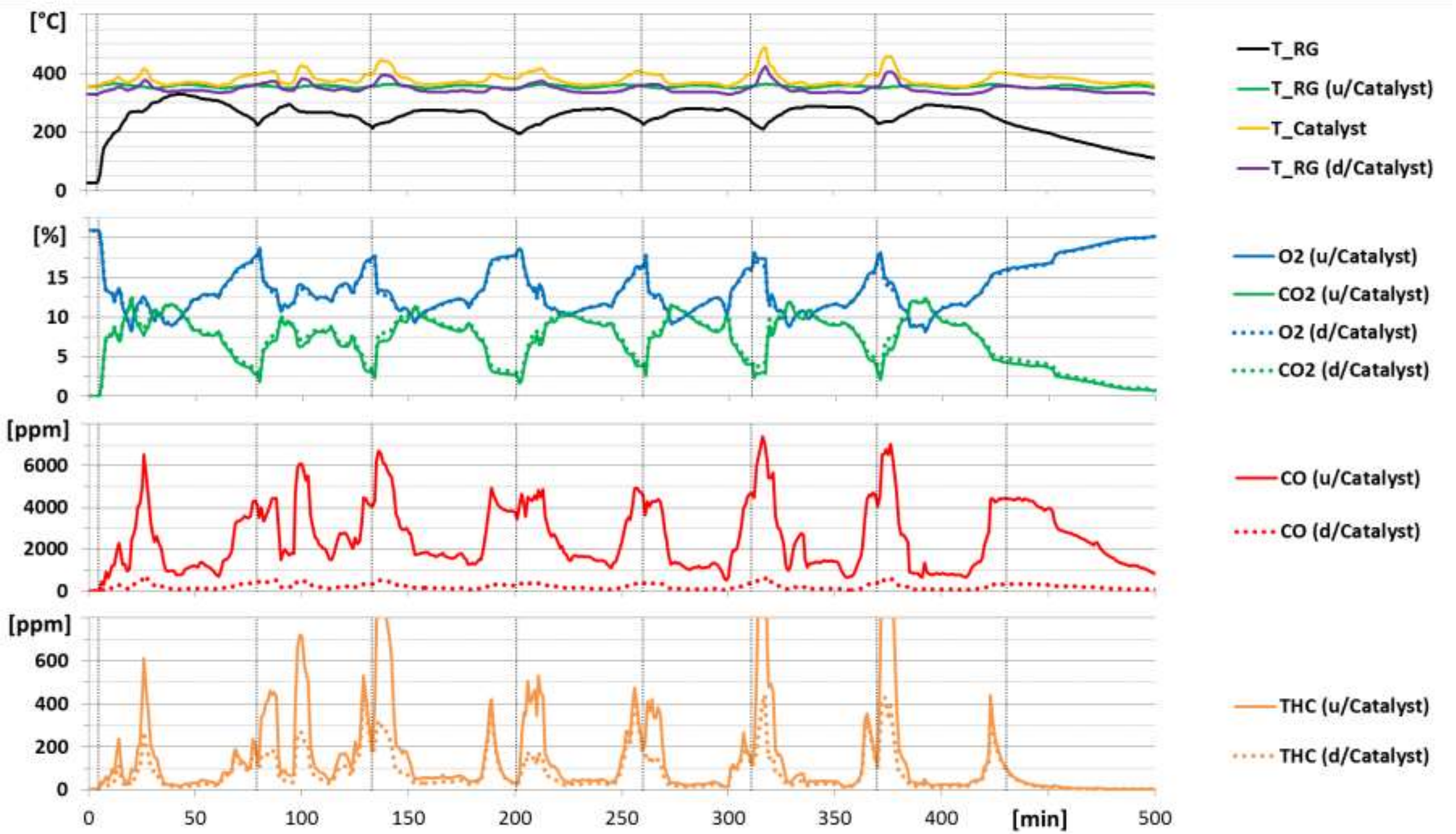
Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Testing other catalysts – Model 3 (I)

- **Manufacturer**
  - **Applied Ceramics**
- **Type & Size**
  - **Honeycomb catalyst**
  - **Dimension: ø 148mm, H 50 mm**
- **Catalytic properties**
  - **Base material: ceramic (Cordierite)**
  - **Active material: Platinum/Palladium**
- **Cost estimation**
  - **About 40-60 Euro**
- **Further information**
  - **Cell Density 25 cpsi (square cell), free cross section per cell ca. 5x5mm**



Catalyst evaluation at RISE
Testing other catalysts – Model 3 (II)



Catalyst evaluation at RISE
Testing other catalysts – Model 3 (III)

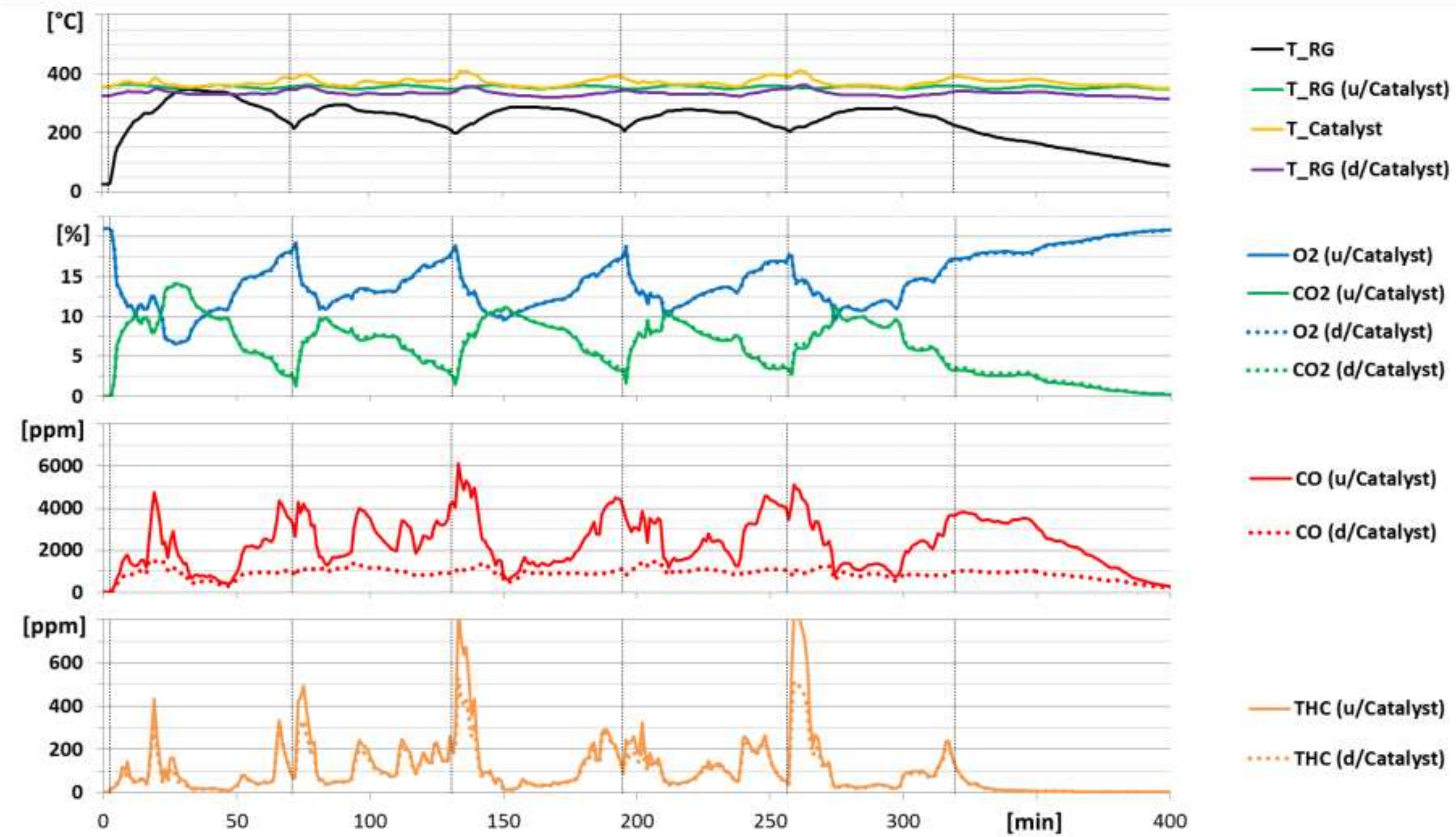
Batch			Ignition	2	3	4	5	6	7
Temperatures	Flue Gas	°C	273	261	254	254	265	267	268
	u/Catalyst	°C	357	354	355	356	354	356	356
	Catalyst	°C	374	386	384	381	373	384	380
	d/Catalyst	°C	345	354	350	347	341	349	347
Upstream catalyst	CO_2	%	7.9	6.8	7.3	7.7	8.2	8.1	8.2
	O_2	%	12.6	13.7	13.2	12.8	12.3	12.4	12.3
	CO at 13% O_2	%	0.19	0.35	0.30	0.27	0.20	0.25	0.22
		mg/m^3_N	2404	4348	3795	3357	2503	3122	2773
	OGC at 13% O_2	mg/m^3_N	173	476	341	286	180	325	340
	PME at 13% O_2	mg/m^3_N	28	27				33	
Downstream catalyst	CO_2	%	8.2	7.2	7.7	8.0	8.5	8.5	8.4
	O_2	%	12.6	13.5	13.0	12.7	12.2	12.3	12.3
	CO at 13% O_2	%	0.022	0.032	0.024	0.022	0.017	0.020	0.018
		mg/m^3_N	274	394	295	270	217	252	225
	OGC at 13% O_2	mg/m^3_N	106	251	169	157	104	145	155
	PME at 13% O_2	mg/m^3_N	22	18				22	
Reduction	CO	%	89	91	92	92	91	92	92
	OGC	%	39	47	50	45	42	55	54
	PME	%	19	35				33	

Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Testing other catalysts – Model 4 (I)

- **Manufacturer**
  - **N/A**
- **Type & Size**
  - **Packed bed catalyst**
  - **Outside dimension: ø 168mm, H 85 mm**
  - **Filled with 1.5 liter metal shavings**
- **Catalytic properties**
  - **Base material: metal (CrNiMo steel)**
  - **Active material: palladium**
- **Cost estimation**
  - **N/A**
- **Further information**
  - **Life time around 16.000 hours, Light-off temperature around 180°C, with optimum temperature range between 300°C and 700°C (stated)**

Catalyst evaluation at RISE
Testing other catalysts – Model 4 (II)

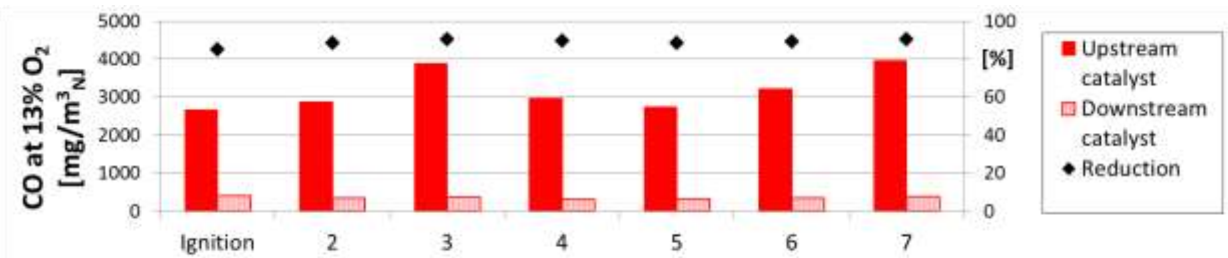


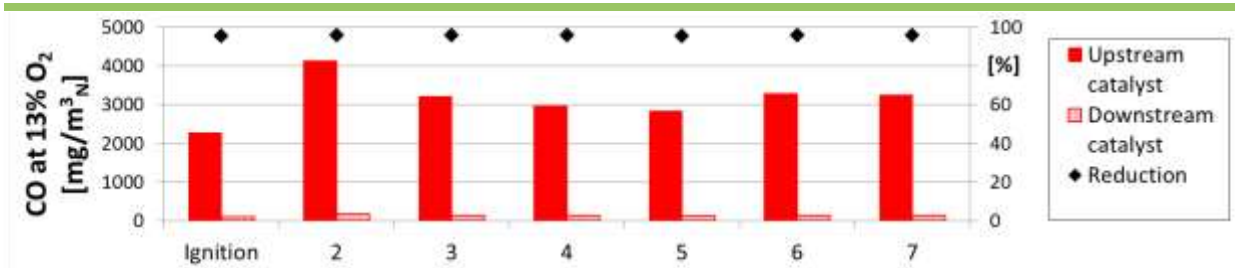
Catalyst evaluation at RISE
Testing other catalysts – Model 4 (III)

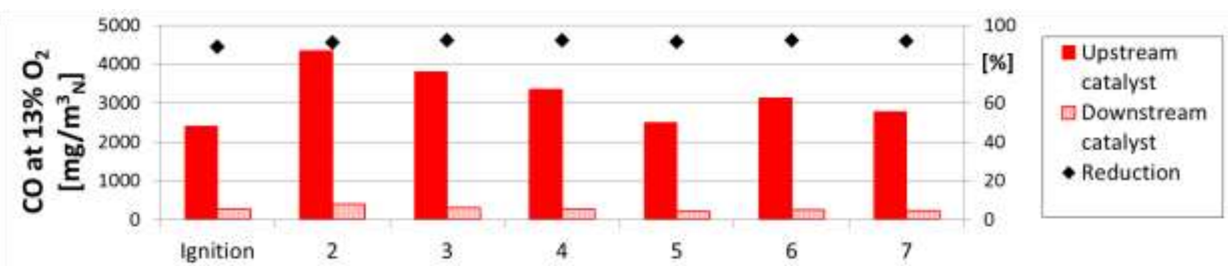
Batch			Ignition	2	3	4	5
Temperatures	Flue Gas	°C	285	261	262	255	259
	u/Catalyst	°C	356	356	356	355	355
	Catalyst	°C	366	374	372	373	370
	d/Catalyst	°C	335	337	333	335	334
Upstream catalyst	CO_2	%	8.4	6.5	7.6	6.8	7.4
	O_2	%	12.2	14.1	13.0	13.8	13.2
	CO at 13% O_2	%	0.17	0.32	0.25	0.31	0.23
		mg/m^3_N	2064	4022	3139	3846	2865
	OGC at 13% O_2	mg/m^3_N	128	316	272	255	285
	PME at 13% O_2	mg/m^3_N	30		25		30
Downstream catalyst	CO_2	%	8.5	6.7	7.8	6.9	7.6
	O_2	%	12.2	14.0	12.9	13.8	13.1
	CO at 13% O_2	%	0.08	0.12	0.09	0.12	0.09
		mg/m^3_N	943	1512	1164	1483	1129
	OGC at 13% O_2	mg/m^3_N	108	272	217	225	213
	PME at 13% O_2	mg/m^3_N	30		18		21
Reduction	CO	%	54	62	63	61	60
	OGC	%	15	13	20	11	25
	PME	%	1		27		30

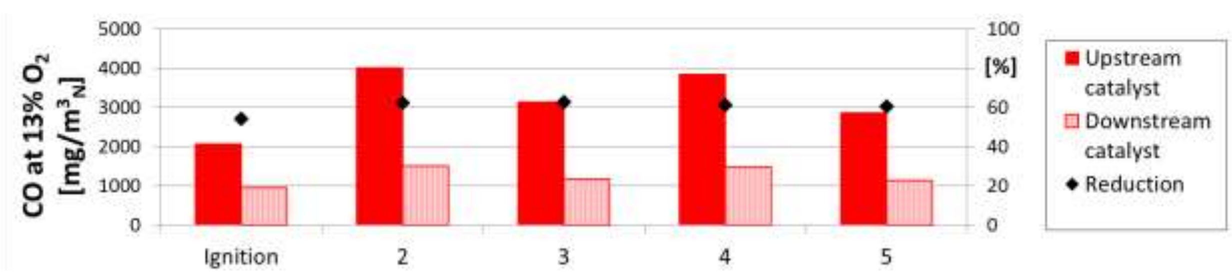
Note: Reduction rates calculated by dividing absolute values, derived from multiplying the relative emission value in question with respective flue gas volume up- and downstream catalyst (flue gas volume according to prEN 16510, based on CO&CO_2)

Catalyst evaluation at RISE
Testing other catalysts – Comparison CO

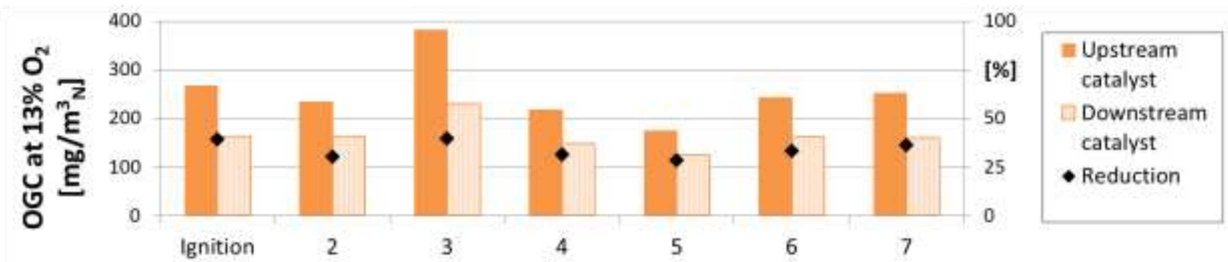


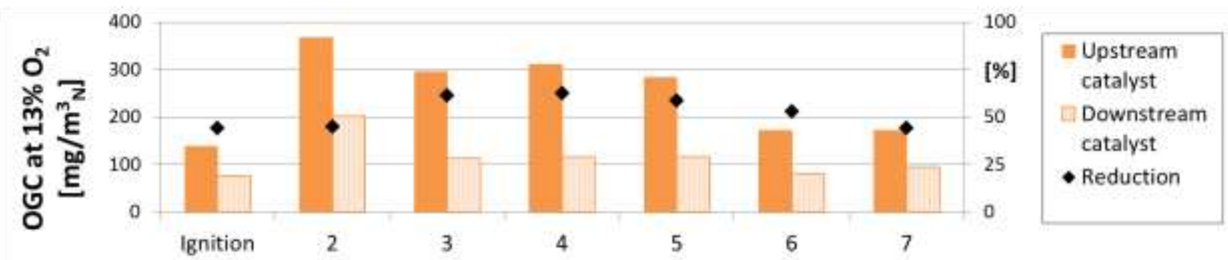


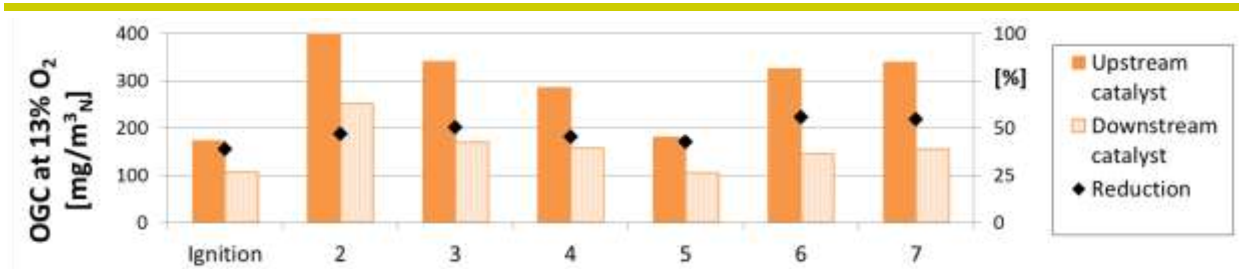


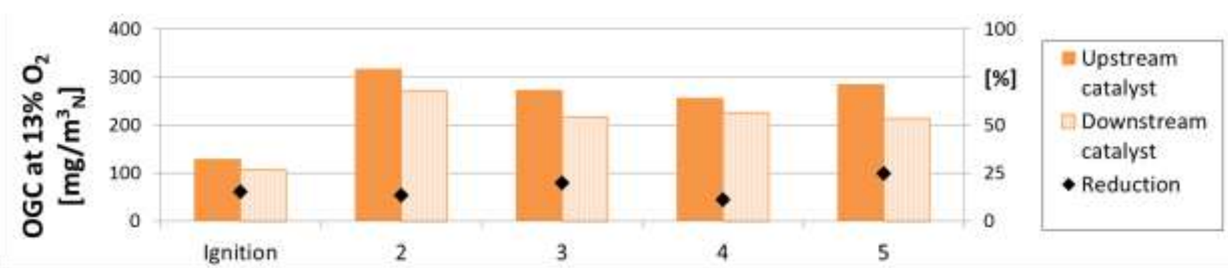


Catalyst evaluation at RISE
Testing other catalysts – Comparison OGC

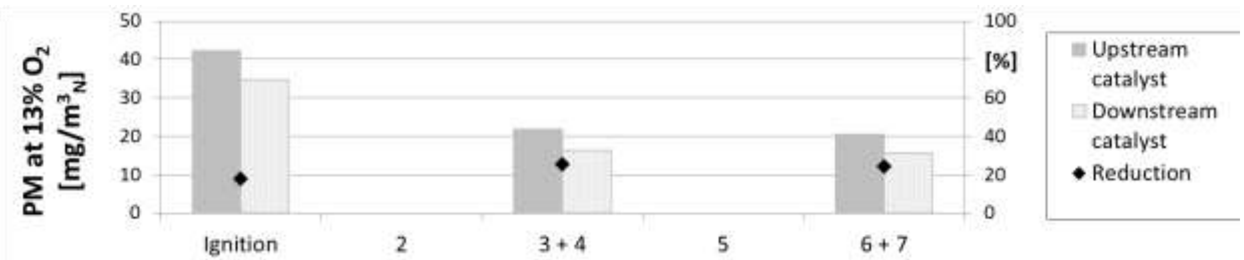


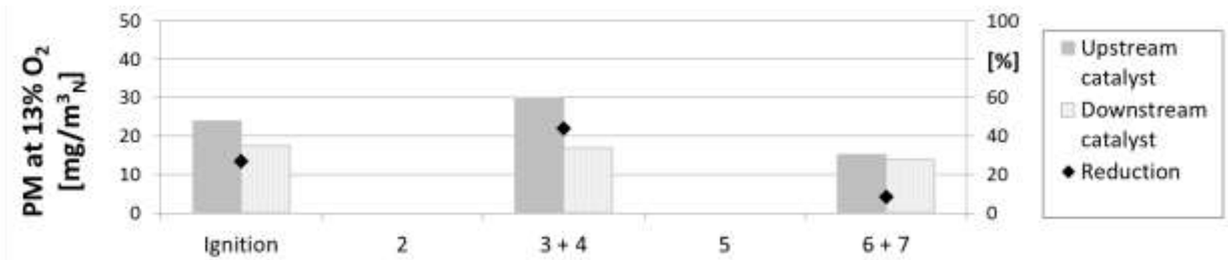


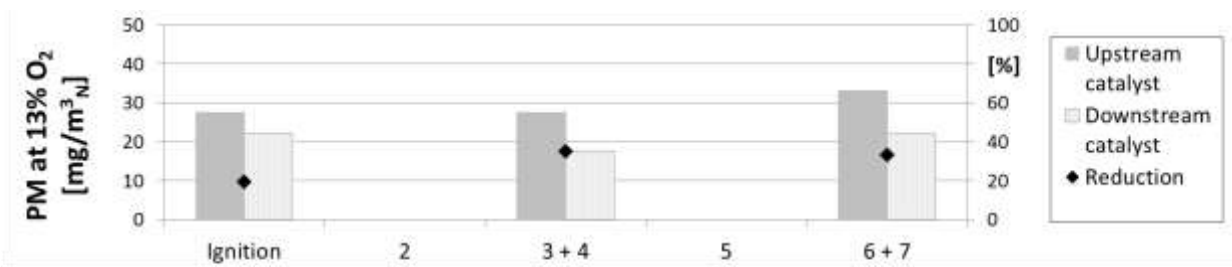


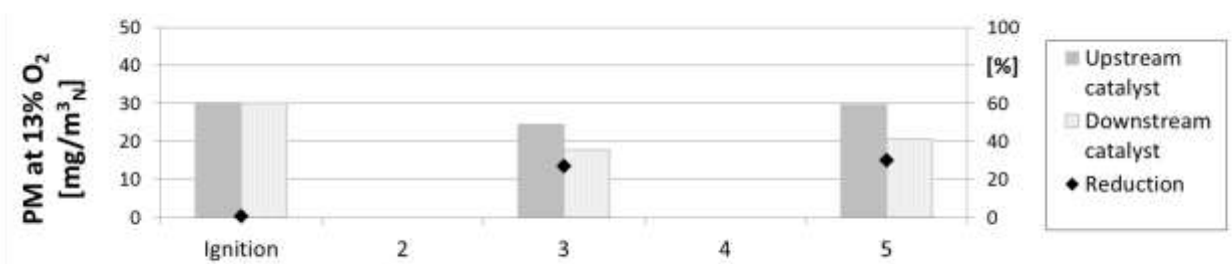


Catalyst evaluation at RISE
Testing other catalysts – Comparison PM

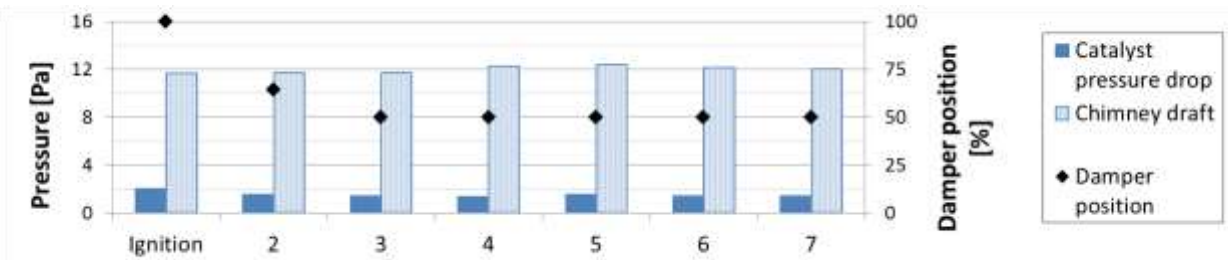


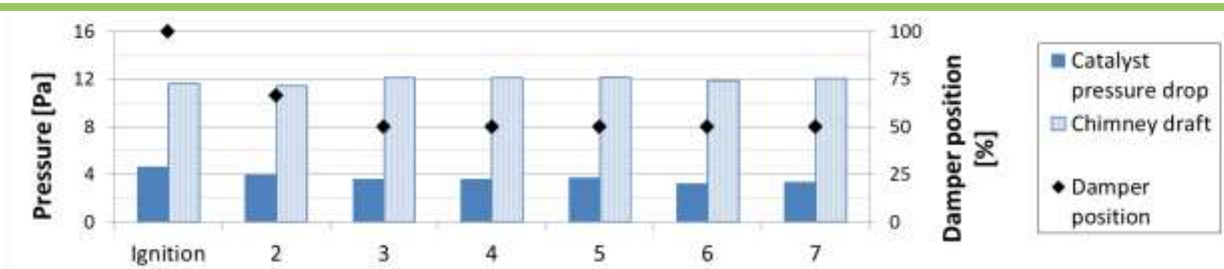


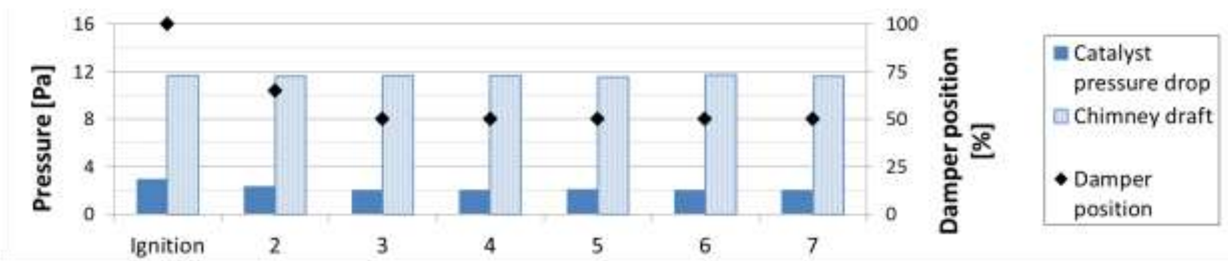


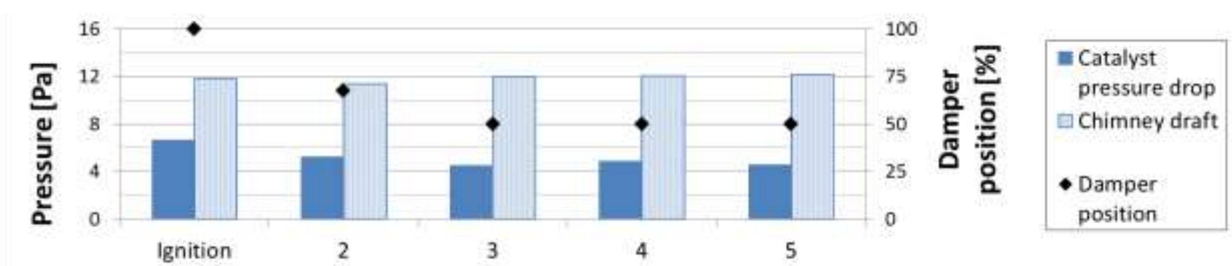


Catalyst evaluation at RISE
Testing other catalysts – Flow resistance









Catalyst evaluation at RISE
Testing other catalysts – Results (I)

- **Conversion of carbon monoxide**
  - **Significant CO reduction for honeycomb catalysts in range 90-95%, with metal based honeycomb (model 2) slightly better than others**
  - **Noticeably lower CO reduction in range 55-65% for packed bed catalyst**
- **Conversion of hydrocarbons**
  - **Hydrocarbon reduction for the circular honeycomb catalysts at 40-60%, again with model 2 slightly higher than model 3**
  - **Hydrocarbon reduction for rectangular honeycomb catalyst (model 1) in range around 30-40%, lower than other honeycomb catalysts (possible impact of coating / active material)**
  - **Hydrocarbon reduction for packed bed catalyst in range 15-25%, again noticeably lower than for other catalysts**

Catalyst evaluation at RISE
Testing other catalysts – Results (II)

Particle

- Particle reduction in the range of 10-40%, strongly correlating with reduction rates for hydrocarbons

Flow resistance

- Pressure drop for honeycomb catalysts in the range between 1.5 – 4 Pa, with model 2 (metal based honeycomb with smaller free cross section per cell) at upper end and model 1 (2 parallel rectangular units) at lower end of range
- Slightly higher pressure drop for packed bed catalyst in the range of 4-6 Pa

Others

- Results cover initial test with fresh catalysts, no statement can be made about long-term behavior
- Regarding reduction of gaseous emissions & particles models comparable to observed reduction rates with mesh catalyst at 25-50% area

Stove integrated catalyst

Evaluation & Results

RISE NIBE

Catalyst evaluation at RISE
Stove integrated catalyst – Test stand

ERA-NET Bioenergy

- **Setup**
  - **Traditional stove with new socket for integration of catalyst (ø 150mm)**
  - **Upstream sampling for gaseous emissions**
  - **Downstream sampling according to prEN 16510**
- **Measurement equipment**
  - **2 sampling trains for gaseous components**
    - M&C PMA 10 (paramagnetic oxygen analyzer)
    - Emerson NDIR analyzer X-Stream XEGC (CO, CO_2)
    - JUM FID 3-300A & JUM FID VE5 (hydrocarbons)
  - **2 sampling trains for particles (gravimetric)**
    - Nozzle ø 12 mm, Sampling volume about 0.6 m^3/h
    - Plane filter, Filter temperature at sampling 180°C
  - **Thermocouples & pressure transmitter**

Catalyst evaluation at RISE
Stove integrated catalyst – Test method

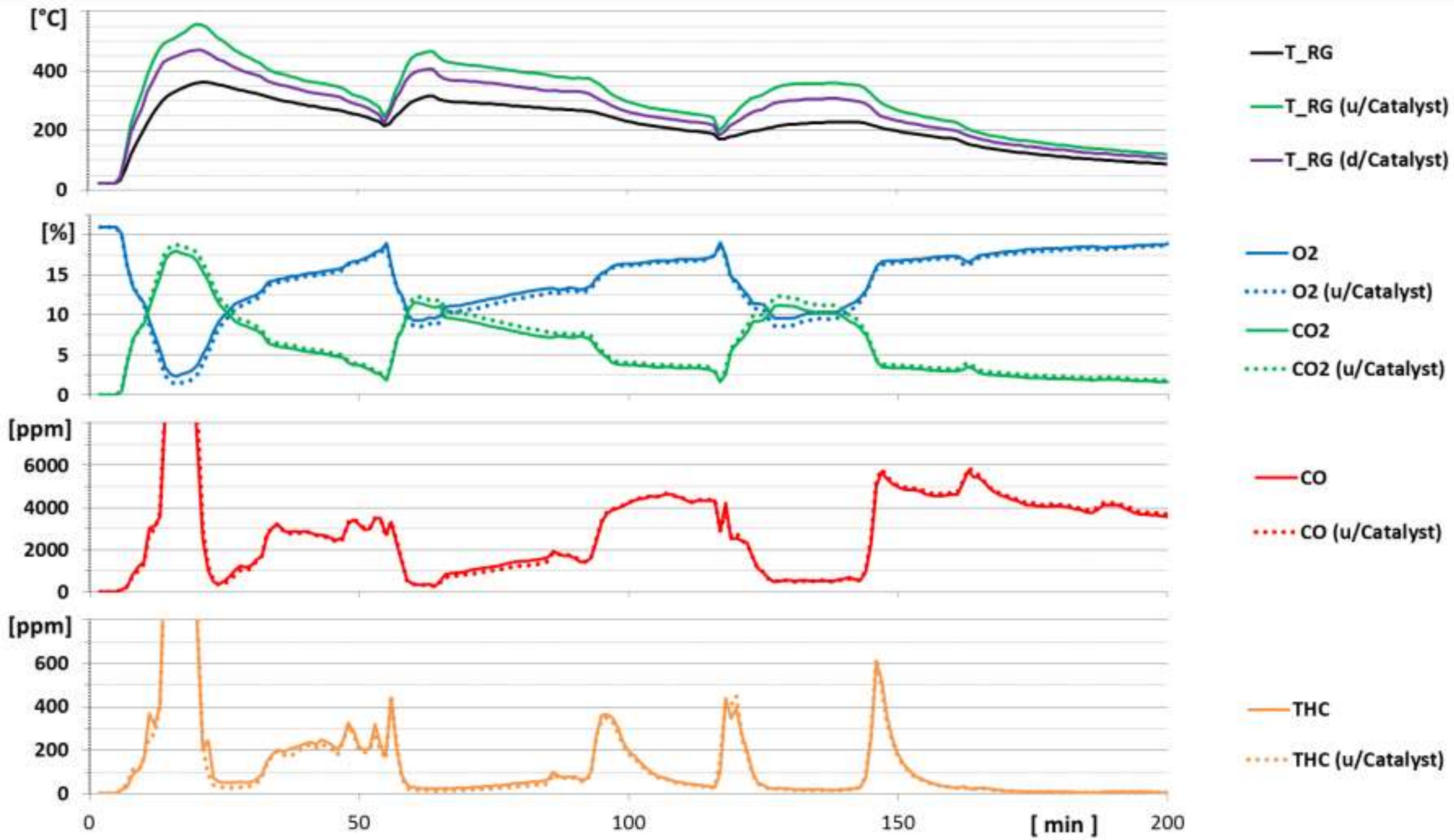
■ Wood Stoves 2020 "close to real life" testing method

- **8 batches (5 nominal load including ignition batch, 3 partial load)**
- **Bark free birch wood, triangular shaped, moisture content 16%**
- **PM sampling during batch 1,3,5 & 7 and complete test (2nd sampling train), sampling during complete batch (open door till open door)**
- **Recharge criterion: CO_2 between 3-4% when CO_2 < 25% of $CO_{2,max}$**
- **Stove settings**
  - Wood mass
    - » 2.2 kg Ignition batch
    - » 1.5 kg batch 2-5 (2 pieces)
    - » 0.75 kg batch 6-8 (2 pieces)
  - Damper settings
    - » 100% at ignition and 2nd batch
    - » 50% at batch 3-5
    - » 40% at batch 6-8

Catalyst evaluation at RISE
Stove integrated catalyst – Test scheme

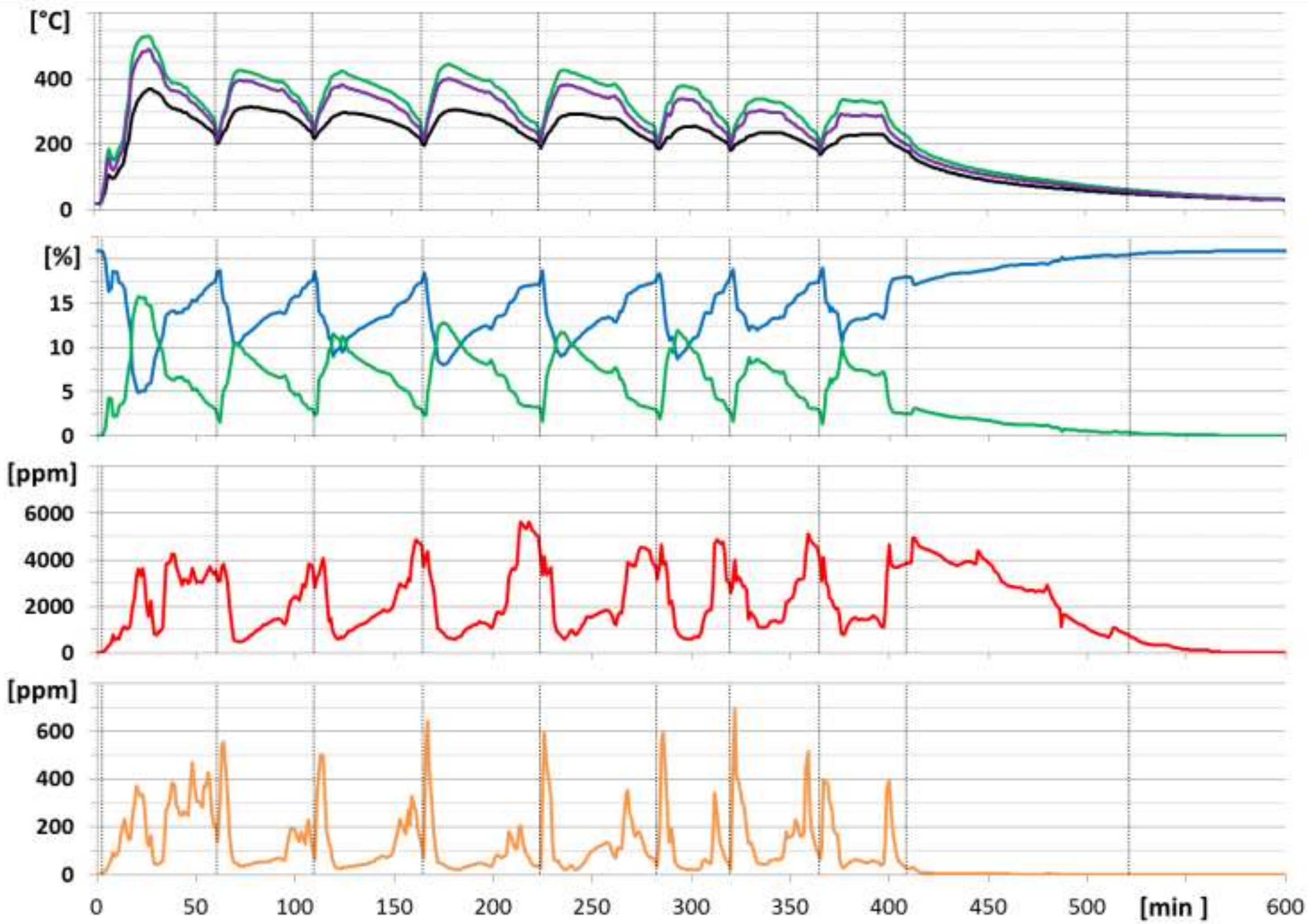
- **Control of sampling locations**
- **Reference test without catalyst**
- **Test with Catalyst(2)**
  - **2 mesh at ø 150mm (equals 18% of original catalyst area)**
  - **Mesh stacked directly above each other**
  - **Following stove settings**
- **Test with Catalyst(4)**
  - **4 mesh at ø 150mm (equals 35% of original catalyst area)**
  - **Mesh stacked with spacer in between**
  - **Modified stove settings, to match air flow for original stove settings**
    - Dampers at 100% for batch 1-5
    - Dampers at 50% for batch 6-8

Catalyst evaluation at RISE
Stove integrated catalyst – Control sampling



Note: Upstream values for CO & THC corrected to O_2 content downstream catalyst

Catalyst evaluation at RISE
Stove integrated catalyst – Reference test (I)

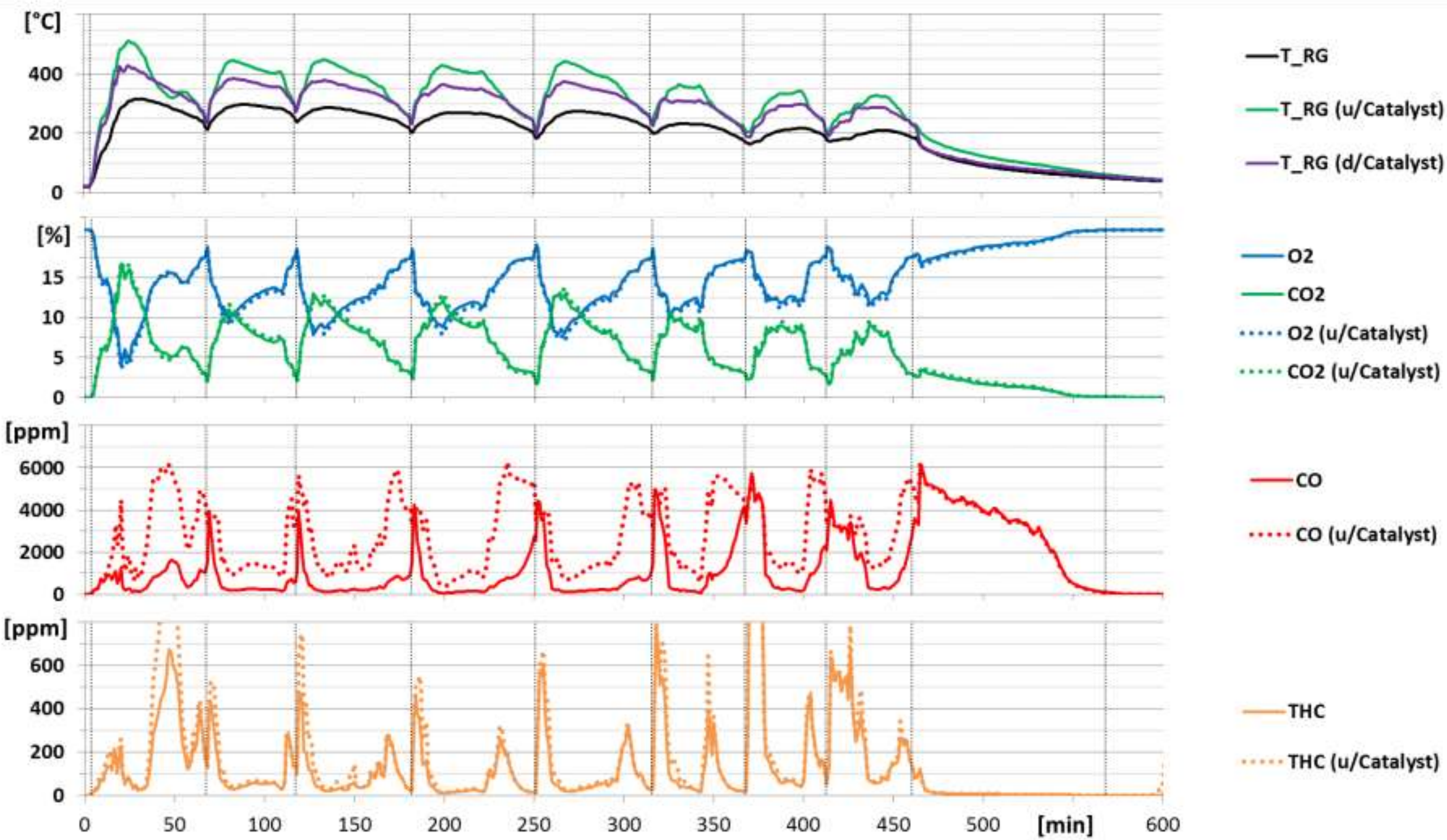


Catalyst evaluation at RISE
Stove integrated catalyst – Reference test (II)

	Batch		Ignition	2	3	4	5	6	7	8	Cool down	Mean NL (Batch 1-5)	Mean PL (Batch 1.2.6-8)	Mean total (Batch 1-8)
General	Fuel mass	kg	2.23	1.50	1.50	1.50	1.50	0.75	0.75	0.75	0	8.22	5.98	10.47
	Batch duration	min	58	49	55	59	59	37	45	44	113	279	232	405
	Flue gas temperature	°C	259	285	269	269	262	231	218	213	88	268	244	253
	Air flow stove inlet	m3/h	19.7	20.0	15.4	15.0	14.9	12.1	11.3	11.3	3.5	16.9	15.4	15.2
Emissions	O_2	%	13.4	14.1	13.3	13.0	13.5	13.2	14.6	14.6	19.2	13.4	14.0	13.7
	CO_2	%	7.2	6.6	7.3	7.5	7.1	7.3	6.0	6.0	1.4	7.2	6.6	6.9
	CO at 13% O_2	mg/m^3_N	3097	2594	2801	2989	3104	2916	3933	3474		2930	3196	3099
	OGC at 13% O_2	mg/m^3_N	417	260	244	170	250	222	384	269		268	319	277
	PM at 13% O_2	mg/m^3_N	48.8		27.2		31.5		49.9			36.0	49.3	38.9
	PM at 13% O2	mg/m^3_N	35.2											35.2
Efficiency	q_a	%	23.0	28.0	23.8	23.0	23.7	20.1	22.4	22.0		24.2	23.3	23.4
	q_b	%	2.0	1.7	1.8	1.9	2.0	1.9	2.5	2.2		1.9	2.0	2.0
	$q_{residue}$	%	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9		3.9	3.9	3.9
	q_{cool}	%									0.4			
	η^*	%	71.2	66.5	70.6	71.2	70.4	74.2	71.3	71.9		69.7	70.4	70.4
	Heat output	kW	7.0	5.2	4.9	4.6	4.6	3.9	3.0	3.1		5.2	4.6	4.6

Notes:
- Mean values from time weighted average calculation; efficiency calculation according to prEN 16510 (except $q_{residue}$)
- $q_{residue}$ based on residue mass of 210 g with 88% glowing losses
- η^* Single batch efficiencies without cool down losses , mean values include q_{cool}

Catalyst evaluation at RISE
Stove integrated catalyst – Catalyst(2) (I)

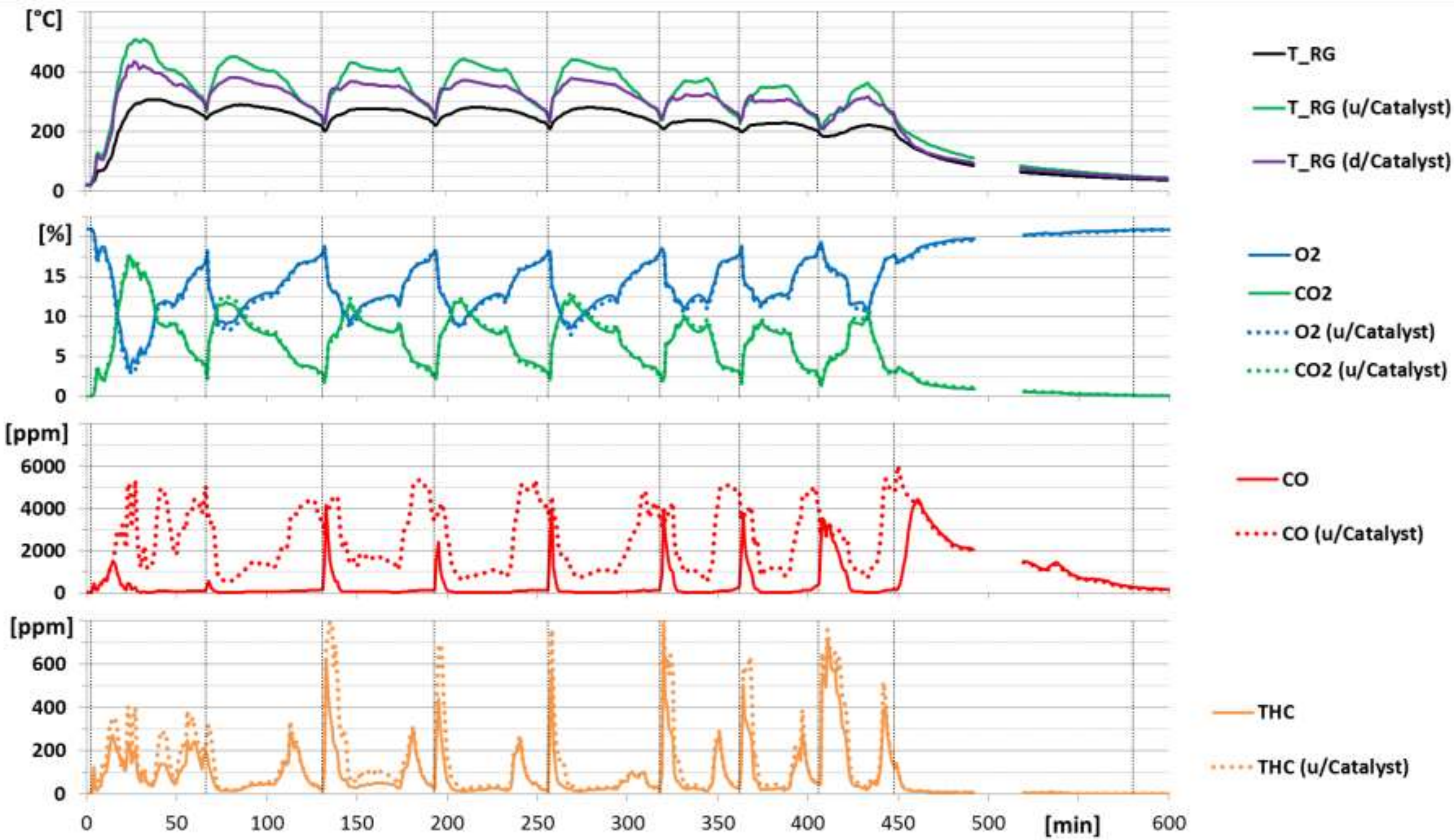


Catalyst evaluation at RISE
Stove integrated catalyst – Catalyst(2) (II)

	Batch		Ignition	2	3	4	5	6	7	8	Cool down	Mean NL (Batch 1-5)	Mean PL (Batch 1.2.6-8)	Mean total (Batch 1-8)
General	Fuel mass	kg	2.20	1.50	1.50	1.50	1.50	0.75	0.75	0.75	0	8.20	5.95	10.45
	Batch duration	min	64	50	64	69	65	52	45	48	108	311	258	455
	Flue gas temperature	°C	253	280	265	250	250	217	199	195	89	259	231	241
	Air flow stove inlet	m3/h	16.2	16.6	13.0	13.2	12.9	10.6	10.4	10.2	3.7	14.3	13.0	13.0
Emissions	O_2	%	13.0	13.2	12.7	13.2	12.8	14.2	14.4	14.8	19.2	12.9	13.8	13.4
	CO_2	%	7.8	7.5	8.0	7.5	7.9	6.4	6.3	5.9	1.4	7.7	6.8	7.2
	CO at 13% O_2	mg/m^3_N	888	682	611	922	819	2129	2433	2690		791	1699	1304
	OGC at 13% O_2	mg/m^3_N	384	183	166	152	192	307	691	601		216	423	313
	PM at 13% O_2	mg/m^3_N	47.9		22.5		20.5		83.7			30.2	62.7	40.3
	PM at 13% O2	mg/m^3_N	33.0											33.0
Catalyst	O_2 (upstream Catalyst)	%	12.7	12.8	12.4	12.9	12.4	14.0	14.1	14.5		12.6	13.5	13.1
	CO_2 (upstream Catalayst)	%	7.8	7.8	8.1	7.6	8.1	6.5	6.5	6.1		7.9	7.0	7.4
	CO at 13% O_2 (u/Catalyst)	mg/m^3_N	3680	2401	3157	3550	2935	5093	4734	4777		3184	4103	3721
	CO Reduction	%	76	71	80	74	72	58	48	43		75	60	67
	OGC at 13% O_2 (u/Catalyst)	mg/m^3_N	562	220	228	194	222	386	747	654		287	510	382
	OGC Reduction	%	31	16	26	21	13	20	7	7		22	17	18
	Pressure drop	Pa	5.4	5.6	4.2	4.3	4.7	3.8	4.0	4.5	1.0	4.8	4.7	4.6
Efficiency	q_a	%	21.5	24.7	22.0	21.9	20.9	21.2	19.7	20.4		22.1	21.5	21.6
	q_b	%	0.6	0.4	0.4	0.6	0.5	1.4	1.6	1.7		0.5	1.1	0.8
	$q_{residue}$	%	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6		3.6	3.6	3.6
	q_{cool}	%									0.4			
	η^*	%	74.4	71.3	74.0	73.9	75.0	73.8	75.2	74.3		73.4	73.4	73.6
	Heat output	kW	6.5	5.5	4.4	4.1	4.4	2.7	3.2	3.0		4.9	4.3	4.3

Notes:
- Mean values from time weighted average calculation; efficiency calculation according to prEN 16510 (except $q_{residue}$)
- $q_{residue}$ based on residue mass of 191g with 89% glowing losses
- η^* Single batch efficiencies without cool down losses , mean values include q_{cool}

Catalyst evaluation at RISE
Stove integrated catalyst – Catalyst(4) (I)



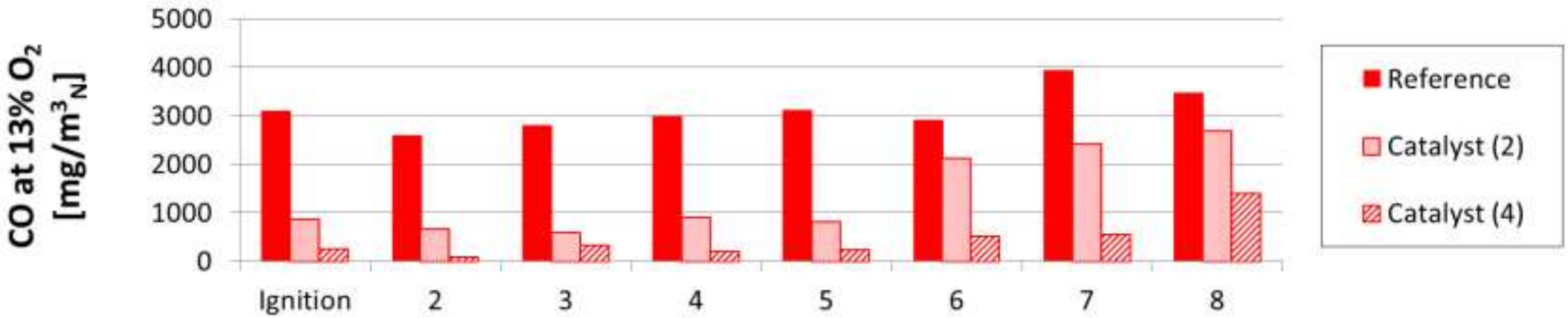
Note: Total power outage during cool down phase for about 20 min resulting in complete shutdown of measurement equipment & flue gas fan; could have had an effect to some extent on cool down performance & residue amount

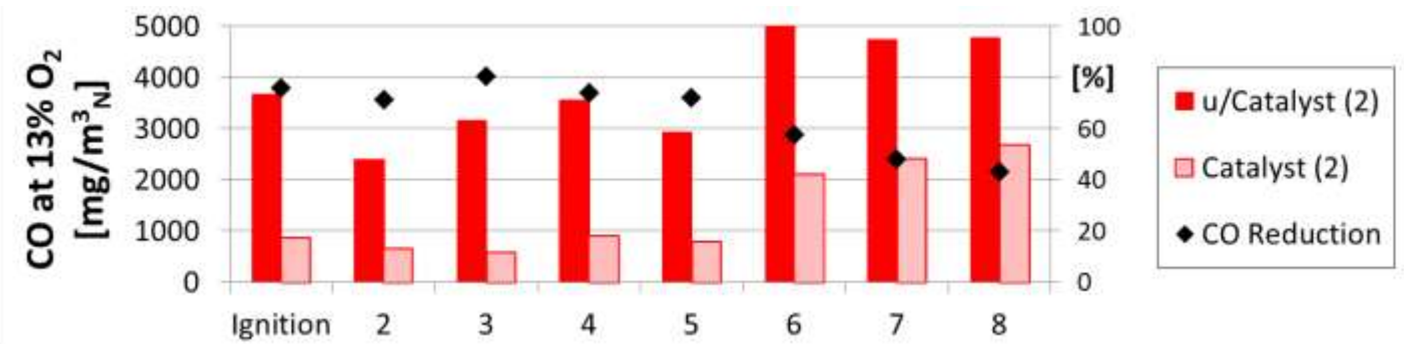
Catalyst evaluation at RISE
Stove integrated catalyst – Catalyst(4) (II)

	Batch		Ignition	2	3	4	5	6	7	8	Cool down	Mean NL (Batch 1-5)	Mean PL (Batch 1.2.6-8)	Mean total (Batch 1-8)
General	Fuel mass	kg	2.20	1.50	1.50	1.50	1.50	0.75	0.75	0.75	0	8.20	5.95	10.45
	Batch duration	min	63	65	62	63	62	44	44	42	132	314	257	444
	Flue gas temperature	°C	236	267	261	263	261	229	220	205	81	258	235	246
	Air flow stove inlet	m3/h	14.2	14.9	14.5	14.5	14.0	11.9	11.6	11.3	3.5	14.4	13.1	13.6
Emissions	O_2	%	11.8	13.3	13.3	13.2	13.0	14.2	14.4	14.7	19.8	12.9	13.5	13.4
	CO_2	%	8.9	7.4	7.4	7.5	7.7	6.5	6.3	6.0	0.9	7.8	7.2	7.3
	CO at 13% O_2	mg/m^3_N	274	97	336	206	241	522	556	1407		230	504	402
	OGC at 13% O_2	mg/m^3_N	203	130	191	123	105	232	228	518		150	245	201
	PM at 13% O_2	mg/m^3_N	22.5		23.1		17.2		23.7			20.9	23.0	21.5
	PM at 13% O2	mg/m^3_N	21.6											21.6
Catalyst	O_2 (upstream Catalyst)	%	11.5	12.9	13.3	13.1	12.7	13.9	14.2	14.5		12.7	13.2	13.1
	CO_2 (upstream Catalayst)	%	9.1	7.6	7.3	7.4	7.8	6.7	6.4	6.2		7.9	7.4	7.4
	CO at 13% O_2 (u/Catalyst)	mg/m^3_N	2912	2793	3638	3021	2613	4004	3962	3951		2994	3416	3279
	CO Reduction	%	90	96	91	93	91	87	86	64		92	86	88
	OGC at 13% O_2 (u/Catalyst)	mg/m^3_N	296	163	342	194	154	338	345	621		229	331	288
	OGC Reduction	%	31	19	43	36	31	30	33	15		32	25	30
	Pressure drop	Pa	8.4	8.2	8.6	8.9	8.8	6.8	7.0	7.1	1.3	8.6	7.6	8.1
Efficiency	q_a	%	17.5	23.8	23.1	23.1	22.4	22.3	21.9	21.0		22.0	21.2	21.9
	q_b	%	0.2	0.1	0.2	0.1	0.2	0.3	0.4	0.9		0.1	0.3	0.3
	$q_{residue}$	%	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7		4.7	4.7	4.7
	q_{cool}	%									0.4			
	η^*	%	77.6	71.4	72.0	72.1	72.8	72.7	73.1	73.4		72.8	73.3	72.7
	Heat output	kW	6.9	4.2	4.5	4.4	4.5	3.2	3.2	3.4		4.8	4.3	4.4

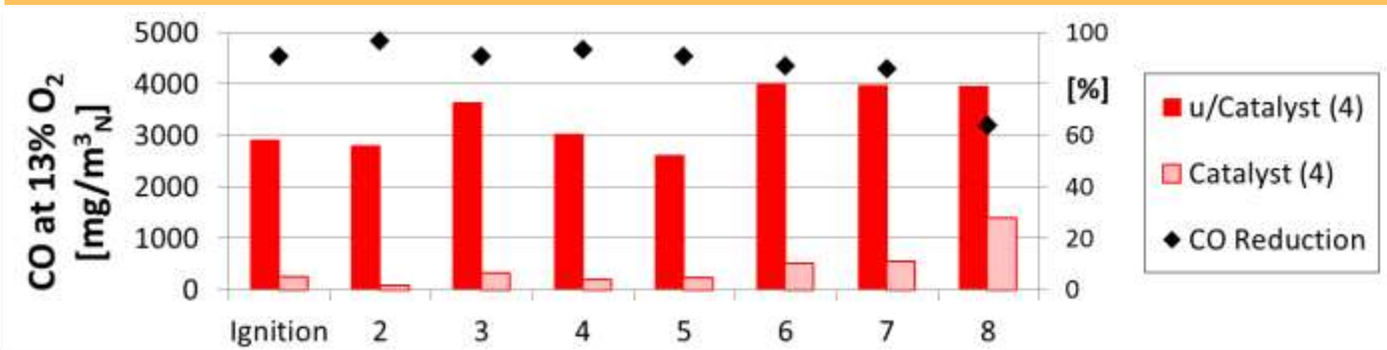
Notes:
- Mean values from time weighted average calculation; efficiency calculation according to prEN 16510 (except $q_{residue}$)
- $q_{residue}$ based on residue mass of 248g with 90% glowing losses
- η^* Single batch efficiencies without cool down losses , mean values include q_{cool}

Catalyst evaluation at RISE
Stove integrated catalyst – Comparison CO



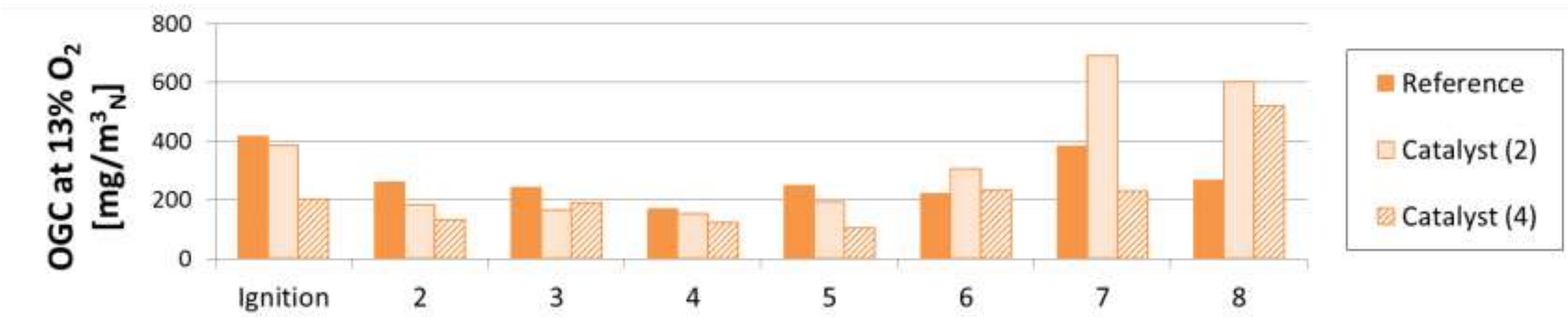


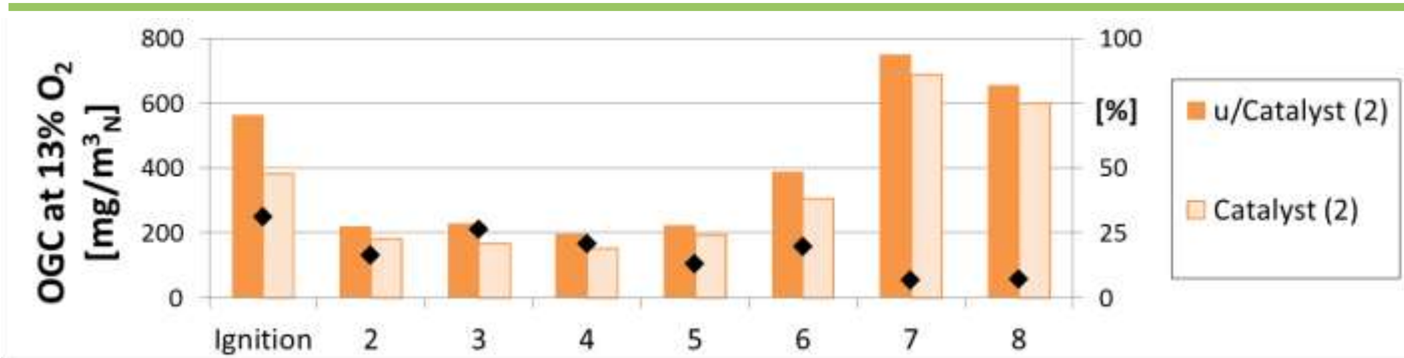
Test run with 2 pcs. mesh catalyst



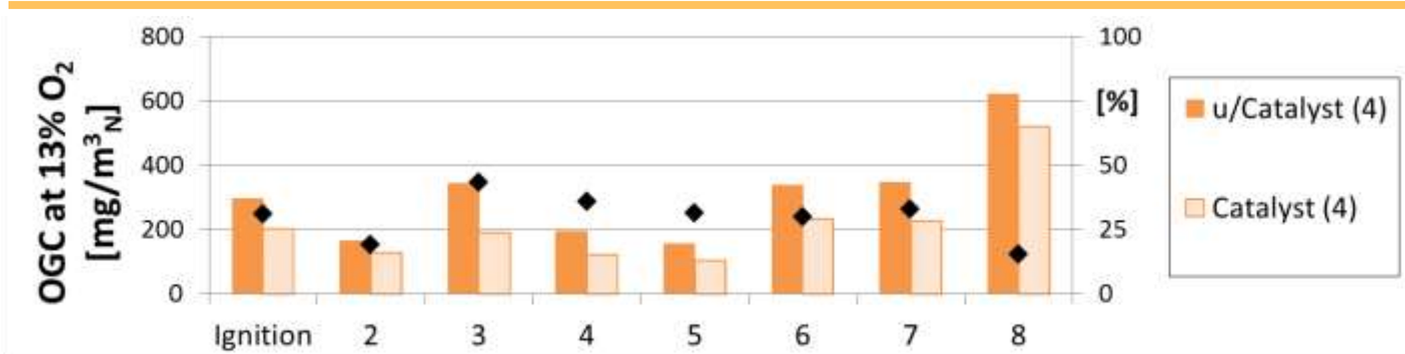
Test run with 4 pcs. mesh catalyst

Catalyst evaluation at RISE
Stove integrated catalyst – Comparison OGC



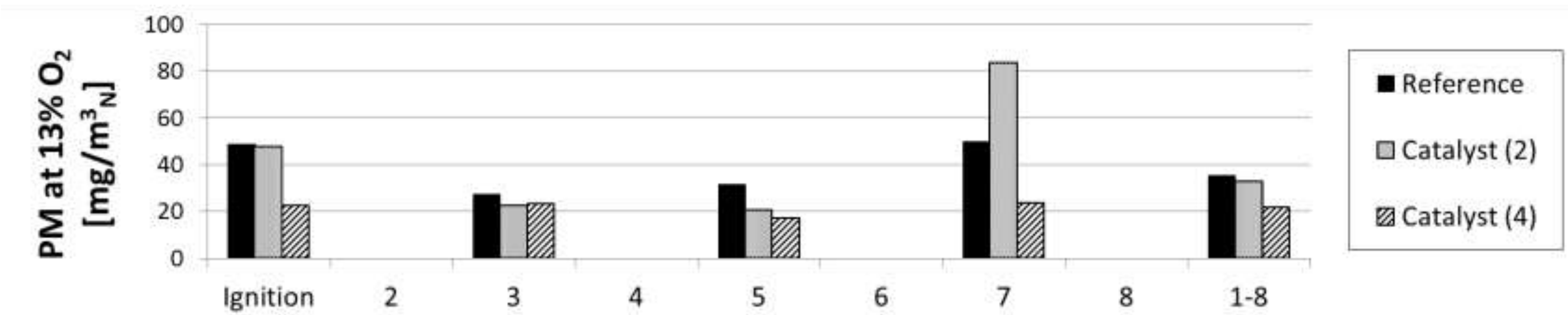


Test run with 2 pcs. mesh catalyst



Test run with 4 pcs. mesh catalyst

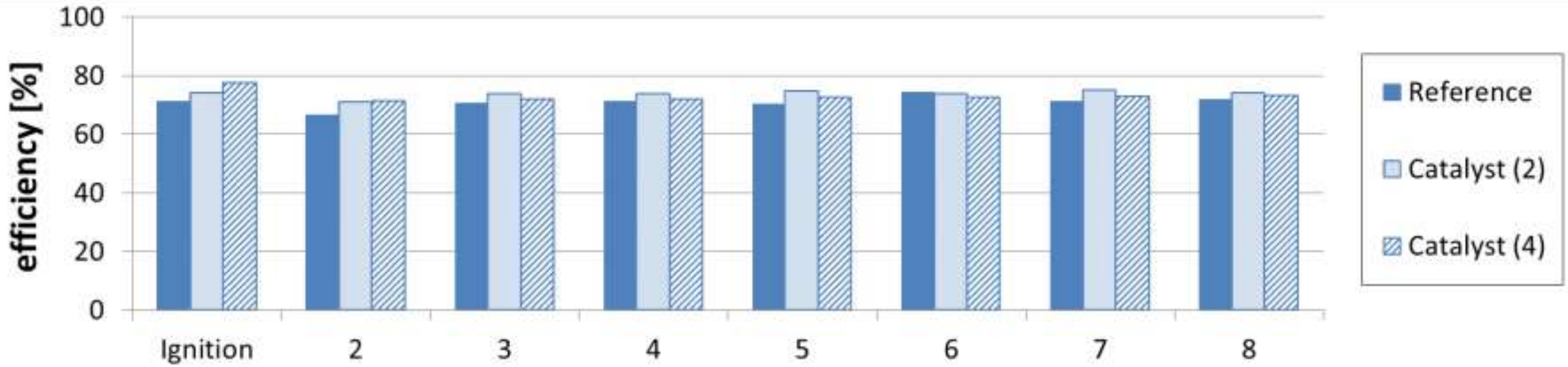
Catalyst evaluation at RISE
Stove integrated catalyst – Comparison PM

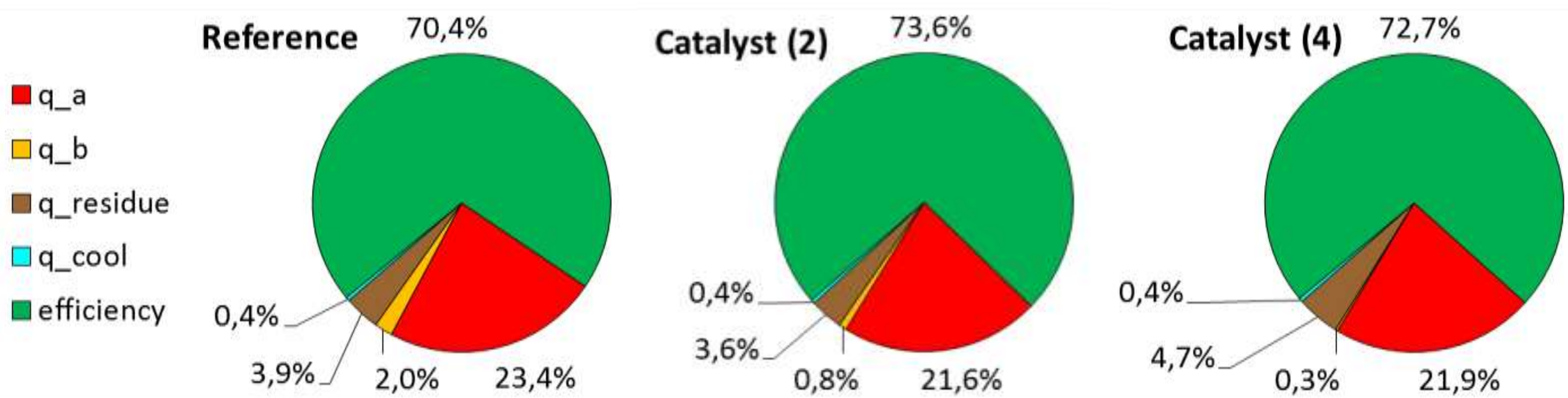


Notes:

- Chart with particle sampling results for single batches 1,3,5 & 7 and complete test run (batch 1-8)
- Catalyst meshes before (left) and after stove test (right)

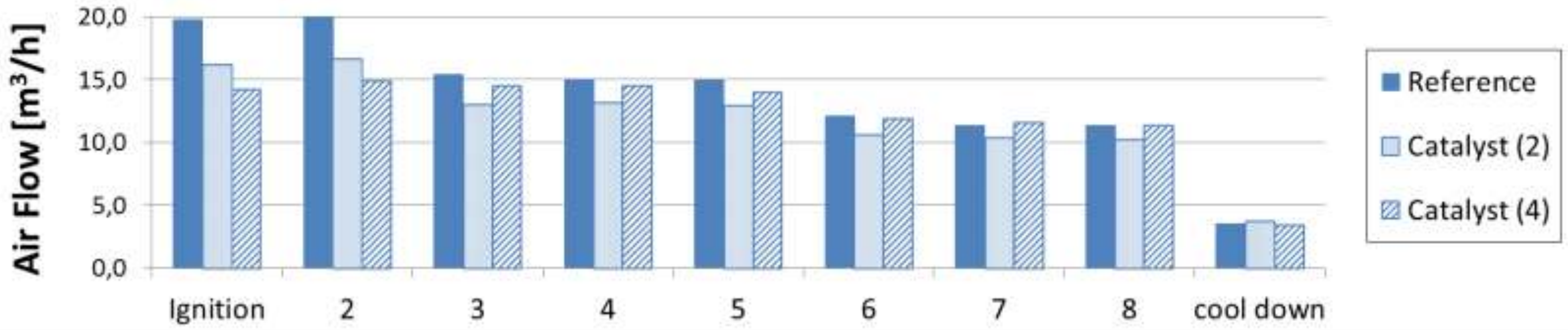
Catalyst evaluation at RISE
Stove integrated catalyst – Efficiency

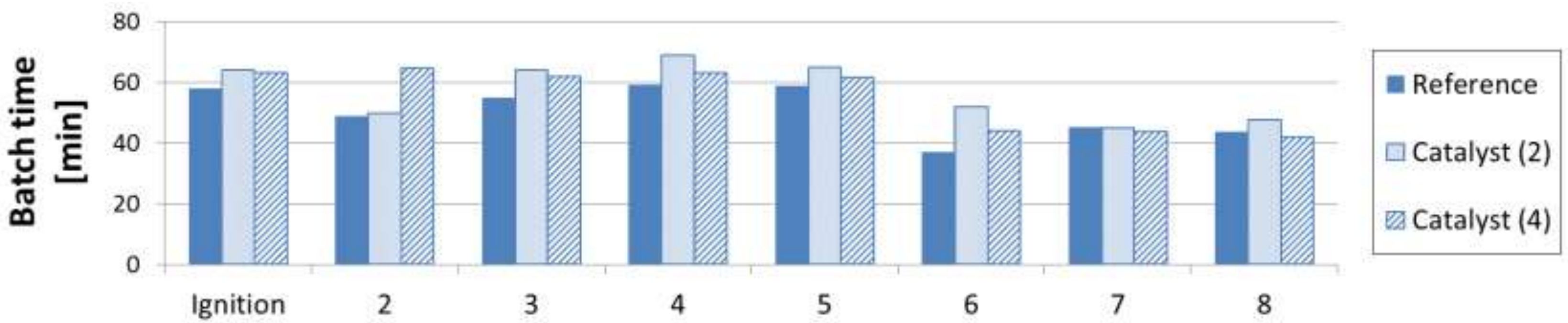


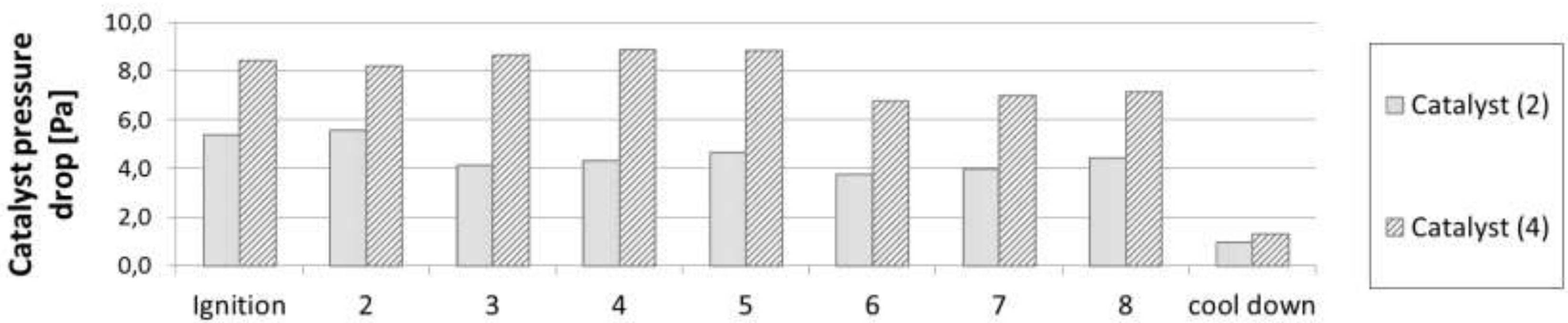


Notes:
- Total stove efficiency for testing cycle including thermal losses (q_a), chemical losses (q_b), losses from unburnt material at the grate (q_residue) and cool down losses (q_cool)
- Single batch efficiencies without cool down losses

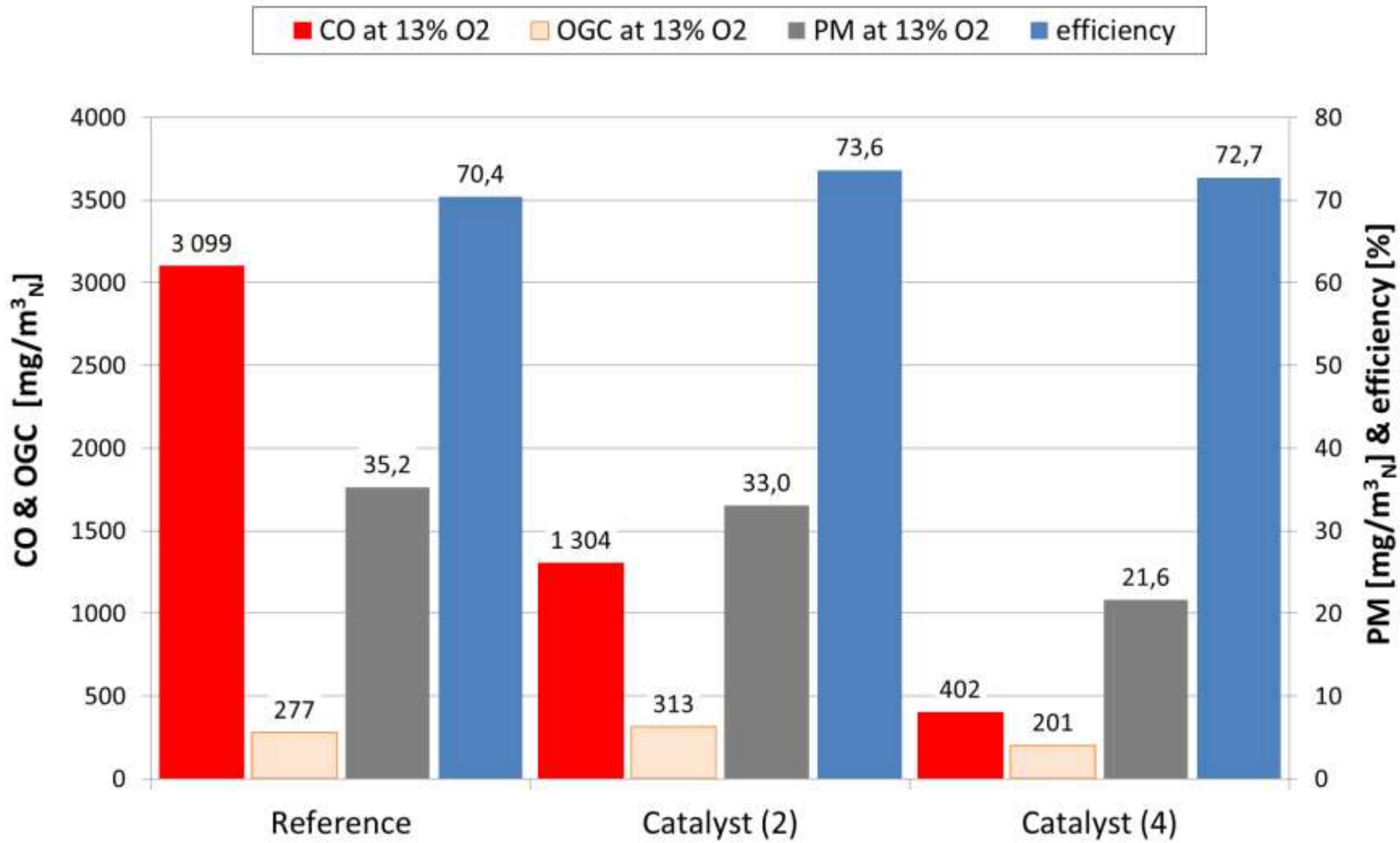
Catalyst evaluation at RISE
Stove integrated catalyst – Other parameters







Catalyst evaluation at RISE
Stove integrated catalyst – Performance data



Catalyst evaluation at RISE
Stove integrated catalyst – Results (I)

Significant catalyst impact on combustion conditions

- **Increased flow resistance results in lower air flow if dampers are not modified**
  - Worse ignition conditions at recharging and longer batch durations
- **Higher CO_2 values at end of batch due to CO reduction**
  - Delay of recharging when following test method (compared to run without catalyst impact) result in lower combustion chamber temperatures and less char bed at recharge

Placement of catalyst not optimal

- **Catalyst temperature dropped below light-off temperature at recharging**
  - Decrease in reduction rate at beginning of each batch (represent at the same time period with highest hydrocarbon emissions)
- **Catalyst did not operate long time at elevated temperatures**
  - Eventual conversion of short-chain hydrocarbons (e.g. methane) could not be accomplished
  - Presumably increasing particle deposit on catalyst surface could not be regenerated, thus probably leading to faster increase in flow resistance and shorter cleaning intervals
- **Altered location closer to combustion chamber more favorable to operate catalyst at higher temperatures**

Catalyst evaluation at RISE
Stove integrated catalyst – Results (II)

Flow resistance

- **Noticeable catalyst pressure drop**
  - In range 4-6 Pa for Catalyst(2) and 7-9 Pa for Catalyst(4)
  - Consider reduced cross section for single meshes when comparing to catalyst test rig results
- **Altered location for increasing cross section should be beneficial**

Impact on emissions

- **Carbon monoxide**
  - Significant CO reduction of almost 60% for Catalyst(2) and 90% for Catalyst(4) when comparing final numbers to reference test
  - Compared to emissions upstream catalyst, CO reduction for Catalyst(2) even higher at 65%, thus indicating negative impact of catalyst on general combustion conditions in that test (causes mentioned on slide before)
  - When operating above light-off temperature nearly complete CO conversion for Catalyst(4) test run, thus indicating potential for altered catalyst position
- **Hydrocarbons**
  - Comparing only final numbers there is an almost 30% reduction of hydrocarbons in the Catalyst(4) test run, but a more than 10% increase for the Catalyst(2) test run

Catalyst evaluation at RISE
Stove integrated catalyst – Results (III)

- **Hydrocarbons (continued)**
  - However comparing to upstream values even the Catalyst(2) test run shows a 20% reduction in hydrocarbons, pointing again to the worsen general combustion conditions in that test
  - Differences between up- and downstream values of hydrocarbons at sufficient catalyst temperatures indicate again the potential for reduction capacity with altered catalyst position, especially since most hydrocarbons are released during the first phase of each batch
- **Particles**
  - Comparing particle numbers from the complete test run sample, Catalyst(2) test run results in overall on the same particle level, while at the Catalyst(4) test run PM is reduced by 40%
  - But a look at single batch samples indicates a more or less clear reduction even for the Catalyst(2) test for all particle samples except the part load batch (bad combustion, high HC)
  - Particle reduction for Catalyst(4) test run at least partly caused by reduced air flow at first batches compared to reference run (100% damper opening for both cases)

Efficiency increase due to decrease in chemical & thermal losses

- **Decrease in chemical losses due to CO reduction; conversion of hydrocarbons (HC not considered as loss in standard) gives extra benefit in reality**
- **Decrease in thermal losses mainly based on first two batches due to reduced air flow into stove (resulting in higher average CO_2)**

Catalyst evaluation at RISE
Conclusions & recommendations

Catalyst evaluation at RISE
Conclusions & recommendations (I)

- **Mesh catalyst with significant emission reduction capacity**
  - Nearly complete CO conversion and significant reduction of hydrocarbons and particles when operating at right temperatures
  - Catalyst provides a ”safety guard” function, since hydrocarbon & particle reduction even increase at times with bad combustion & high emissions (for example at user induces operation errors)
  - Catalyst activation starts already at low temperature levels of around 250°C, reaching complete CO conversion above 300°C
  - Recommended operation condition at slightly higher temperature levels, in a range above 400°C (further improvement in conversion, self cleaning effect)
- **Thin metal mesh form provides wide design choice opportunities for integrating catalyst into stove**
- **Catalyst position is crucial**
  - Place where activation temperature is reached quickly after stove ignition
  - Place where temperature stays above light-off temperature during recharge
  - Place where catalyst operates long time at required higher temperatures
  - Place which is still easy accessible for the user (cleaning and exchange)

RISE NIBE

Catalyst evaluation at RISE
Conclusions & recommendations (II)

ERA-NET Bioenergy

Catalyst durability

- Stable conversion efficiencies during first 200 hours of operation
- Simple cleaning procedure removed deposits & restored initial flow resistance
- Extended evaluation period with stove integrated catalyst recommended to obtain more information regarding stove-catalyst interaction, eventual deactivation signs and identify suggested cleaning intervals

Flow resistance

- Noticeable pressure drop observed, with even higher values during recharging (open door) and further increasing when operating at low temperatures
- High flow resistance generates problems for operating catalysts at low draft chimneys, especially at cold start condition
- Corrective measures: increase catalyst cross section (less mesh stacked above each other will lower flow resistance) and/or the use of a flue gas fan

Costs

- Increase in stove price due to catalyst will limit market potential
- Potential for decreasing costs by optimizing catalyst size (determine minimal required size) and large order volumes

Concluding summery and recommendations

Concluding summery and recommendations (I)

- **Evaluation of high temperature catalysts at BIOS:**
  - **The implementation of a high temperature catalyst at the outlet of the post combustion chamber (temperature range of about 500 °C) is not recommended as tests showed unstable reduction efficiencies.**
  - **High temperature catalysts, which are mounted at the outlet of the main combustion chamber (temperature range 600 - 800 °C) showed sufficiently high emission reduction efficiencies regarding CO (69 – 73%) and OGC (27 – 38%) and seem basically to be suitable for logwood stoves.**
  - **In particular, a catalytically-coated foam ceramic, which was mounted at the outlet of the main combustion chamber (temperature range 600 - 800 °C), showed sufficiently high and almost stable emission reduction efficiencies regarding CO and OGC over 3 weeks and therefore this catalyst seems basically to be suitable for logwood stoves.**
  - **However, the emission reduction efficiency decreased for the catalysts over the testing period of about 100 hours of operation and manual cleaning showed no positive effect.**

Concluding summery and recommendations (II)

- **Evaluation of medium temperature metal based mesh catalysts at RISE:**
  - **Nearly complete CO conversion and significant reduction of hydrocarbons and organic particles when operating at right temperatures**
  - **Catalyst activation starts already at low temperature levels of around 250°C, reaching complete CO conversion above 300°C**
  - **Recommended operation condition at slightly higher temperature levels, in a range above 400°C (further improvement in conversion, self cleaning effect)**
  - **Stable conversion efficiencies during first 200 hours of operation**
  - **Noticeable pressure drop observed, with even higher values during recharging (open door) and further increasing when operating at low temperatures**
  - **High flow resistance generates problems for operating catalysts at low draft chimneys, especially at cold start condition**

Concluding summery and recommendations (III)

- Evaluation of the long-term feasibility of foam ceramic filters or their replacement by a catalyst insert at TFZ:
  - Expectations for PM reductions by foam ceramic elements were not met (particularly for non-catalytic elements).
  - Catalytic foam ceramic elements can reduce gaseous flue gas emissions (CO, OGC).
  - The first results on long term testing have shown a significant decrease of reduction rates, which could not be completely regenerated by cleaning the catalyst.
  - It is desirable to achieve higher surface temperatures (> 700 °C) on catalytic elements.
  - Retrofitting of catalytic foam ceramic elements may be an interesting option.

Concluding summery and recommendations (IV)

- **In general, tests over a whole heating period would be needed to be able to evaluate the long-term performance of catalysts for wood stoves as well as the possible need of cleaning.**
- **A catalyst should mainly have the function to further reduce emissions, especially at the beginning and at the end of the combustion cycle, and to act as a safety guard for unexpected situations. This will also contribute to ensure a longer lifetime with slower degradation.**
- **Furthermore, catalysts need enough surface to achieve a sufficient reduction efficiency. This is usually provided by narrow channels which cause a certain pressure drop. The pressure drops are usually too high for an operation of the stove with natural draught only.**
- **Therefore, either a flue gas fan is needed if a catalyst should be integrated or the dimension of the catalyst needs to be increased.**

Concluding summery and recommendations (V)

- Oxidation needs oxygen. The catalyst will not work if there is no sufficient oxygen available (overall and locally). A good instruction will help to reduce user induced errors in fuel handling as for example using too much or wrong sized wood with wrong moisture content. Good geometric design of combustion chamber and air nozzles together with the right catalyst placement has to be applied to ensure a sufficient mixing of the flue gas.
- Find and provide solutions for phases where insufficient draft can occur, most critical are the cold start and re-filling. Using a bypass is a possibility but will release unwanted emissions during these phases. It is more advisable to try to keep a low pressure drop across the catalyst even during these phases by choosing a sufficient catalyst size and structure, or to implement a flue gas fan supporting the stove operation.

Concluding summery and recommendations (VI)

- Choose a sufficient location for operating the catalyst in the appropriate temperature range. The mounting position of integrated catalysts has to be carefully evaluated in terms of operating conditions (existing temperature) and materials used.
- The aim is to ensure a fast warm-up with reaching activation temperature shortly after a cold start, to stay as long as possible above the activation temperature for phases with charcoal burnout, but also to avoid exceeding the maximum catalyst temperature limit.
- Make the catalyst easy accessible for the user in order to enable a removal for cleaning and replacing.
- Provide clear instructions on how to operate the stove in general - to protect the catalyst from excessive exposure - and during specific phases. Provide information on recommended cleaning intervals and procedure and on expected life span and replacement.