Gasification of biomass for Gas-fired cogeneration

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cpga www.cpga.cz
Czech Pyrolysis and Gasification Association

Gasification of biomass

Biomass (+H_2O, + CO_2)

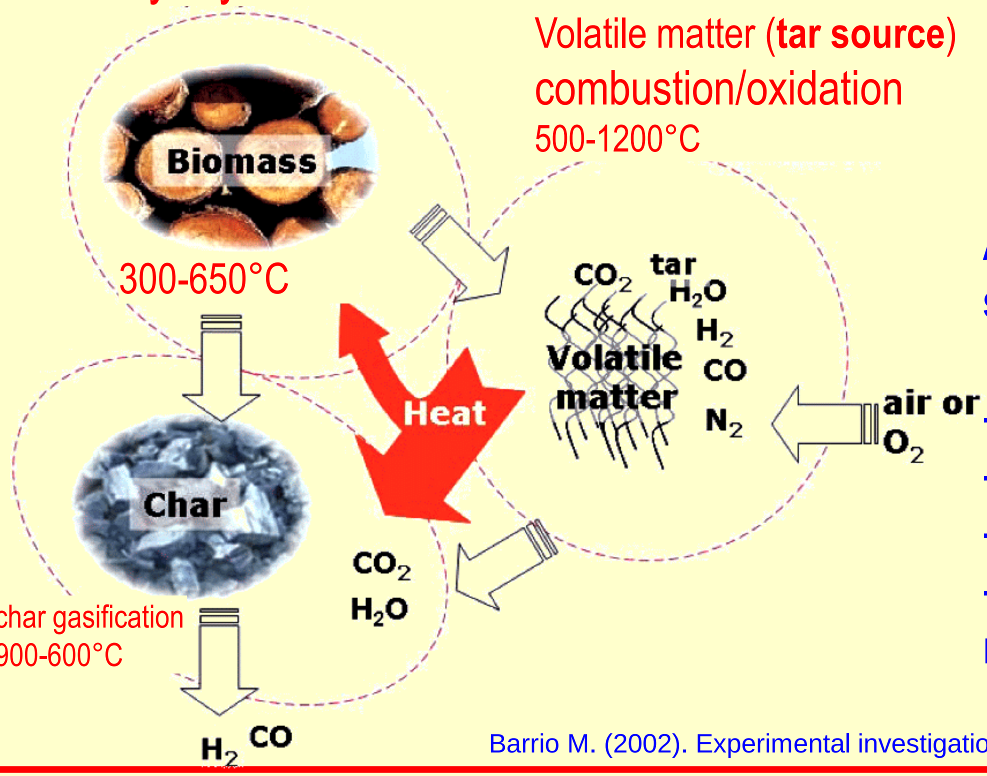
$$C_xH_yO_z + O_2\ (N_2) \rightarrow CO + H_2 + CH_4 + CO_2 + (N_2 + C_xH_y) + \text{dust} + \text{tar}$$

Gas production efficiency (η_{ce}) and gas quality depends:

- Type of a Gas generator (countercurrent, co-current, imbert, fluidized bed, **two stage, twin-fire**)
- Efficiency of gas heat utilization: from autothermal to allothermal or combination
- Operating condition (gasification medium, gasification ratio, temperatures...)

Pyrolysis

Volatile matter (**tar source**)
combustion/oxidation
500-1200°C



char gasification
900-600°C

History "tar free" gasifier:

- updraft charcoal gasifier
- imbert
- internal tar recycling gasifier

Advantages of sub process separation in **two stage** gasifiers **:**

-increase of cool gas efficiency (η_{ce}>85%)
-decrease of tar content on safe level (**< 0,1 g/m^3**)
-better gas quality (higher heating value)
-better process parameters control and heat management

Barrio M. (2002). Experimental investigation of small-scale gasification of woody biomass. Ph. D. Thesis, NTNU.

The overall electrical efficiency for cogeneration

$$\eta_t = \eta_{CE} * \eta_{CU}$$

η_{CE} - cold gas efficiency, which takes into account only the chemical energy stored in the gas

η_{CU} - cogeneration unit efficiency (IC motor+ el. gen.)

η_t - overall cogeneration unit efficiency (IC motor+ el. gen.)

Type of cogeneration	cold gas efficiency η_{CE}, %	gas to electricity efficiency, η_{cu}, %	Overall el. efficiency η_t, %	**Inst. costs** thousd.czk /kW_e
1. power plant with steam turbine (11 MW_e) Green boiler (Zeleny kotel, 33 MW_t),2010, Plzeň	-	-	**27,6**	80
2. downdraft „Imbert“ gasifier (100 kW_e) Boss engineering ltd,Louka,2005, Staré město,2009	65	max. 30 liaz M1.2,12dm^3,6 C	**max. 19,5**	60
3. downdraft gasifier„GP300“ with adw. heat recovery (200 kW_e) Tarpo ltd, Kněževes, 2009	75	~ 32 ČKD 6S160,27 dm^3,6C	**~ 24**	60-70
4. Prototype of Two Stage gasifier (200kW_e) Tarpo ltd, Kněževes, 2011/2012	min. 80	**~32** (see 3) **max. 36** (see 5)*	**~ 26** **~ 29**	80-90 **80-100**
5. Two Stage gasifier GP750 (750kW_e) Tarpo ltd, Air Technic s.r.o. Hadlová (2x), Bor Biotechnology (5x)	**~ 85**	**~ 36***	**~ 32**	**100********
6. Model: Two Stage gasifier, **3,5-8 MW_e**	~90	~45 ***	**~ 40**	????

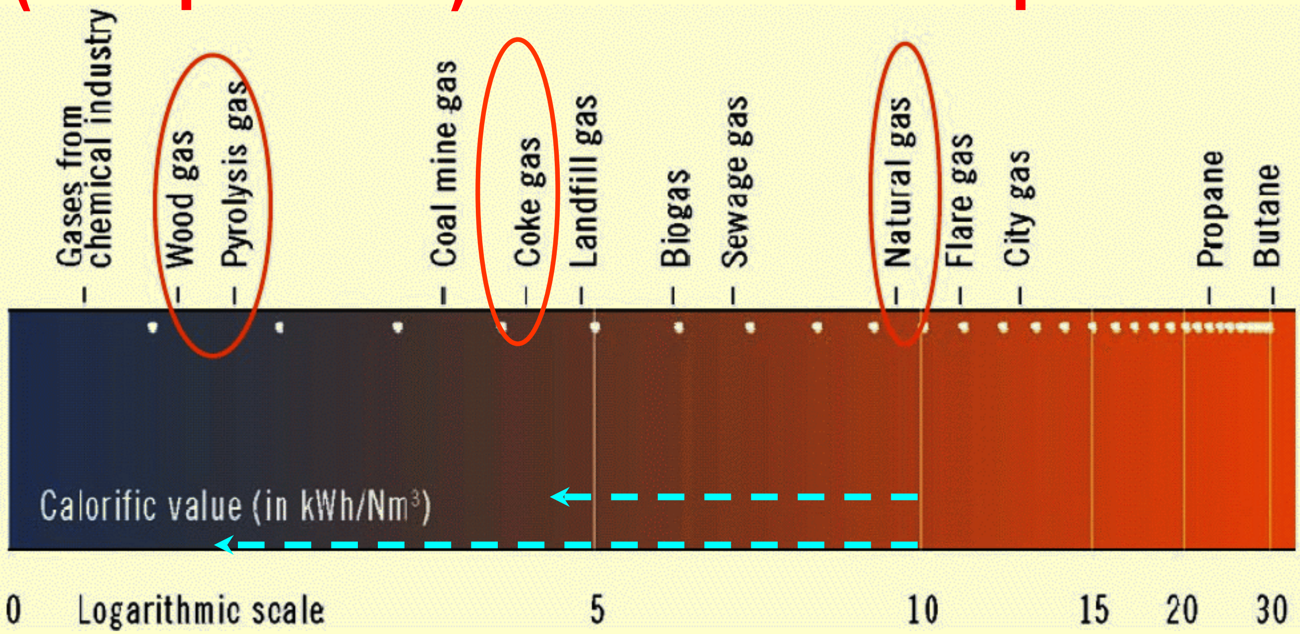
* Jenbacher AB, J316 GC (J320GC)

*** Jenbacher, J624* GC with 2 stage turbocharger η_{cu}, = **46,1**% 4,35 MW_e,J920* GC with 2 stage turbocharger η_{cu},= **48,7**%(NG) 9,5MW_e

**** The commercial implementation in SR and CR

Gas quality (composition) influence on IC power output

•Heating Value of gas (LHV) In kWh/m³



More important is a calorific value (energy content) of **mix**ture (gas and air). Stoichiometric combustion ratio (ER =1) for different gaseous fuel (NG, LPG, SG, Wood gas) demand the different **Air to Fuel Ratio** (AFR).

fuels	AFR (ER=1)	LHV, MJ/m³ (kWh/m³)	MIX LHV kWh/m³
Natural gas	9,5	35,8 (9,7)	0,92
Propene	23,8	93,2 (25,9)	1,04 (+13%)
LPG (summer)	28,7	106 (29,5)	0,99 (+7%)
Synthetic gas (Vřesová)	**3,7**	**15,7 (4,35)**	**0,93**
Wood gas	**1,1-2**	**4-8 (1,1-2,2)**	**0,75 (-19 %)**

The energy of the fuel-air mixture in the combustion chamber for wood gas is only about 15-20% lower !!!.

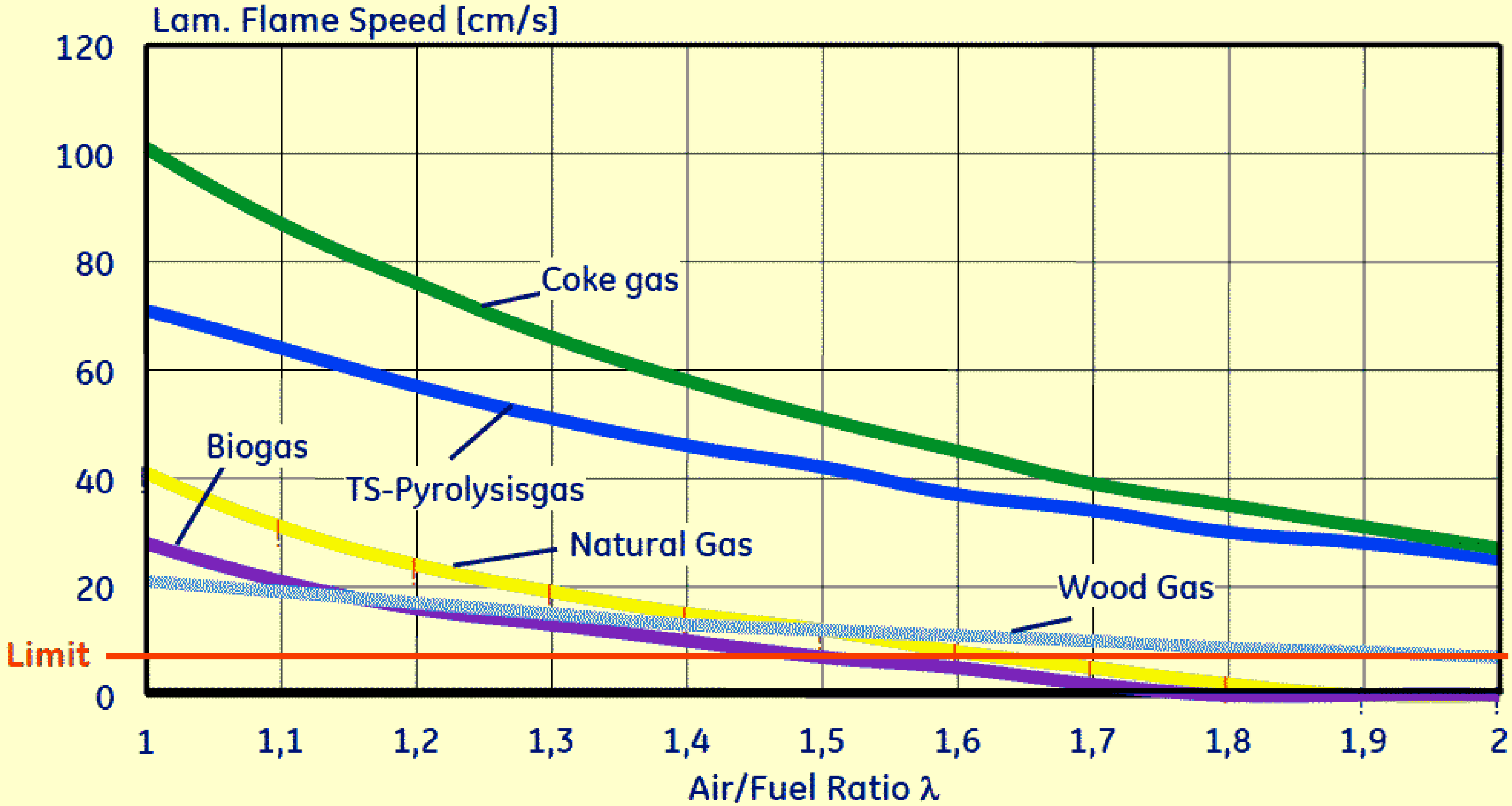
Thomas Elsenbruch, Latest Developments in the Use of Wood Gas in Gas Engines, IDGTE Toronto, Canada; 12. June 2008

Gas quality (composition) and IC engine operation

Laminar Flame Speed

Laminar flame speed is the speed at laminar front at which the oxidation takes place

concentration of $\mathbf{H_2}$ strongly increase LFS, **CO** slowly decrease).



Thomas Elsenbruch, Latest Developments in the Use of Wood Gas in Gas Engines, IDGTE Toronto, Canada; 12. June 2008

Gas quality (composition) and IC engine operation

Critical parameter for knocking resistance

Knock is an abnormal combustion phenomenon that adversely affects performance, emissions, and service life of spark-ignited (SI) internal combustion (IC) engines.

During knock the end gas auto ignites and combusts before the arrival of the flame front and produces a rapid pressure rise and extremely high local temperatures.

Prevention of Knocking on fuel side

"Octane Number" (ON) for **liquid fuels** (0-100),

"Methane Number" (MN) for **gaseous fuels** (0-160).

"Methane Number" defined as the percentage by volume of $\mathbf{CH_4}$ blended with $\mathbf{H_2}$ (MN<100) that exactly matches the knock intensity of the unknown gas mixture under specified operating conditions (ER=1) in a knock testing engine.

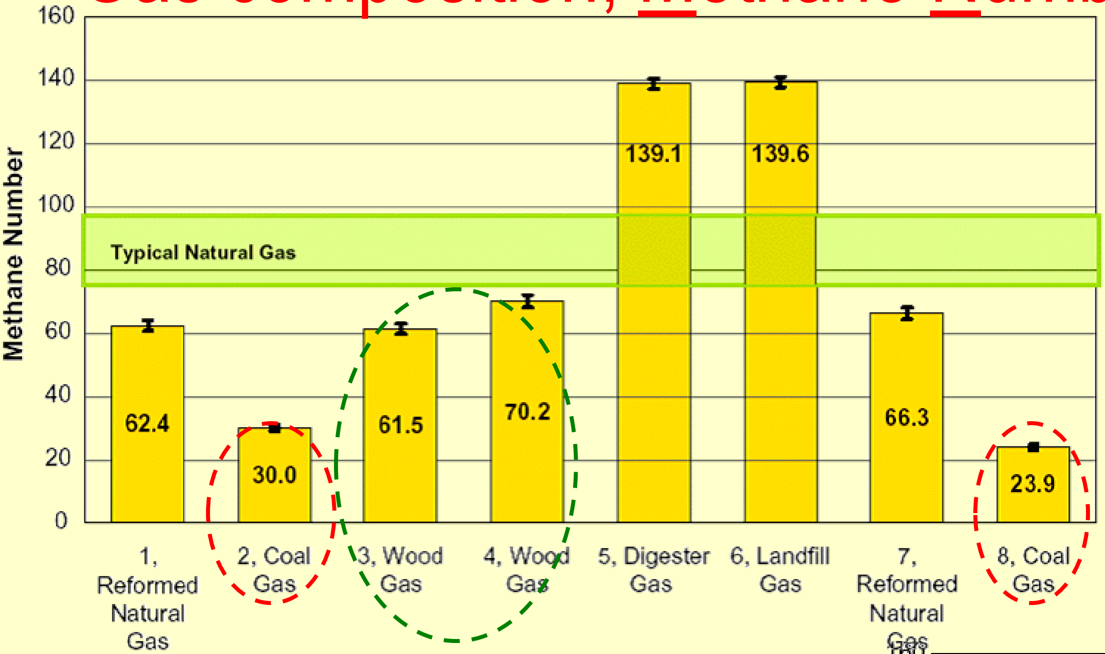
For the range above 100 MN, $\mathbf{CH_4}$-$\mathbf{CO_2}$ mixtures were used as reference mixtures for test.

In this case, in accordance with the definition, the MN is 100 plus the percent CO_2 by volume in the reference CH_4-CO_2 mixture.

MN=80 composition: 80% CH_4+ 20% H_2
MN=140 composition: 60% CH_4+ 40% CO_2

Malenshek M, Olsen D.B.: Methane number testing of alternative gaseous fuels, Fuel 88 (2009) 650–656

Gas composition, Methane Number, Compression Ratio



Different gas composition and influence on MN and CR

Gas	CH_4	H_2	N_2	CO	CO_2	MN_{ex}
1. Reformed NG	38,1	44,5	2,1	2,3	13,0	59.3
2. Coal gas	-	22,3	13,3	63,1	1,3	30,0
3. Wood gas	8,3	39,7	2,4	24,3	25,3	61,5
4. Wood gas	1,6	30,9	33,8	17,4	16,2	70,2
5. Digester gas	60,8	-	1,5	-	37,8	139,1
6. Landfill gas	60,5	-	-	-	39,5	139,6
7. Reformed NG	1.4	30,2	47,4	13,9	7,1	66,3
8. Coal gas	6,6	44,4	-	42,9	6,1	23,9

equivalence ratio ER (φ) = 1

MN (CR)↓ decrease

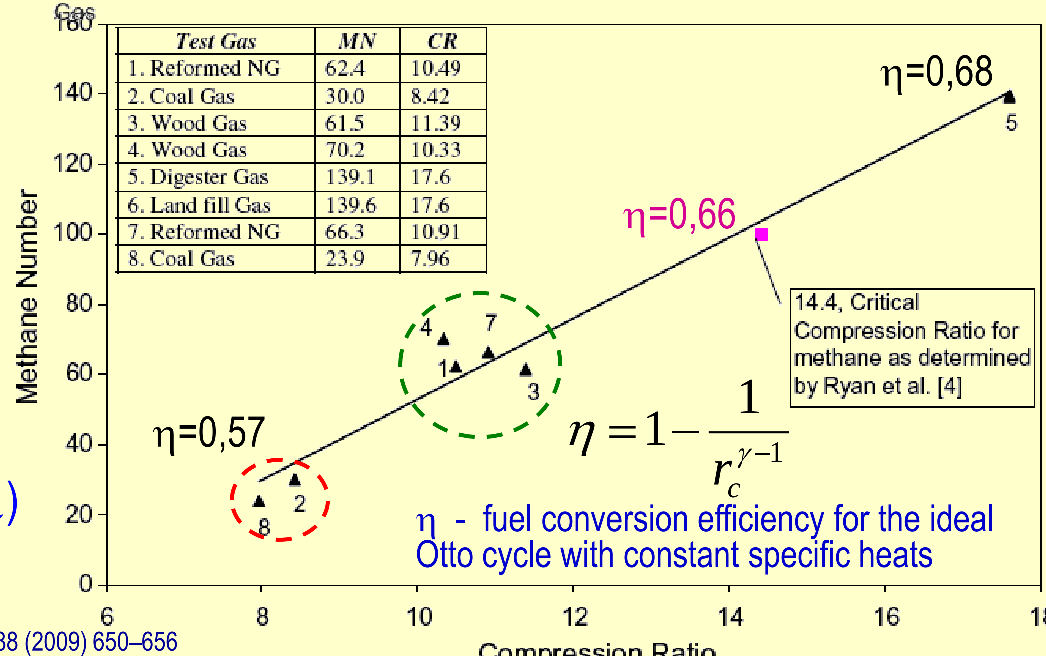
- increasing of H_2 (↑) and CO (↑) conc.
- decrease CO_2 (↓) and N_2 (↓)

MN (CR) ↑ increase

- increasing of CO_2 (↑) and N_2 (↑)
- CO_2 acting as a knock suppressor

Posibile compensation of CR decreasing:

- decrease ignition advance (crank angle) (↓)
- ?? Increase equivalence ratio (φ)↑



Test Gas	MN	CR
1. Reformed NG	62.4	10.49
2. Coal Gas	30.0	8.42
3. Wood Gas	61.5	11.39
4. Wood Gas	70.2	10.33
5. Digester Gas	139.1	17.6
6. Land fill Gas	139.6	17.6
7. Reformed NG	66.3	10.91
8. Coal Gas	23.9	7.96

Malenshek M, Olsen D.B.: Methane number testing of alternative gaseous fuels, Fuel 88 (2009) 650–656

MN and critical CR for typical gases from gasification

Gas source	H_2	CO	CH_4	CO_2	N_2	LHV	MN	CR
		Volume fraction, %				MJ/m^3	Exp.	Crit.
1. Gusing (FICFB)	40,0 38,2	24,0 24,1	10,0 10,3	23,0 22,6	3,0 4,76	10,95	55,6	10,6
2. Viking (two stage)	30,5 29,4	19,6 17,5	1,6 2,61	15,4 14,8	33,3 35,7	6,32	54,6	10,5
3. IISc (Open Top Downdraft)	19,0 20,7	19,0 19,0	1,5 1,98	12,0 12,6	48,5 45,7	5,10	125,7	13,1
4. Harboore (updraft)	19.3 20,6	22,8 22,3	5,3 5,95	11,9 12,6	40,7 38,3	6,87	105,6	12,1
5. CPC (Downdraft)	18,8 19,9	21,0 21,3	2,2 3,05	1,4 2,04	56,7 53,6	5,49	57,5	10,3

- There are large differences in MN (critical CR) among producer gas compositions
- H_2 and CO_2 acting as a knock propagator and knock suppressor, respectively
- 1% increase in CO_2 conc. increased the CR by 0,32 units and a 1% increase in H_2 conc. decreased the CR by 0,14 units
- Impact of CO_2 changes on the critical CR is over two times high that impact of H_2

Arunachalam A, Olsen D.B.: Experimental evaluation of knock characteristics of producer gas, Biomass and Bioenergy 37 (2012) 169 -176

Requirements for gas quality for IC engines

Parameters	Values
Gas input temperature, ˚C	< **40**
Relative gas humidity, %	< 80
dust content, $mg.m^{-3}$	max. < 50, recommended: < **5**
particle size, μm	< 10, < **5**
Tar content, $mg.m^{-3}$	< 500, < 100, 50-100 recommended: < **50** ,< 30, < 5
Acid content, $mg.m^{-3}$	< 50
Total sulfur content, $mg.m^{-3}$	< 700
(HCl+2xHF), $mg.m^{-3}$	< 100
NH_3, $mg.m^{-3}$	< 50

How much tars can contain gas for safe motor operation ..?

- **Tar Definition metod (Tar Protocol ?)**
- **Tar Determination method**
- **The specific motor design and operation condition**

Reinhard Rauch: Integration Aspects in the Next Generation of CHP Plants Based on Gasification, International Seminar on Gasification 2012, 18-19.10.2012,Stockholm

Consequences of „dirty“ gas combustion

Clogging pipes by dust particle increased engine wear (turbocharger !!!)

Higher contents of particles (> 50 mg.m^{-3})

- ✓Clogging the exhaust manifold carbonaceous residues
- ✓**erosion and wear of moving parts**
- ✓**corrosion of engine parts (water+tar)**, mainly aluminum parts, intake ports in cylinder head - is related to the presence of metals in oil

Faster contamination of engine oil

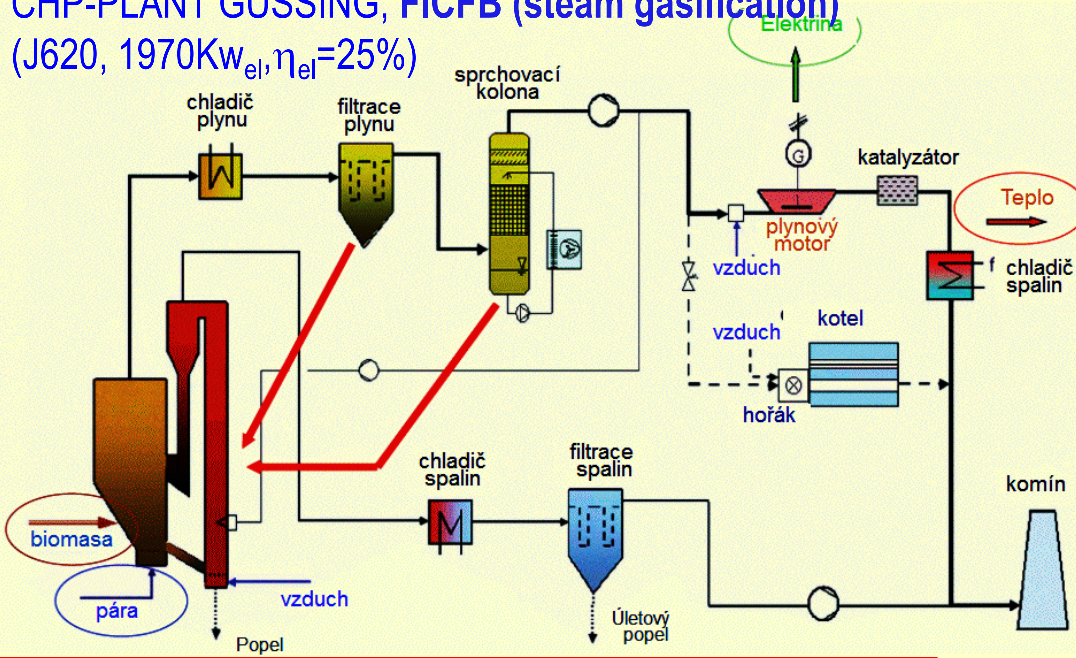
small particles (d_p**< 10 (< 5)** μm) and quantity (**< 50** mg.m^{-3})

- ✓oil life reduced to about ¼ to ½ times the carriage of oil used for NG
- ✓ Increase of oil alkalinity, oil analysis shows the presence of metals (K, Na)
- ✓analysis showed the of potassium presence in oil - in operation at normal fuel (NG,LPG) does not occur, the cause of the fine ash particles in biomass gasified gas

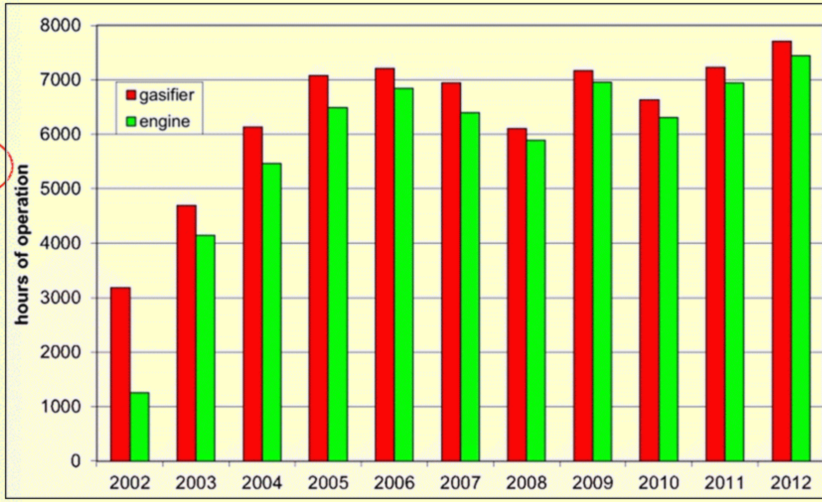
Jan Černohorský, Dřevní plyn z pohledu výrobce spalovacího motoru, Jihlava 2010, TEDOM-VKS s.r.o.

Requirements for Tar contents in gas IC engines

CHP-PLANT GÜSSING, **FICFB (steam gasification)**
(J620, 1970Kw_{el}, η_{el}=25%)



Operation of GÜSSING



Location	Usage / Product	Fuel input /Product MW, MW	Start up	Status
Güssing, AUT	Gas engine	8.0_{fuel} / 2.0_{el}	2002	Operational
Oberwart, AUT	Gas engine / ORC/H_2	8.5_{fuel} / 2.8_{el}	2008	Operational
Villach, AUT	Gas engine	15_{fuel} / 3.7_{el}	2010	on hold
Senden/Ulm, DEU	Gas engine / ORC	14_{fuel} / 5_{el}	2011	Operational
Burgeis, ITA	Gas engine	2_{fuel} / 0.5_{el}	2012	Operational
Göteborg, SWE	BioSNG	32_{fuel} / 20_{BioSNG}	2013	Operational
California, USA	R&D	1 MW_{fuel}	2013	Operational
Gaya, FRA	BioSNG R&D	0,5 MW_{fuel}	2016	Operational
Thailand	Gas engine	4_{fuel} / 1_{el}	2016	Operational

Reinhard Rauch: Integration Aspects in the Next Generation of CHP Plants Based on Gasification, International Seminar on Gasification 2012, 18-19.10.2012,Stockholm

Gas composition after gas cleaning

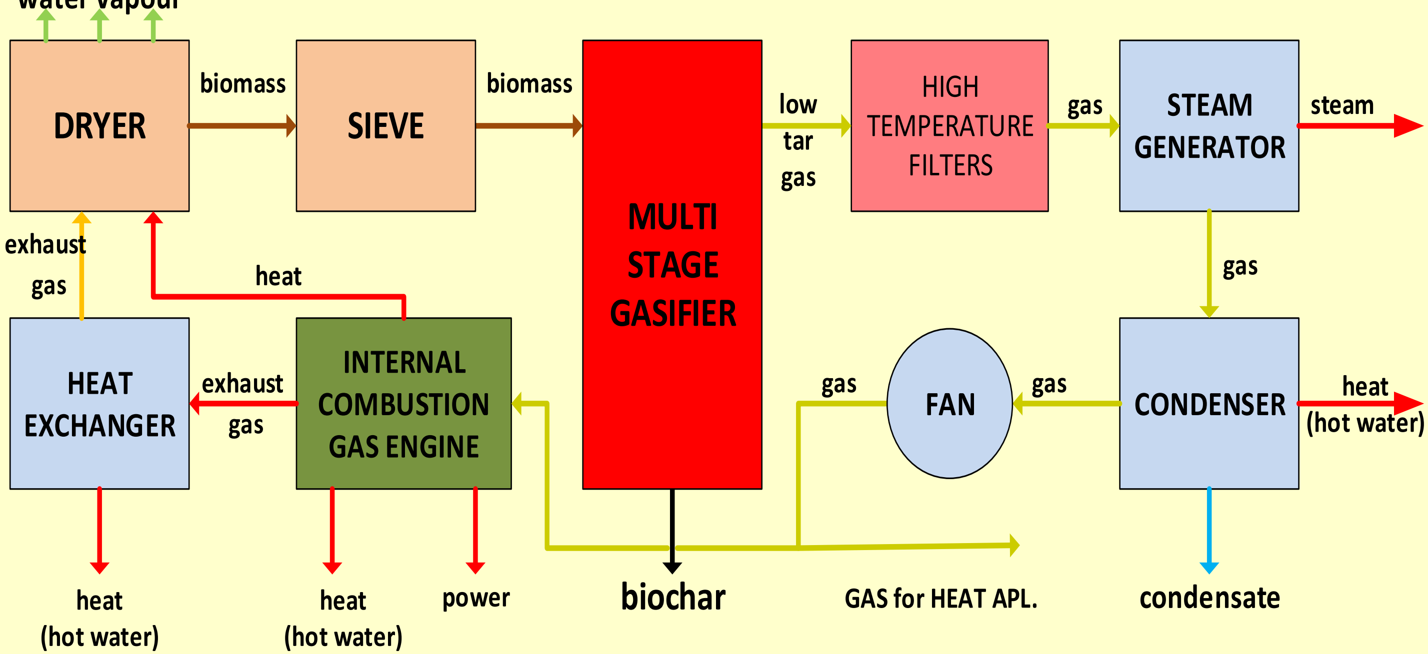
Main Components		
H_2	%	35-45
CO	%	22-25
CH_4	%	~10
CO_2	%	20-25
Minor Components		
C_2H_4	%	2-3
C_2H_6	%	~0.5
C_3H_4	%	~0,4
O_2	%	< 0,1
N_2	%	1-3
C_6H_6	g/m^3	~8
C_7H_8	g/m^3	~0,5
$C_{10}H_8$	g/m^3	~2
TARS	mg/m^3	20-30

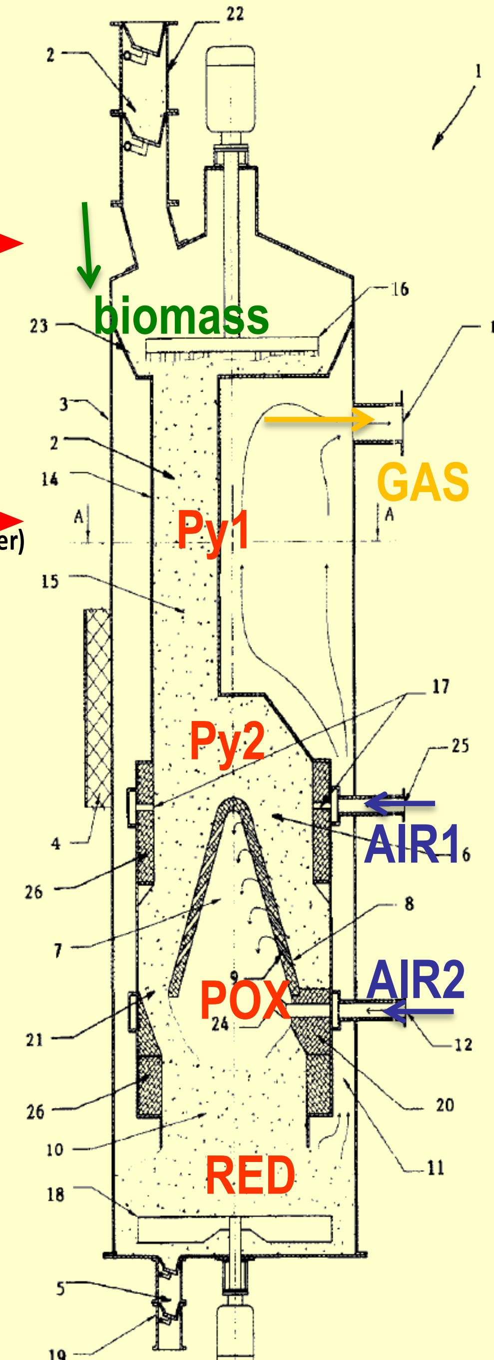
Possible poisons		
H_2S	mgS/Nm^3	~200
Mercaptans	mgS/Nm^3	~30
Thiophens	mgS/Nm^3	~7
HCl	ppm	~3
NH3	ppm	500-1000
Dust	mg/Nm^3	< 20

TAR(Tar Protokol) = ~0,5 +~2+0,03 ≅ 2,53 g/m^3

≅ 2530 mg/m^3 (??)

Two-stage gasifiers GP750 used for cogeneration





Main parameters of GP750 unit used in Kozomín:

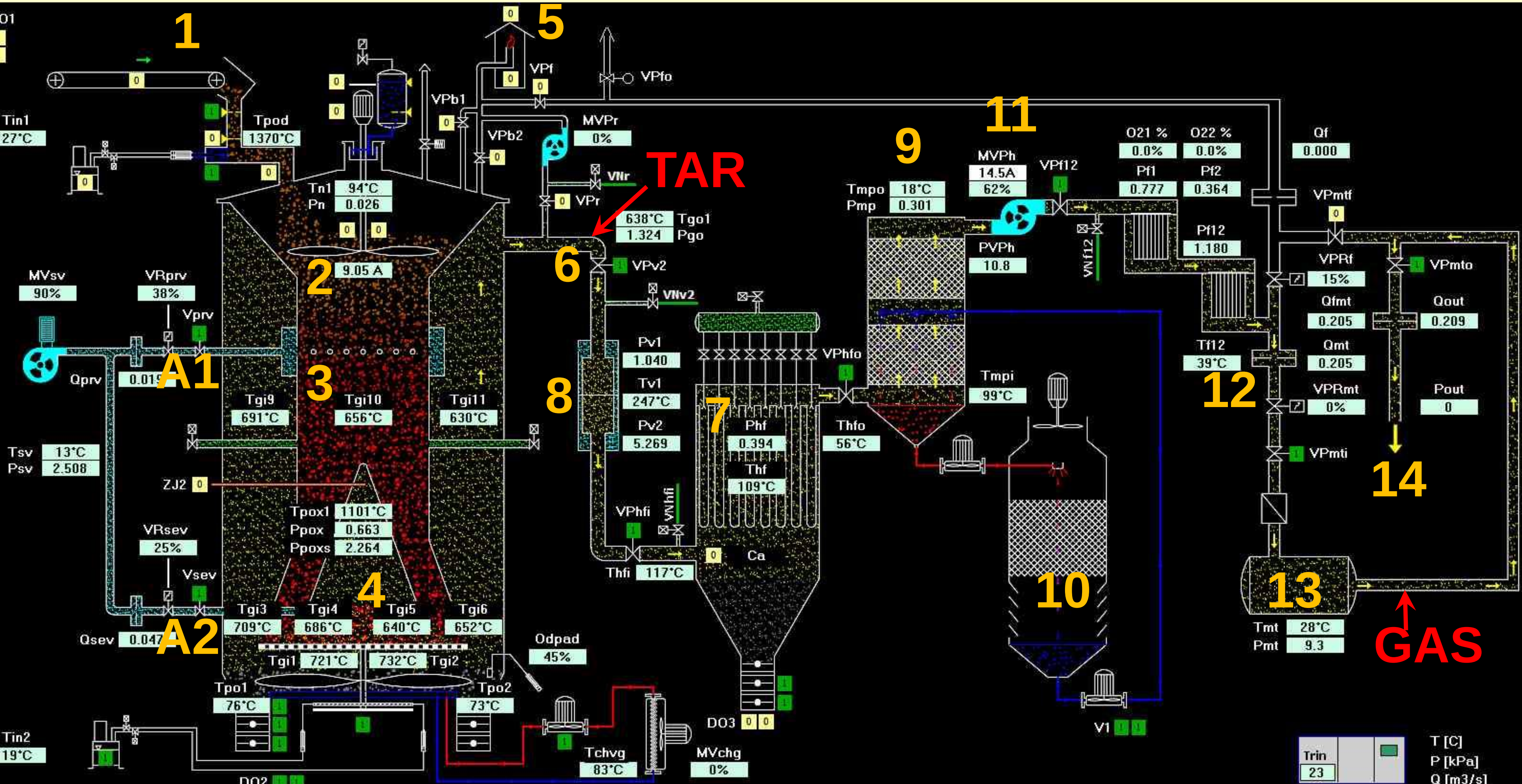
Nominal electric power	**710 kW**
Nominal wooden chips consumption (dry)	550 kg/h.
Chips dimension	6 to 50 mm
Biomass moisture (dryer input/output)	up to 60/<10 wt. %
Gas flow, max. (m^3/h (n.c.)	1400
Overall efficiency (calculated from LHV)	**32 %**
Nominal fuel (dry) consumption	**0,7 kg/kWh**
Nominal electric output	**1,4 kWh /kg**

Two-stage gasifiers in Czech and Slovak Republic

Location	Start of operation	IC engine /Power	Gas cleaning	Current status
1. Kněževes (CZ)	2012,GP200 [1)]	ČKD, 2x6S160/ 200 kW_e	ceramic candle, water washing/cooling	from 2014 out of permanent operation
2. Odry (CZ)	2013, 2xGP500[1)]	Jenbacher, 2xJ316/ 2x500 kW_e	ceramic candle, water washing/cooling	operation with lower output: 2x400 kW_e for sell from 06/2016
3. Olešnice (CZ)	2014/15, GP200XL[1)]	ČKD, 2x6S160/200 kW_e	bag filter, water washing	transformed to twin-fire, in operation
4. Handlová (SK)	2014, 2xGP750 [2)]	Guascor, FBLD560 (570 kW_e) FBLD480 (430 kW_e)	bag filter/ceramic candle, water washing	in operation from 4/2015
5. Dobříš (CZ)	2015,1xGP750 [2)]	Guascor,FBLD560(650 kW_e)	bag filter, water washing	in operation for six months, from 10/2016 transformed to twin-fire
6. Kozomín (CZ)	2014, 5xGP750 [2)]	Jenbacher, 3xJ320/ 2,1 MW_e,	bag filter/ceramic candle, water washing	pilot operation of five GP750 units for sell from 10/2017(out of service)

[1)] preheated air was used for gasification [2)] generator has an increased pyrolyser surface area

Power plant Kozomín (Handlová, Dobříš), original flowsheet

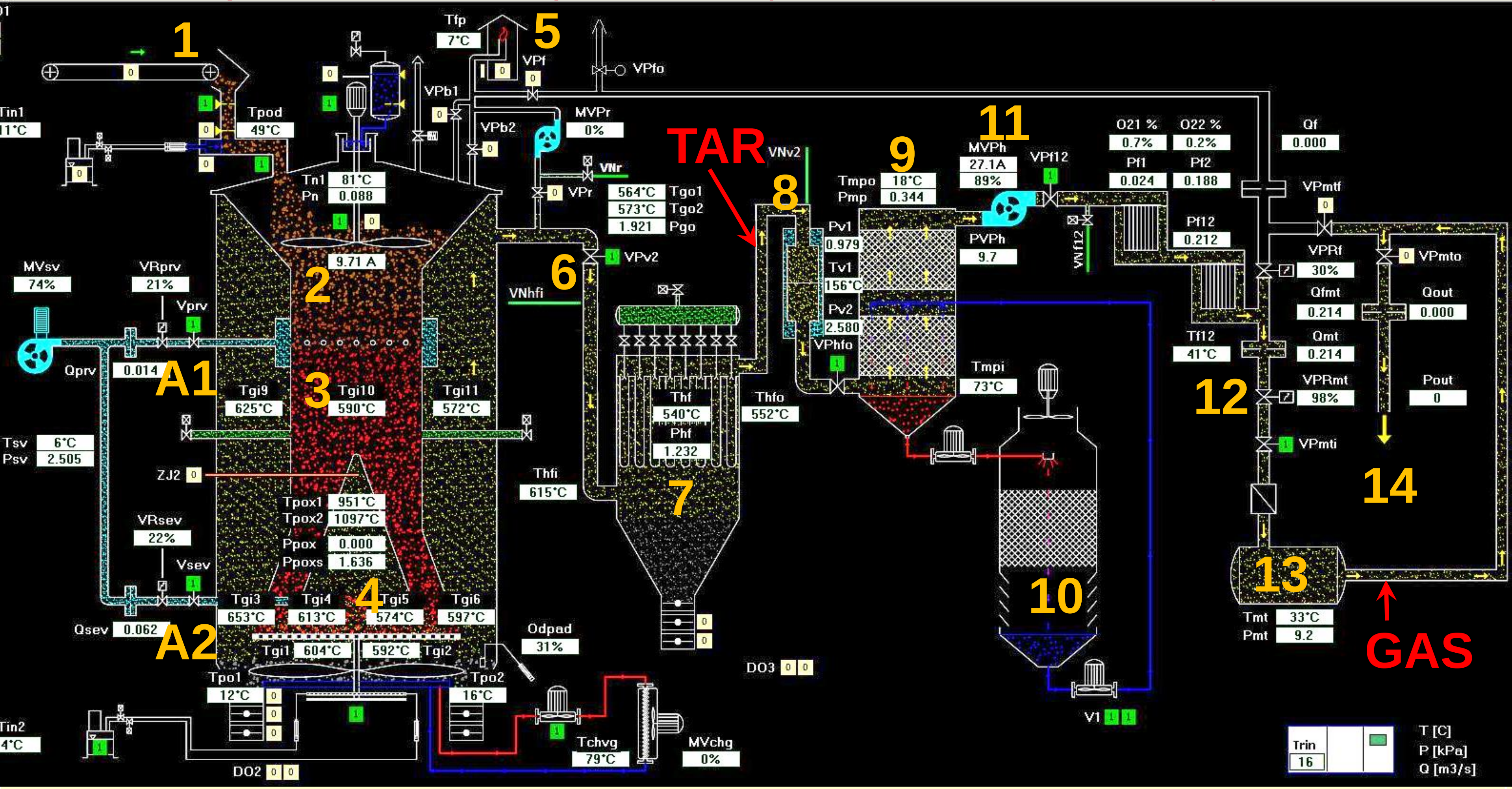


1 - entry of the fuel into the GP750, 2 - allothermal pyrolysis section, 3 - autothermal pyrolysis section, 4 - POX section, 5 - combustion flare, 6 - gas output, 7 - bag filter, 8 - heat exchangers (gas/water), 9 - contact water cooling, 10 - cooling tower, 11 - gas blower, 12 - gas flow measurement , 13 - mix tank, 14 - pipe to IC motor.

A1-primary air inlet, A2- secondary air supply

GAS - point for gas quality sampling (on-line, off-line), TAR - point for gas sampling according to Tar Protocol

Power plant Kozomín (Handlová) after reconstruction, flowsheet



1 - entry of fuel into the GP750, 2 - allothermal pyrolysis section, 3 - autothermal pyrolysis section, 4 - POX section, 5 - combustion flare, 6 - gas output, 7 - hot filters (CERAFIL XS 3000), 8 - heat exchangers (gas/water), 9 - contact water cooling, 10 - cooling tower, 11 - gas blower, 12 - gas flow measurement , 13 - mix tank, 14 - pipe to IC motor

A1 - primary air inlet, A2 - secondary air supply

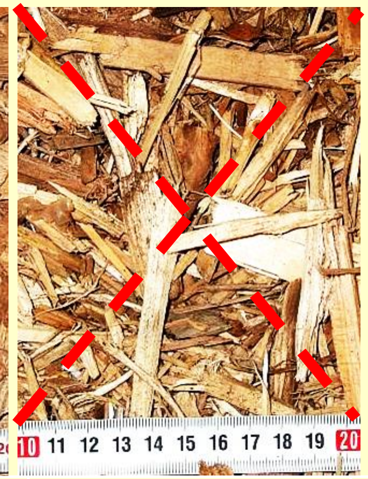
GAS - point for gas quality sampling (on-line, off-line), TAR-point for gas sampling according to Tar Protocol.

Generators hall (BOR Biotechnology Inc.)

Generators hall (BOR Biotechnology, Inc.)

Fuel properties and their effects on generator operation

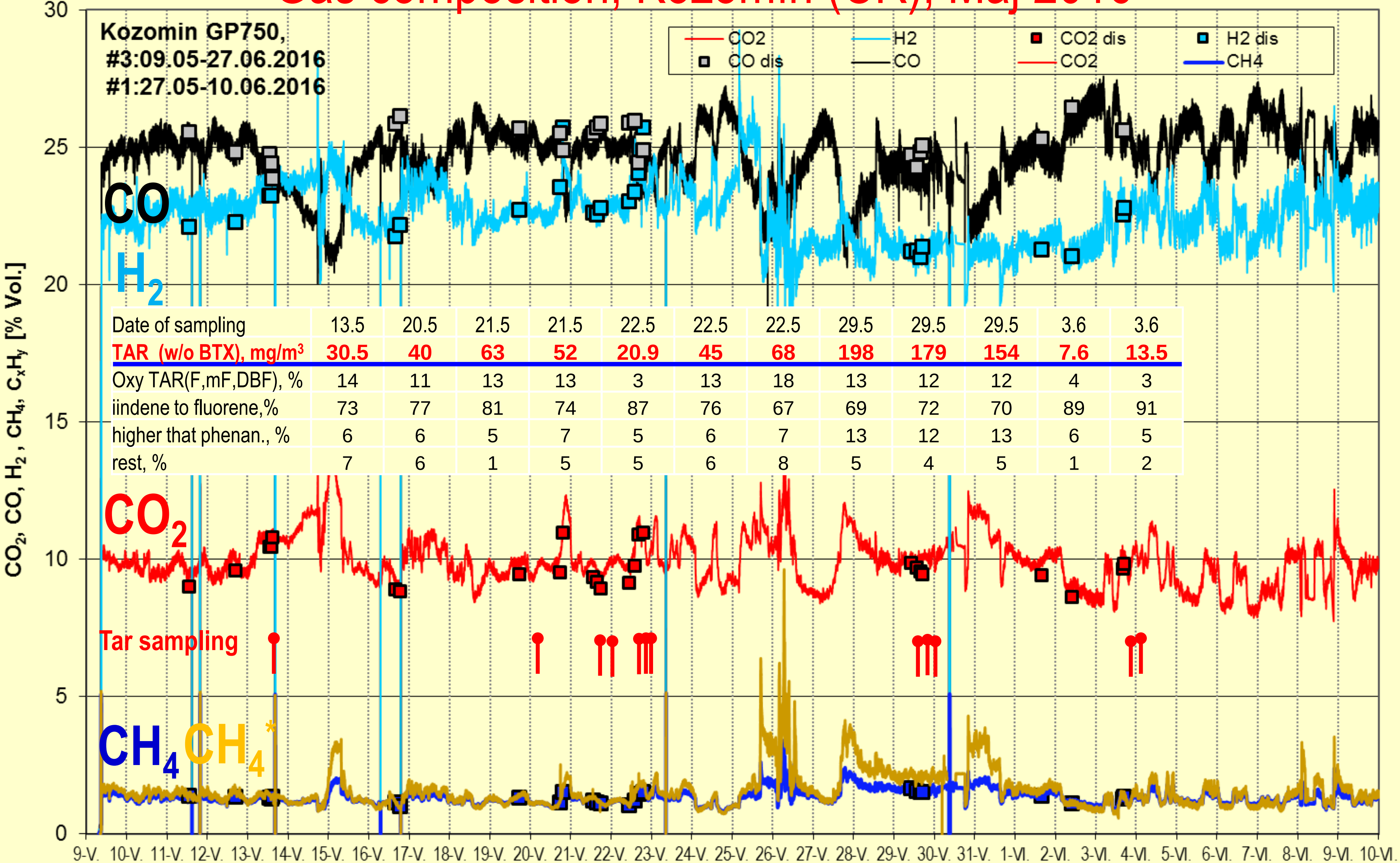
Proximate and ultimate analysis of selected fuels

fuel properties	Handlová, 2014	Kozomín, 2015	Kozomín*), 2016	Kozomín, 2016
moisture, W^a	5.00	14.00	2.61	2.89
ash, A^d	1.08	2.78	1.03	0.98
volatile matter, V^d	79.75	78.80	78.84	78.21
fixed carbon, F_c^d	19.17	18.42	20.14	20.81
Q_i^a	16.94	14.72	16.71	17.23
Q_i^{daf}	18.16	18.02	17.40	17.99
ultimate analysis, ^{d}				
C	49.58	50.28	48.62	48.40
H	6.30	6.15	5.88	6.08
N	0.50	0.27	0.23	0.19
O	42.52	40.48	44.24	44.34
S	0.02	0.04	0.01	0.01

*)chips stored for long period in the open air

Gas composition, Kozomín (ČR), Maj 2016



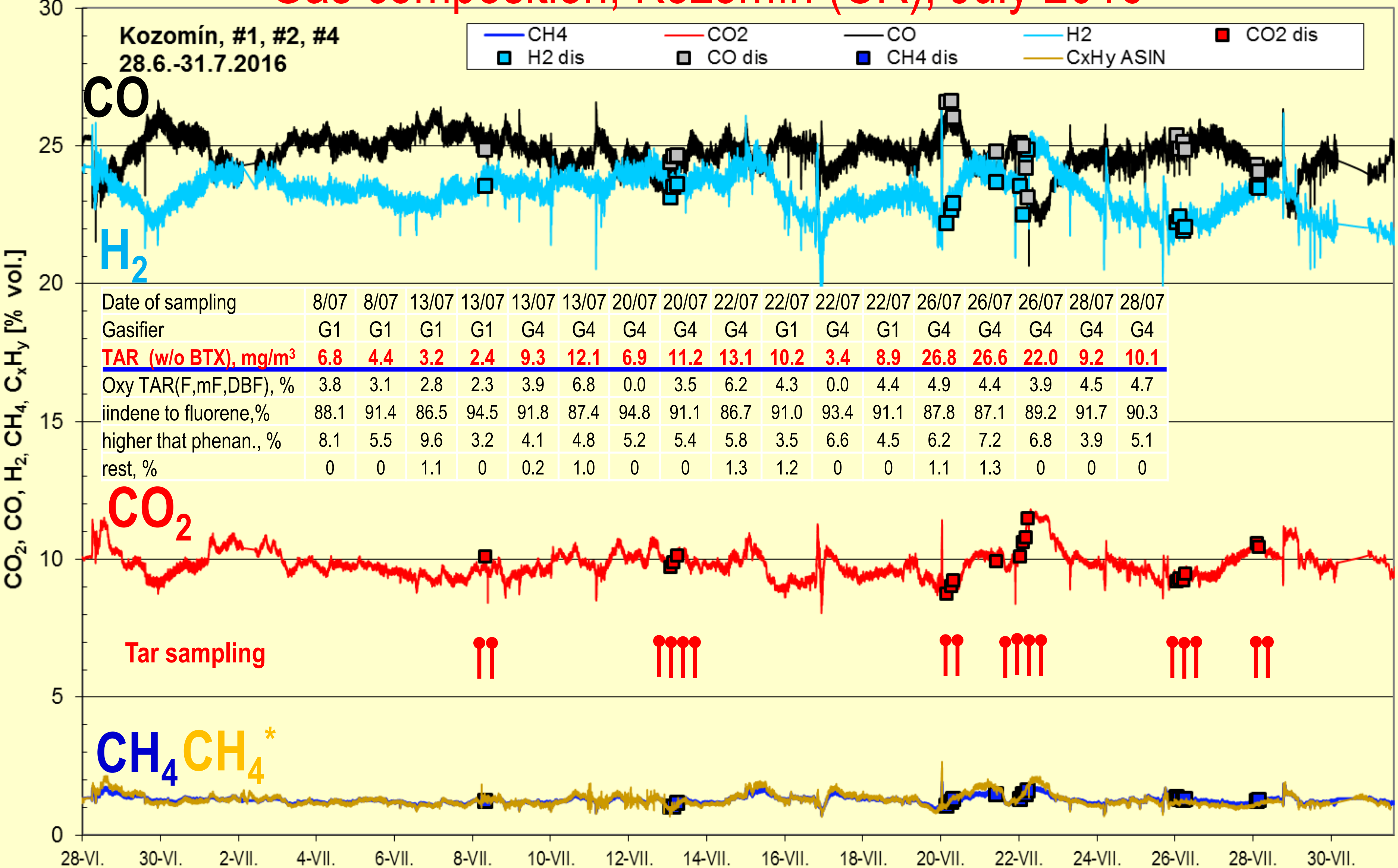
Date of sampling	13.5	20.5	21.5	21.5	22.5	22.5	22.5	29.5	29.5	29.5	3.6	3.6
TAR (w/o BTX), mg/m³	**30.5**	**40**	**63**	**52**	**20.9**	**45**	**68**	**198**	**179**	**154**	**7.6**	**13.5**
Oxy TAR(F,mF,DBF), %	14	11	13	13	3	13	18	13	12	12	4	3
iindene to fluorene,%	73	77	81	74	87	76	67	69	72	70	89	91
higher that phenan., %	6	6	5	7	5	6	7	13	12	13	6	5
rest, %	7	6	1	5	5	6	8	5	4	5	1	2

Gas generator: GP750 IC motors: Jenbacher J320 (550-630kW$_e$)

Dust removal: **Hot FILTR, 500-600°C**

Final gas *treatment:* *water washing/cooling tower*

Gas composition, Kozomín (ČR), July 2016



Date of sampling	8/07	8/07	13/07	13/07	13/07	13/07	20/07	20/07	22/07	22/07	22/07	22/07	26/07	26/07	26/07	28/07	28/07
Gasifier	G1	G1	G1	G1	G4	G4	G4	G4	G4	G1	G4	G1	G4	G4	G4	G4	G4
TAR (w/o BTX), mg/m³	**6.8**	**4.4**	**3.2**	**2.4**	**9.3**	**12.1**	**6.9**	**11.2**	**13.1**	**10.2**	**3.4**	**8.9**	**26.8**	**26.6**	**22.0**	**9.2**	**10.1**
Oxy TAR(F,mF,DBF), %	3.8	3.1	2.8	2.3	3.9	6.8	0.0	3.5	6.2	4.3	0.0	4.4	4.9	4.4	3.9	4.5	4.7
iindene to fluorene,%	88.1	91.4	86.5	94.5	91.8	87.4	94.8	91.1	86.7	91.0	93.4	91.1	87.8	87.1	89.2	91.7	90.3
higher that phenan., %	8.1	5.5	9.6	3.2	4.1	4.8	5.2	5.4	5.8	3.5	6.6	4.5	6.2	7.2	6.8	3.9	5.1
rest, %	0	0	1.1	0	0.2	1.0	0	0	1.3	1.2	0	0	1.1	1.3	0	0	0

Gas generator: GP750

Dust removal: **Hot FILTR, 500-600°C**

Final gas *treatment:* *water washing/cooling tower*

IC motors: Jenbacher 3xJ320 (550-630kW$_e$)

Mass and energy balance during long time operation

Operation period (2016)	July	August	September	October	November	December
Wet fuel consumption [tons]	1733	1427	1395	1530	1376	1390
Average water content in fuel [wt. %]	40,0	38,2	38,5	40,5	41,3	42,7
Dry fuel consumption [tons]	**1039**	**882**	**858**	**911**	**808**	**796**
LHV of wet fuel [MJ·kg^{-1}]	9,7	10,1	10,0	9,7	9,5	9,3
Biochar production [tons]	**38,1**	**45,2**	**26,4**	**25,7**	**29,4**	**26,2**
Biochar yield (dry fuel) [wt. %]	**3,7**	**5,1**	**3,1**	**2,8**	**3,6**	**3,3**
Electric production [MWh]	**1427**	**1309**	**1244**	**1327**	**1063**	**1083**
Dry fuel consumption [kg·kWh^{-1}]	0,728	0,673	0,690	0,687	0,760	0,735
Overall efficiency [%]	**30,6**	**32,9**	**32,1**	**32,4**	**29,3**	**30,3**
Overall efficiency (w/o biochar) [%]	**32,4**	**35,7**	**33,7**	**33,8**	**31,0**	**32,0**

Biochar sample (dry)	Hardwood	Softwood	Mix
Ash content [wt.]	**17,2**	**16,5**	**32,0**
Volatile matter [wt.]	4,5	2,9	4,9
Fixed carbon [wt.]	78,3	80,6	63,1
Specific surface area (S_{BET}) [m^2·g^{-1}]	**600**	**659**	**401**

Typical gas composition from downdraft and staged gasifiers

gasifier type	Downdraft Imbert 100 kW_{el}	GP300 200 kW_{el}	Viking DTU 75 kW_{th}	staged gasifier		
				GP200	**GP500**	**GP750**
Biomass moisture, wt.	<10	<10	35-45	<10	<10	<10
CO	25,5	24,6	19,6	26,7	25,0	25,3
H_2	17,2	16,4	30,5	23,0	22,3	22,7
CH_4	***3,0***	***2,2***	***1,2***	***1,1***	***2,0***	***1,3***
CO_2	9,6	9,6	15,4	8,0	9,5	9,7
N_2	***43,5***	***46,1***	***33,2***	***40,6***	***41,1***	***40,9***
Other	1,2	1,1	0,1	0,6	0,2	0,1
Tar content, mg/m^3	**1000-2000**	**1300-2000**	**<5**	**0,5-2,0**	**5,0-40**	**20-200**
LHV (15 °C), MJ/m^3	6,3	5,7	5,6	5,9	5,9	5,8

Conclusion

- **Staged gasifier (GP750) is capable to high efficiency gas production with low tar contents suitable for gas-fired cogeneration.**
- Gas quality produced by GP750 is suitable for different types of IC engines (Guascor, Jenbacher, ČKD..).
- GP750 produces low tar gas (typically below 50 mg·m^{-3}), HHV = 6,5 MJ·m^{-3}.
- Gas treatment consists of: hot candle ceramic filters for particles removal (optionally: bag filters) and water scrubber for cooling < 40 °C.
- **Possibility of simultaneous high quality biochar production (500-900m^2/g)**
- Gas quality and biochar production depends on:
  - fuel properties (size distribution, moisture content, ash content),
  - operating parameters (ratio of primary and secondary air, frequency of grating, temperature in POX chamber).

Thank for you attention

Questions ?

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