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EVROPSKO TERITORIALNO SODELOVANJE
EUROPÄISCHE TERRITORIALE ZUSAMMENARBEIT

PM emission measurements at small-scale biomass boilers in Carinthia, southern Styria and Slovenia

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Naložba v vašo prihodnost
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TU Graz
Das Land Steiermark
Klagenfurt am Wörthersee

Contents

- Objectives
- Methodology
- Results of the test runs performed
  - Combustion system descriptions
  - Selected emission trends
  - Emission factors
- Summary, conclusions and recommendations

Objectives (I)

- **Determination of emission factors for residential biomass heating systems typically applied in the regions of**
  - Klagenfurt
  - Leibnitz
  - Maribor

- **Parameters of interest**
  - TSP, PM_1, OGC, CO emissions
  - chemical composition of PM_1 (OC, EC, IC, inorganic compounds)

Objectives (II)

- **Performance of field tests at 6 households in Klagenfurt, Leibnitz and Maribor**
  - measurement of 3 typical operation cycles for each location
  (3 measurement days)

- **Field tests - advantages:**
  - measure over typical operation cycles
  - include user behavior
  - perform measurements at heating systems as they are applied
  (no optimized settings, no optimized hydraulics, used systems)

- **Field tests - disadvantages:**
  - high efforts for installation of measurement equipment
  - find appropriate users

Methodology – measurement and sampling program (I)

- **Continuous measurements**
  - Flue gas composition (O_2, CO, OGC)
  - Combustion chamber temperature (if possible)
  - Flue gas temperature (at the measurement point) and temperature of the diluted flue gas
  - Chimney draught
  - Particle size distribution and number concentration of PM_1 in the diluted flue gas with an electrical low-pressure impactor (ELPI), (dilution was done with 2 ejector diluters)

Methodology – measurement and sampling program (II)

- **Discontinuous measurements and samples taken**
  - TSP emission measurements in the undiluted flue gas
  - PM_1 particle size distribution and concentration in the diluted flue gas
    - flue gas dilution has been applied in order to condense all condensable hydrocarbons present in the flue gas at the sampling point and to gain a realistic picture of the emissions at chimney outlet (when the flue gas mixes with the ambient air)
    - dilution was done with particle free pressurized air and a porous tube diluter
  - Mass of the fuel applied and the bottom ashes produced

Methodology – measurement and sampling program (III)

- **Analyses**
  - Analyses of representative fuel samples regarding
    - moisture and ash content
    - C, H, N, Ca, Si, Mg, Fe, Al, Mn, K, Na, S, Cl, Zn, Pb
  - Analyses of grate ashes (solid combustion residues)
    - regarding TOC and TIC, inorganic elements
  - Analyses of PM emission samples
    - regarding OC and EC, inorganic parameters (K, S, Cl, Zn) for selected test runs

Methodology – measurement setup (I)

Measurement and sampling

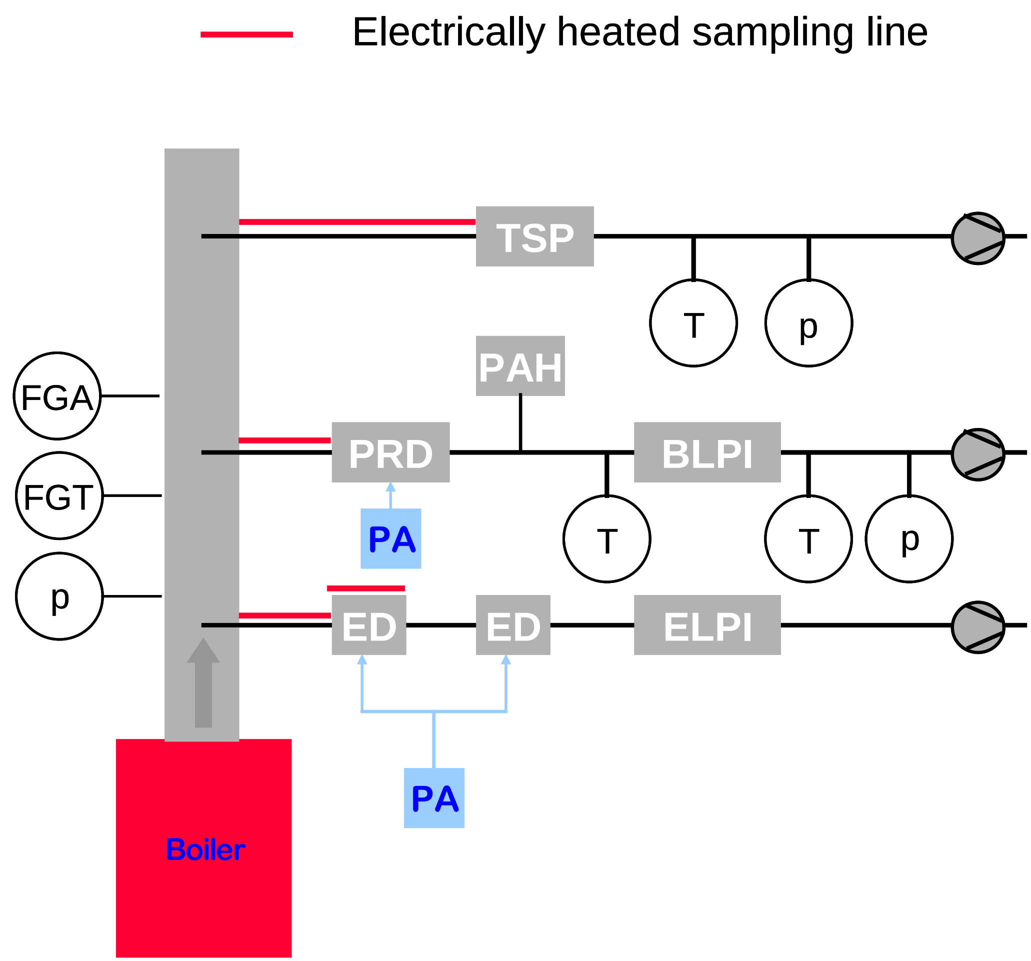
TSP Total suspended particles
BLPI Berner-type low-pressure impactor
ELPI electrical low-pressure impactor
PAH sampling for PAH analyses

Plant operation parameters

FGA flue gas analysers (O_2, CO, OGC)
CCT combustion chamber temperature
FGT flue gas temperature

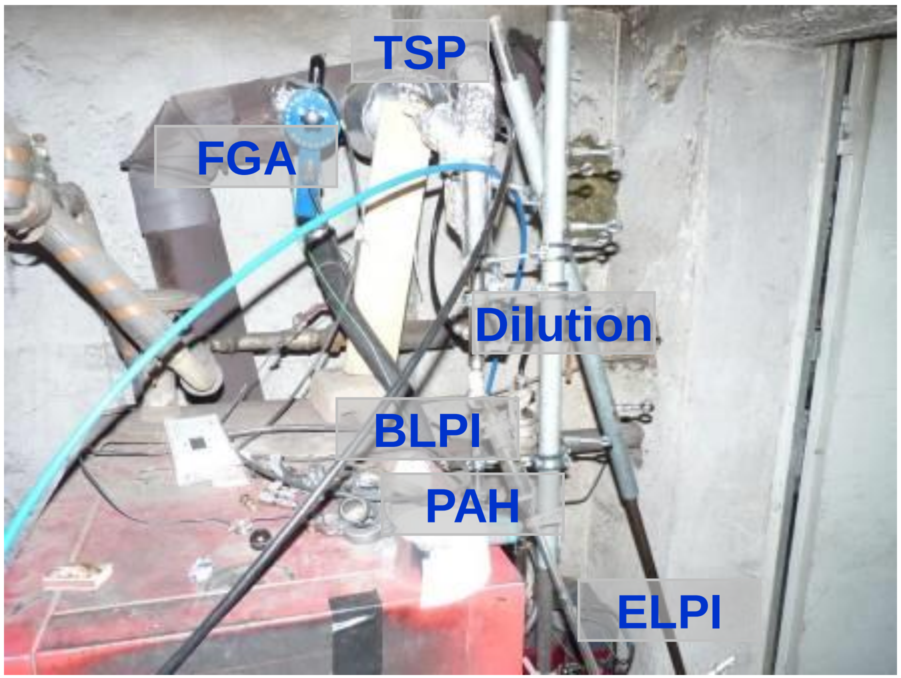
Flue gas dilution systems

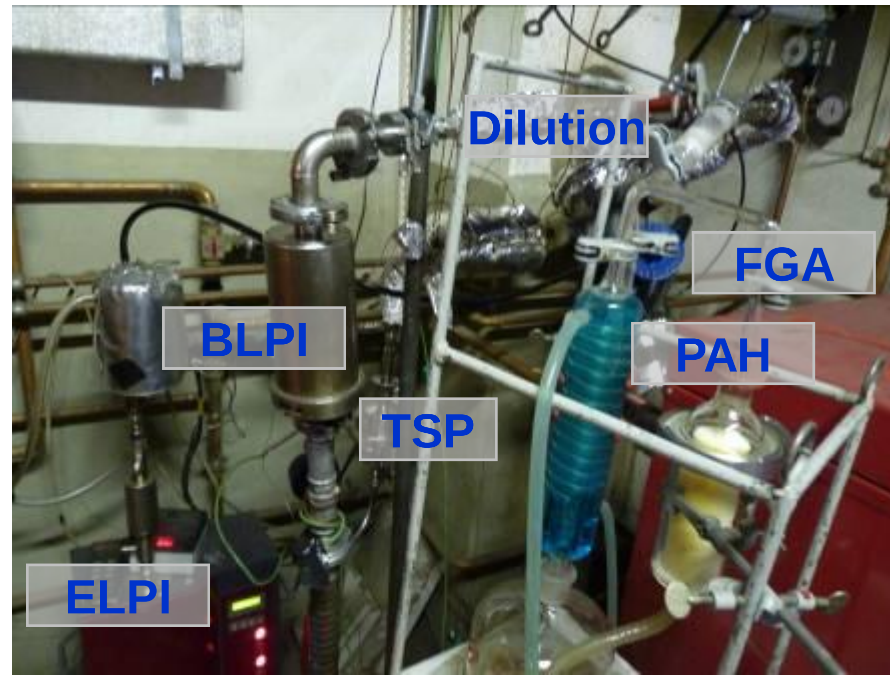
PRD porous tube diluter
ED ejector diluter
PA pressurised air
p pressure measurements
T temperature measurements



Methodology – measurement setup (II)

Setup examples





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Overview over the test runs performed

- **Leibnitz I** — Solid fuel boiler (1996) 18.8 kW
  09.02.2011 - 11.02.2011
- **Klagenfurt I** — Solid fuel boiler (1992) 20 kW
  22.02.2011 - 24.02.2011
- **Maribor I** — Log wood boiler (1990) 35 kW
  23.03.2011 - 25.03.2011
- **Klagenfurt II** — Log wood boiler (2000) 48 kW
  29.03.2011 - 31.03.2011
- **Leibnitz II** — Log wood boiler (1990) 20 kW
  05.12.2011 - 07.12.2011
- **Maribor II** — Kitchen stove ~12,5 kW
  13.12.2011 - 15.12.2011

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Boiler operation – general aspects

General remarks regarding heating practice

- During the test runs the boilers were operated by their owners
- The owners were advised to operate the boilers as they usually do
- No recommendations regarding correct boiler operation were given by the TU Graz measurement team
- Usual fuels applied by the owners were used

General remark regarding the fuels applied

- All users applied wood logs with
  - different sizes and shapes
  - from various wood types
  - from different sources (sometimes also wood wastes)

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Boiler operation – example

- Ignition practice
  - Paper and kindling wood were used
  - Ash door was left open during the ignition phase
  - Smaller ignition batch
- Main charging after 20 minutes with common log wood, rather small fuel amount (half of possible fuel mass)
- Random fuel placement, no adjusted placement of the logs

Boiler operation – fuels and ash

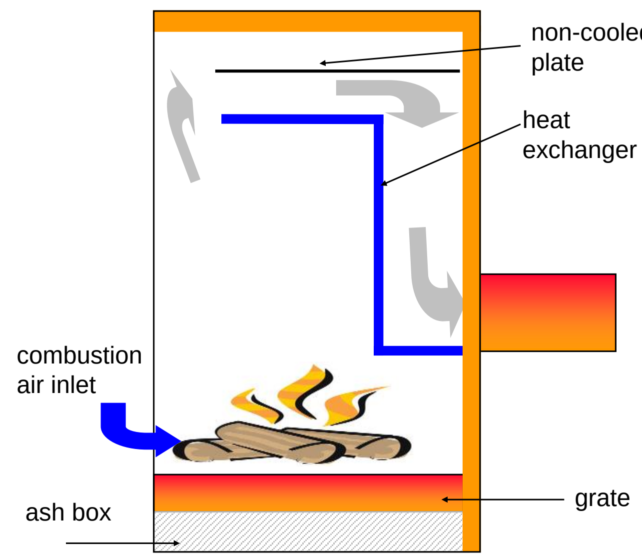
Mass determination of the fuels used and the ashes produced

(example Leibnitz I)

“Leibnitz I” - Combustion system

Test run Leibnitz I

- Year of manufacture: 1996
- Nominal capacity: 18.8 kW
- Description
  - 7.5 to 18.8 kW solid fuel boiler
  - combustion principle: updraft
  - single combustion chamber layout
  - manually controlled primary air flap



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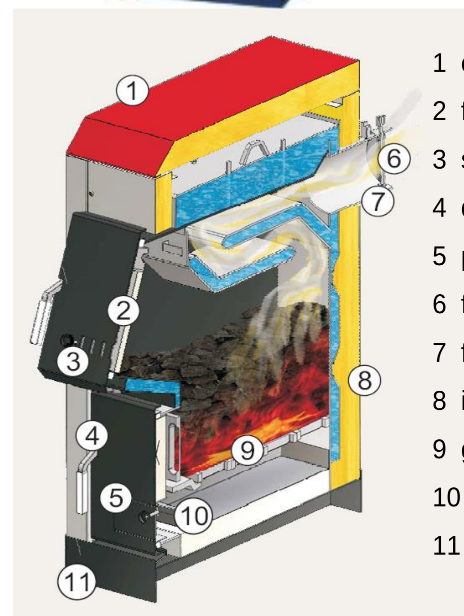
"Klagenfurt I" - Combustion system

Test run Klagenfurt I

- Year of manufacture: 1990
- Nominal capacity: 20 kW
- Description:
  - 9 to 20 kW solid fuel boiler
  - combustion principle: updraft
  - single combustion chamber layout
  - manually controlled primary air flap



1 casing
2 filling door
3 secondary air
4 door
5 primary air
6 flue gas valve
7 flue gas channel
8 isolation
9 grate
10 ash box
11 socket

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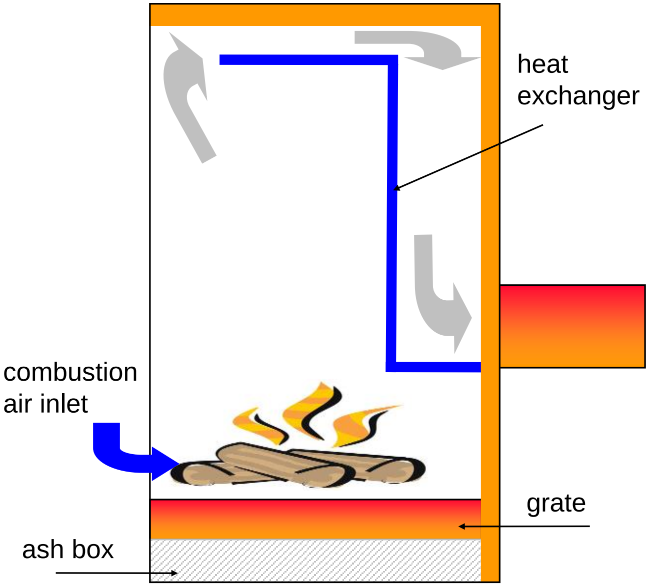
“Maribor I” - Combustion system

Test run Maribor I

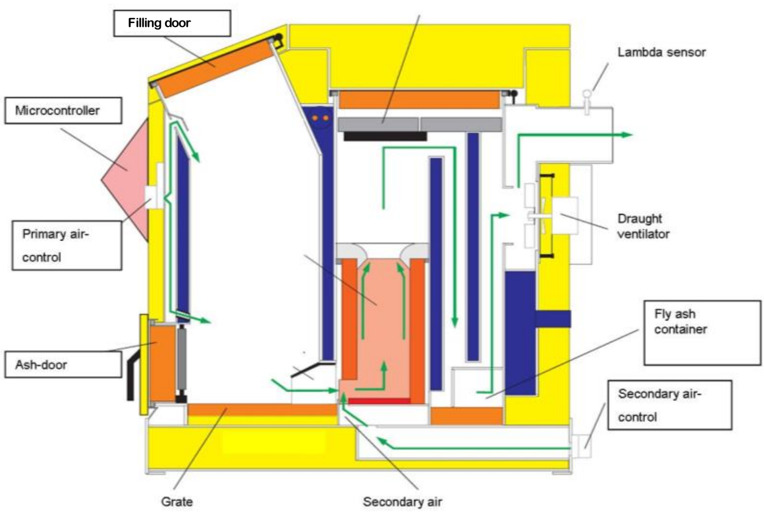
- Year of manufacture: 1992
- Nominal capacity: 35 kW
- Description:
  - 14 to 35 kW solid fuel boiler
  - combustion principle: updraft
  - single combustion chamber layout
  - manually controlled primary air flap



"Klagenfurt II" - Combustion system

Test run Klagenfurt II

- Year of manufacture: 2000
- Nominal capacity: 48 kW
- Description:
  - 24 to 48 kW log wood boiler
  - combustion principle: downdraft
  - separated primary and secondary combustion zone
  - automatic lambda control, draught fan

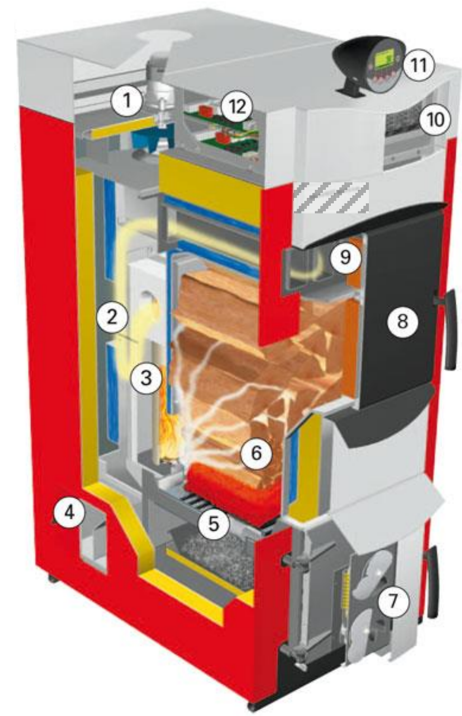


"Leibnitz II" - Combustion system

Test run Leibnitz II

- Year of manufacture: 1990
- Nominal capacity: 20 kW
- Description:
  - 12 to 24 kW solid fuel boiler
  - combustion principle: downdraft
  - flue gas fan
  - primary and secondary combustion chamber
  - automatically controlled air flaps, temperature controlled operation

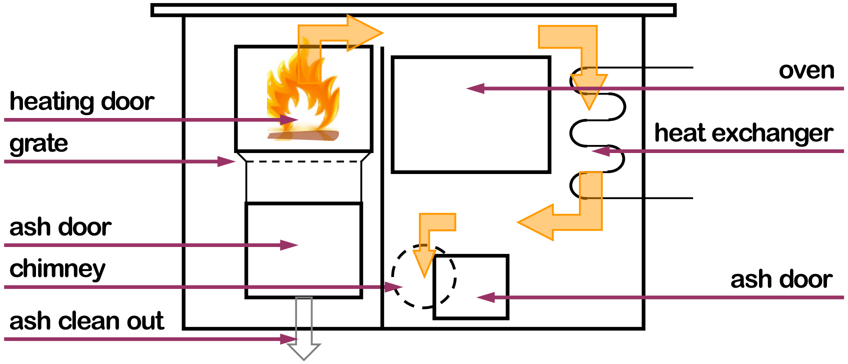
1. Ventilation system
2. Thermocouple
3. Secondary combustion zone
4. Cleaning door
5. Secondary air preheating
6. Wood chamber
7. Air control flaps
8. Filling door
9. Gas takeoff during refilling
10. Control system
11. User interface
12. Combustion monitoring



"Maribor II" - Combustion system

Test run Maribor II

- Year of manufacture: unknown
- Nominal capacity: calculated to 12.5 - 13 kW
- Description:
  - kitchen stove with heat exchanger for central heating
  - combustion principle: updraft
  - natural draught
  - air holes in ash door (below grate) and in heating door, further air through cooking plate



Composition of the fuels applied

(average values of 2 samples analysed)

		Leibnitz I	Klagenfurt I	Maribor I	Klagenfurt II	Leibnitz II	Maribor II	IPPT-Database	
								mean	s
C	[wt% d.b.]	48.13	48.79	47.94	48.58	48.79	49.18	48.12	0.42
H	[wt% d.b.]	6.19	6.54	6.11	6.26	6.04	6.06	6.21	0.10
N	[wt% d.b.]	0.14	0.13	0.26	<0,1	0.19	0.17	0.17	0.06
Moisture content	[wt% w.b.]	9.15	13.61	9.72	12.68	13.94	23.00	12.84	1.92
ash content	[wt% d.b.]	1.22	0.81	1.34	0.61	1.24	1.12	0.91	0.30
S	[mg/kg d.b.]	261.0	163.0	227.0	110.0	260.0	175.0	124.0	37.0
Cl	[mg/kg d.b.]	115.0	119.0	64.5	89.2	53.0	58.0	17.0	14.0
Ca	[mg/kg d.b.]	3,460.0	1,640.0	4,900.0	1,900.0	4,120.0	3,440.0	2,075.0	1,220.0
K	[mg/kg d.b.]	2,000.0	2,100.0	881.0	708.0	1,120.0	1,400.0	1,530.6	399.2
Mg	[mg/kg d.b.]	311.0	167.0	360.0	236.0	392.0	494.0	415.0	133.0
Si	[mg/kg d.b.]	92.3	75.0	59.8	<50	< 200	< 199	168.0	61.0
Fe	[mg/kg d.b.]	29.1	35.9	35.4	11.0	7.4	19.8	n.d.	n.d.
Al	[mg/kg d.b.]	47.3	43.7	35.2	30.2	29.2	22.2	n.d.	n.d.
Na	[mg/kg d.b.]	20.7	45.3	7.8	19.5	< 5.01	11.8	3.9	3.0
Zn	[mg/kg d.b.]	42.8	138.0	30.8	150.0	6.0	5.7	3.0	1.0

(Explanations: mean ... mean value; s ... standard deviation; blue colored ... value outside 3x standard deviation)

Results – fuel analysis - remarks

- The typical and optimal **fuel moisture content** for logwood is in the range between 10 to 20% H_2O.
  - fuels with 9 to 23% H_2O have been used
- Slightly elevated **ash (as well as Ca) contents** for Leibnitz I, II and Maribor I, II
  - most probably due to a higher bark content
- Elevated **Cl, Zn and Na contents** for Leibnitz I, Klagenfurt I and II as well as Maribor I
  - indicates, that not only chemically untreated logwood has been used

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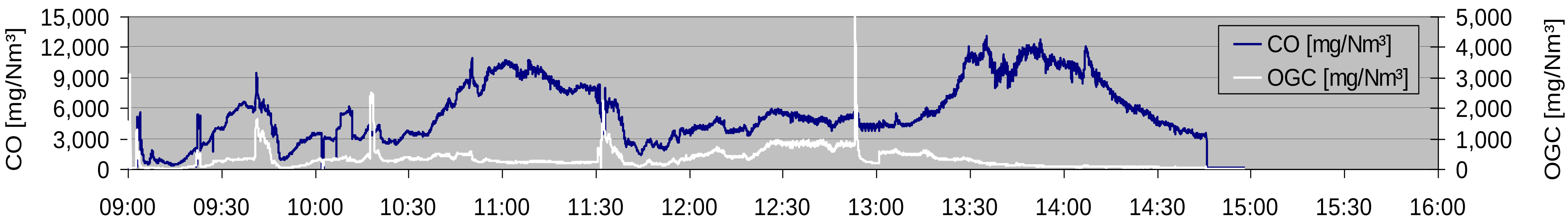
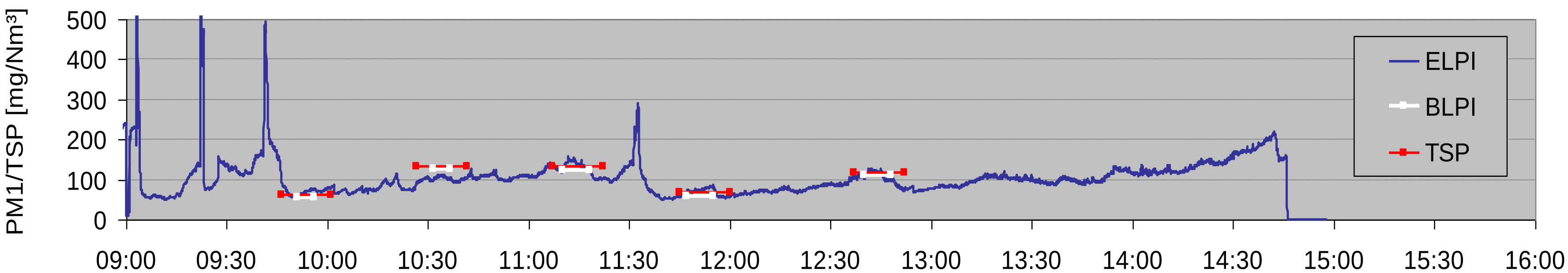
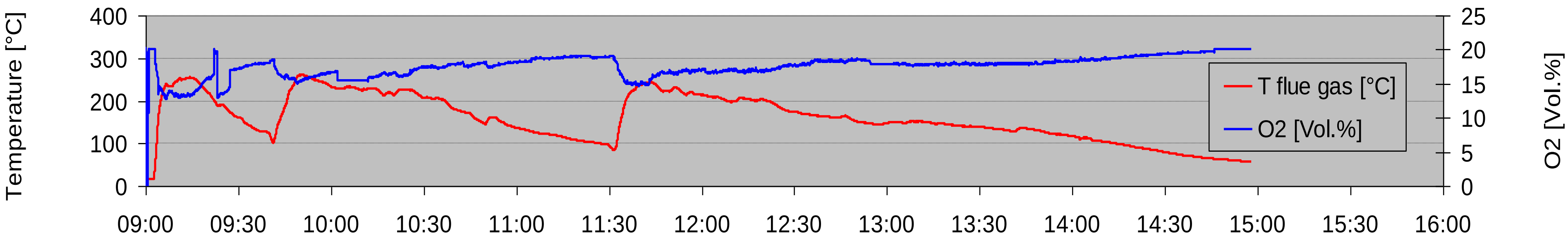
Results – operation data and emission trends (example) (I)

Test run Maribor I – 25.02.2011 (day 3)







Emissions related to dry flue gas and 13 vol% O_2, TSP ... total suspended particulate matter, ELPI ... PM_1 emissions by electrical low pressure impactor, BLPI ... PM_1 emissions by Berner-type gravimetric low pressure impactor

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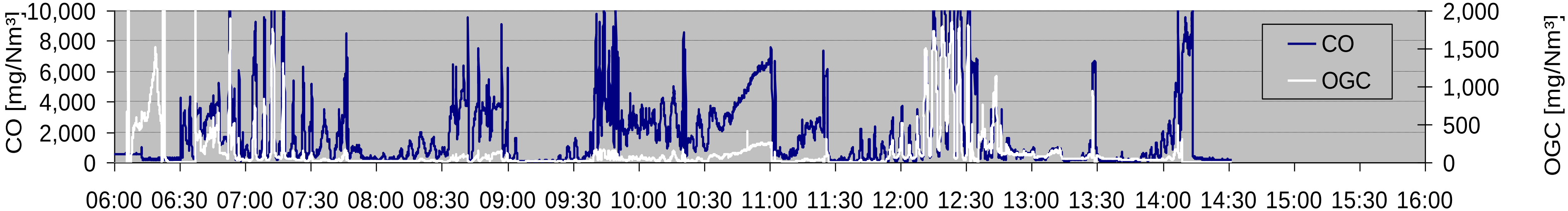
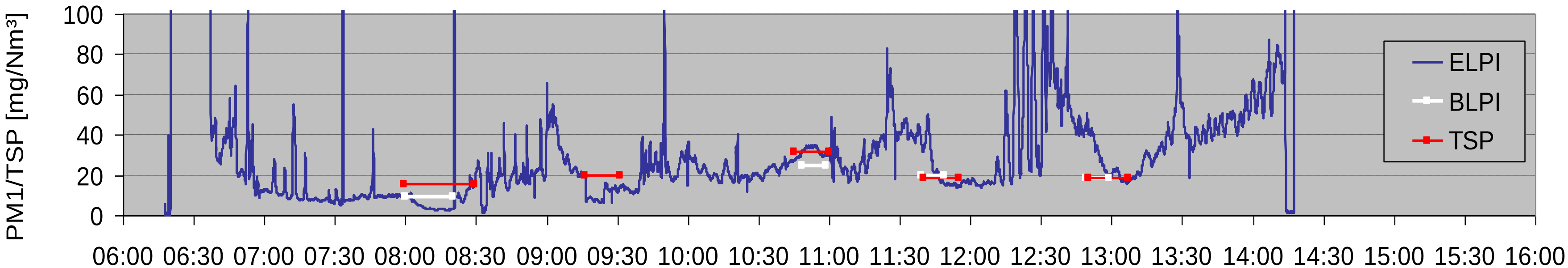
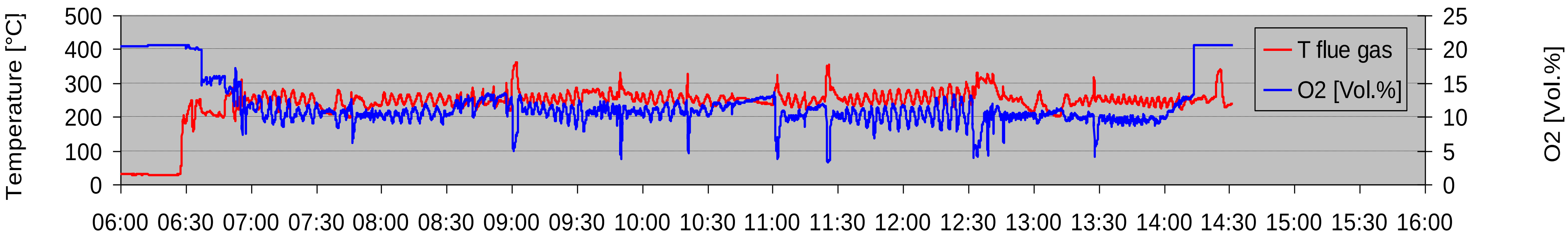
Results – operation data and emission trends (example) (II)

Test run Klagenfurt II – 31.03.2011 (day 3)







Emissions related to dry flue gas and 13 vol% O_2, TSP ... total suspended particulate matter, ELPI ... PM_1 emissions by electrical low pressure impactor, BLPI ... PM_1 emissions by Berner-type gravimetric low pressure impactor

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Results –
energy balance and emission factors

Mean values related to the whole measurement cycle (day)

		Leibnitz I	Klagenfurt I	Maribor I	Klagenfurt II	Leibnitz II	Maribor II
mass balance							
fuel mass applied	[kg w.b. /h]	3.8	12.7	8.3	25.1	11.4	7.7
combustion air flow	[Nm³ w.b. /h]	80.5	167.4	177.3	213	63.7	121.1
exhaust gas flow	[Nm³ w.b. /h]	83.8	178.7	184.6	233	72.7	128.1
ash mass	[kg/h]	0.04	0.11	0.10	0.17	0.09	0.05
energy balance							
fuel energy (NCV*) applied	[MJ/h]	63.9	201	139.6	404	180.7	107.8
utilised energy	[MJ/h]	33.9	103.1	83.2	289	129.9	67.3
utilisation efficiency	[%]	53.1	51.1	59.6	71.5	71.6	62.5
emission factors							
carbon monoxide (CO)	[mg/MJ]	**4,348**	**5,857**	**3,527**	**1,705**	**2,336**	**3,471**
organic gaseous compounds (OGC)	[mg/MJ]	**265**	**481**	**193.6**	**61.3**	**193.8**	**114.9**
fine particulate matter (PM_1)	[mg/MJ]	**102.7**	**39.8**	**72.3**	**20.6**	**16.6**	**30.2**

(*NCV ... net caloric value)

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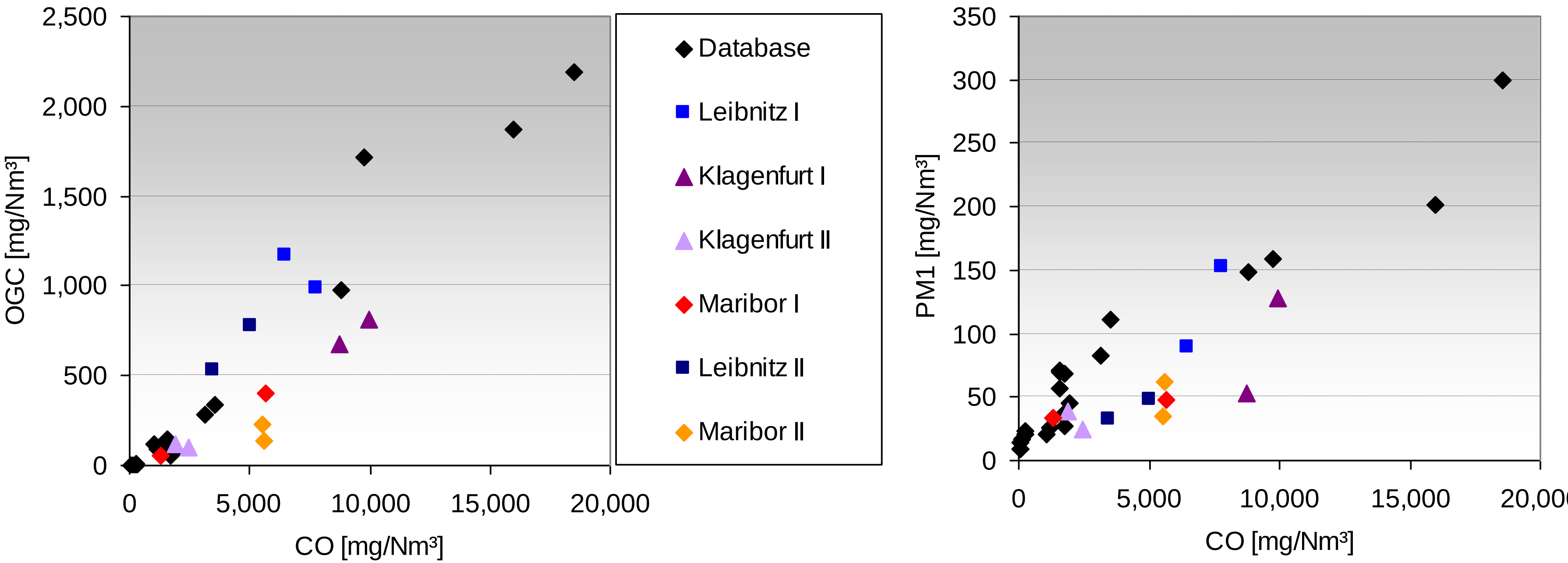
Results – emission correlations

Correlations of average emissions and comparison with database values



Explanations:
Data represent average values over a whole operation cycle (day)
PM1 ... particulate matter with aerodynamic diameter < 1 µm
OGC ... organic gaseous carbon (measured with a flame ionisation detector (FID)
CO ... carbon monoxide; all data related to dry flue gas and 13 vol.% O_2
Database: data from measurements performed by IPPT/TU Graz within former projects

Results – emissions - comments

- **Mass and energy balance**
  - The utilization ratios of the systems have been calculated to 51 – 72%
  - Losses due to high flue gas temperatures (inefficient heat exchanger design) are the main reason for the low utilization ratios
  - High flue gas volume flows (characterized by high oxygen values) and to a lower extent, the burn out quality of ashes and flue gases are also important factors for low system efficiencies

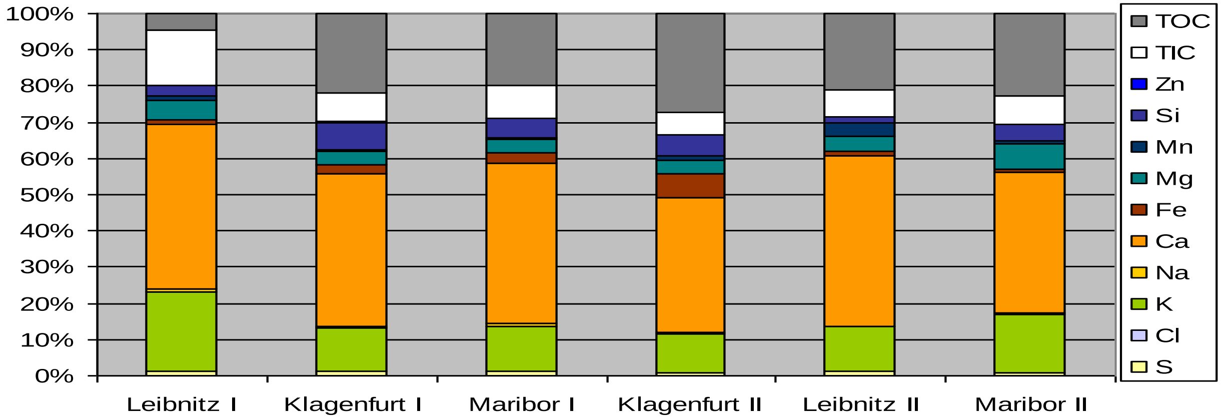
- **Emissions**
  - The results show high deviations regarding the CO, OGC and CO emissions of the different systems reaching for PM_1 from 15 to 105 mg/MJ.
  - The data fit well with database values regarding the trends CO vs. OGC and CO vs. PM_1 emissions.
  - Moreover, the higher emission ranges (older technologies) are in the range of database values gained from other test runs performed at TU Graz as well as literature data from field tests performed in the late 1990ies.

Results –
grate ash analysis

Mean values of the chemical composition of grate ash samples

averages of 2 analyses, TOC ... total organic carbon = sum of EC (soot) and OC (organic carbon), TIC ... total inorganic carbon = carbonate carbon compounds)

compounds	unit	Leibnitz I	Klagenfurt I	Maribor I	Klagenfurt II	Leibnitz II	Maribor II
S	[mg/kg d.b.]	6,320	6,110	7,105	4,005	6,765	5,045
Cl	[mg/kg d.b.]	440	477	572	53.6	410	553
Ca	[mg/kg d.b.]	241,500	231,500	247,500	217,000	306,500	253,000
Fe	[mg/kg d.b.]	5,460	12,180	17,115	38,050	7,630	4,360
K	[mg/kg d.b.]	117,500	65,700	69,600	61,650	81,200	105,500
Mg	[mg/kg d.b.]	29,550	20,450	20,400	19,850	26,950	48,150
Mn	[mg/kg d.b.]	5,590	4,015	3,600	7,195	24,750	3,210
Na	[mg/kg d.b.]	4,445	3,895	4,930	2,455	621	1,890
Si	[mg/kg d.b.]	16,250	39,250	29,100	33,100	10,175	31,600
Zn	[mg/kg d.b.]	560	2,253	719	304	155.0	230
TOC	[mg/kg d.b.]	25,000	121,500	112,250	156,500	136,000	148,500
TIC	[mg/kg d.b.]	80,100	43,500	49,750	37,500	49,000	49,500



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Chemical composition of PM_1 emission samples

(For each test run 4 PM_1 samples have been analyzed)

For samples taken during stable combustion phases:

- The **inorganic part** is dominated by potassium compounds
  - alkali sulphates in the range of 50 – 75%
  - alkali carbonates in the range of 5 – 30%
  - alkali chlorides in the range of 5 – 10 %
  - metal oxides < 2%
- **Soot and organic compounds** (EC an OC)
  - OC and EC values increase with decreasing burnout quality
  - At the modern technology boilers the lowest fractions of EC and OC have been found (about 8 - 15%), while the PM emissions of old technology boilers are dominated by EC and OC (about 50 - 85% of PM_1 mass)

Summary, conclusions and recommendations (I)

Burnout quality and PM emissions

- **The burnout quality is significantly higher for the automatically controlled boiler systems Klagenfurt II and Leibnitz II**
- **Therefore, these boilers also show the lowest PM_1-emissions**
  - Average CO emissions (whole operation cycle): 1,700 – 2,300 mg/MJ compared to 3,500 – 5,900 mg/MJ at old-technology boilers
  - Average PM_1 emissions (whole operation cycle): 17 – 21 mg/MJ compared to 30 – 102 mg/MJ at old-technology boilers
- **Good correlations between OGC, CO and PM_1 emissions exist.**
- **The concentrations of organic carbon and soot in the PM emissions significantly increase with decreasing burnout quality.**

Summary, conclusions and recommendations (II)

- **Main reasons for elevated emissions are**
  - **The maturity of the technology applied**
  - **The quality of the wood logs fired**
  - **The installation situation**
  - **The charging strategy of the user**

Summary, conclusions and recommendations (III)

- **The most efficient way to reduce PM emissions from residential biomass combustion is to replace old combustion systems by modern ones**
  - **Improved burnout in modern technologies**
  - **Decreased emission factors for PM_1**
  - **Lower concentrations of carbonaceous compounds (OC, EC) in the PM emissions (emission of less harmful particles)**

- **Therefore, efforts should be made in order to**
  - **Substitute old residential biomass heating systems by state-of-the-art technologies**
  - **Raise awareness of users concerning**
    - **heating practice**
    - **identification of system errors and maintenance requirement**

Thank you for your attention!

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