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Schemes and new developments in combinations of gasification with fuel gas cleaning for power generation in piston gas engines and gas turbines

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Gasification process scheme

Biomass (coal) + O_2 (N_2) + (H_2O + CO_2)

↓↓↓

Autothermal | **Gas Generator** | Allothermal

↓↓↓

Desirable products: **gas (+ C_xH_y)** ⇒ Direct combustion in turbines, motors, FC electricity and heat production

+

Undesirable products: **dust + tar+ impurities** ⇒ Transformation (tar, NH_3) or removal (dust, S, Cl, alkali) on safe level for downstream apparatus

+

Process wastes: Ash (+unreacted carbon) ⇒ Waste disposal and utilisation,

Gas production efficiency:

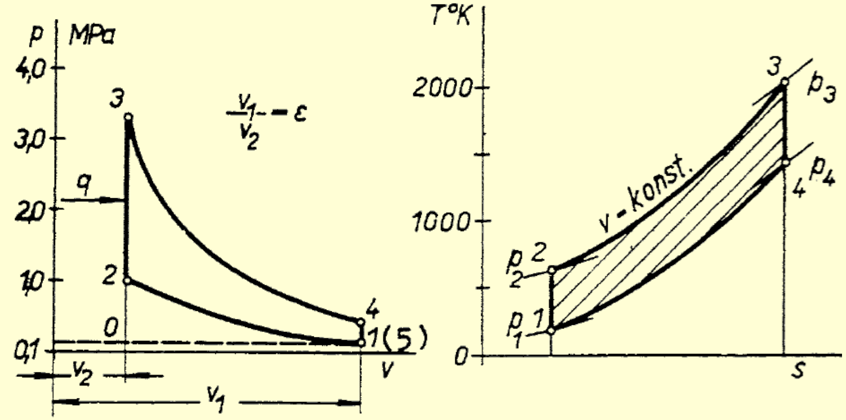
- Type Gas generator (co-current, countercurrent, fluidized bed, two stage generator)
- Efficiency of gas heat utilization: from autothermal to allothermal or combination
- Operation condition (gasification medium, ratio, temperatures..)

Internal combustion engines

Spark-ignition (SI) engines (Otto)

$$\eta_t = 1 - \frac{q_2}{q_1} = 1 - \frac{1}{\varepsilon^{k-1}} \approx 0{,}32$$

- Typical fuels: benzine, LPG,NG, Landfill, BioG, wood, product gas (ON, MN)
- Ignition: spark-ignition of Air/Fuel mixture
- Typical CR: 6 -10,5 for benzine, LPG
  10-12 (17) for NG, Wood gas
  10-12,5 for BioG, Landfill,

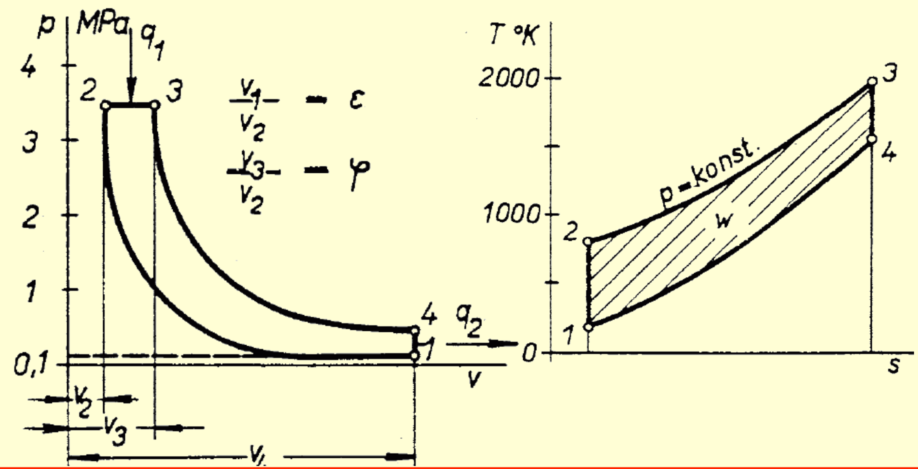


(0-1) intake of air/fuel mixture, (1-2) adiabatic compression, (2-3) spark ignition and combustion (V=cons.), (3-4) adiabatic expansion, (4-1((5)) gas exhaust.
V1/V2 =ε, compression ratio, CR

Diesel/compression-ignition (CI) engines

$$\eta_t = 1 - \frac{q_2}{q_1} = 1 - \frac{1}{\varepsilon^{k-1}} \cdot \frac{\varphi^k - 1}{k(\varphi - 1)} \approx 0{,}36$$

- Typical fuels: diesel oil (cetane number)
- Ignition: selfignition of Injected oil after adiabatic AIR compression (500-600°C)
- Typical CR: 16 – 22 (24)

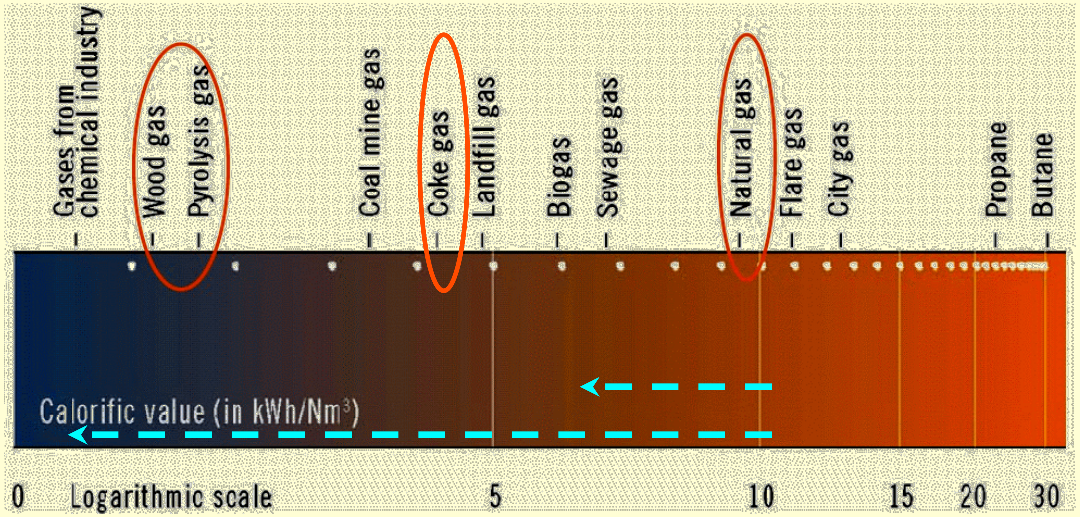


(0-1) intake of air, (1-2) adiabatic compression (600°C), (2) fuel injection (2-3) ignition and combustion at constant pressure, (3-4) adiabatic expansion, (4-1) gas exhaust
V1/V2 = ε, compression ratio, CR, V3/V2=φ (P=cons.)

ENERGETIKA, Vošta J.et al., VŠCHT Praha, 2005

Gas properties affected IC engine operation

•Heating Value of gas (LHV)



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

fuels	AFR (ER=1)	LHV, MJ/m^3 (kWh/m^3)	MIX LHV kWh/m^3
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**
Gen gas /wood gas	**1,4 / 1,1-2**	**6,5 (1,8) / 4-8 (1,1-2,2)**	**0,75 (-19 %)**

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

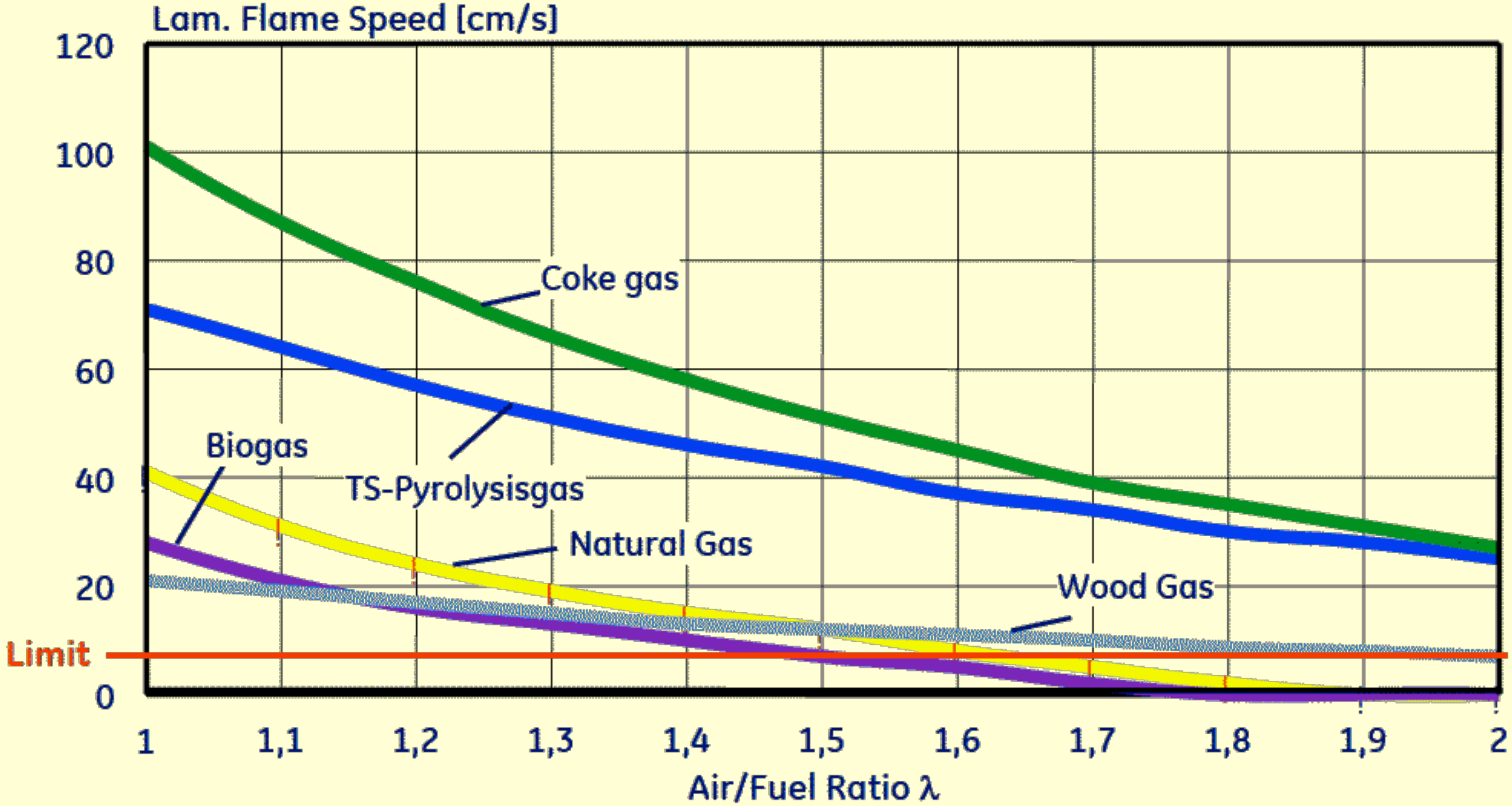
Thomas Elsenbruch, Latest Developments in the Use of Wood Gas in Gas Engines, IDGTE Toronto, Canada; 12. June 2008

Gas properties affected IC engine operation

- **Laminar Flame Speed**

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

concentration of **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 properties affected IC engine operation

•Critical parameter for knocking resistance of a gas

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

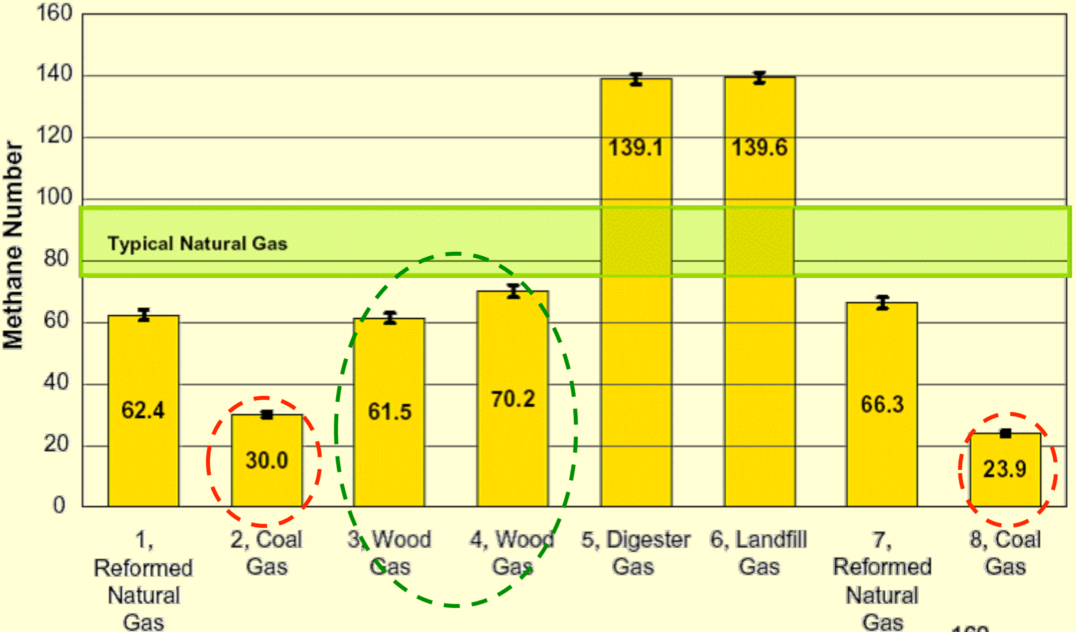
In this case, in accordance with the definition, the MN is 100 plus the percent CO_2 by volume in the reference CH_4-CO_2 mixture.

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

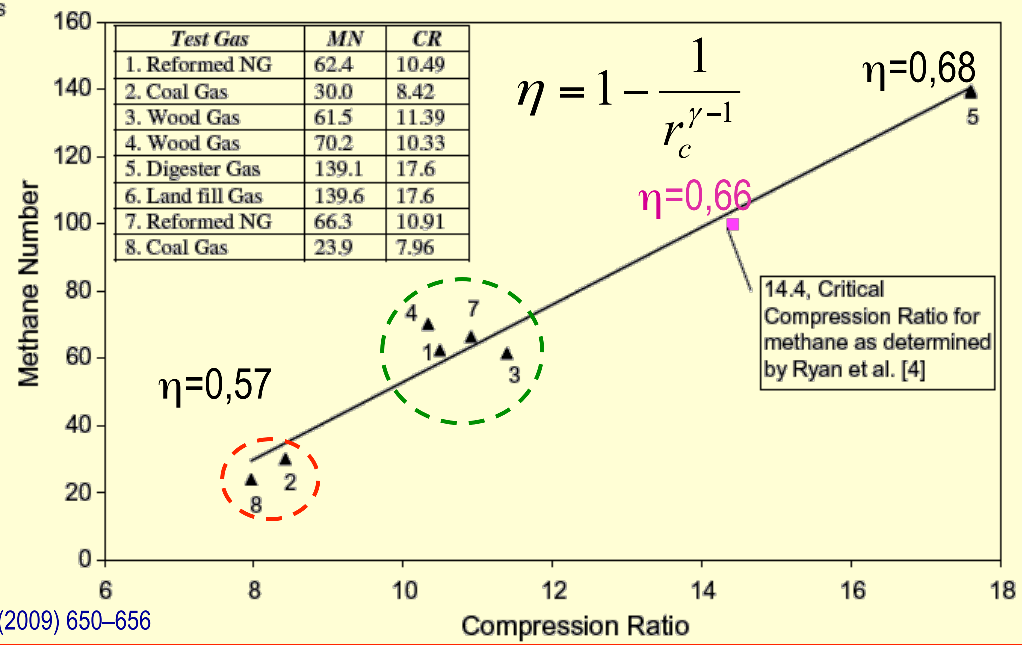
Gas composition effect on MN and CR



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

η - fuel conversion efficiency for the ideal Otto cycle with constant specific heats



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)↑

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**

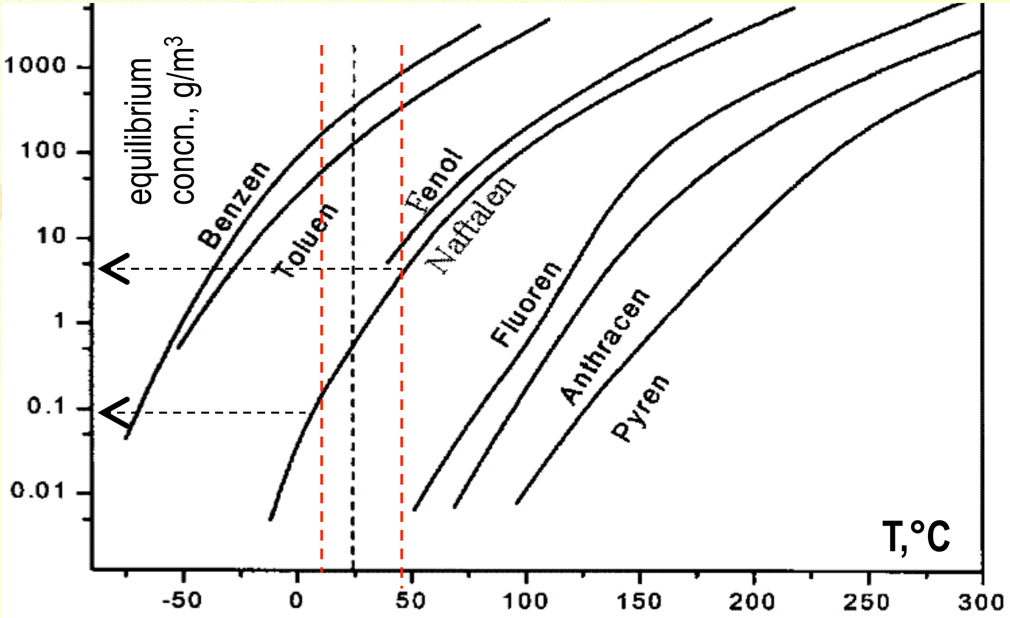
Reinhard Rauch: Integration Aspects in the Next Generation of CHP Plants Based on Gasification, International Seminar on Gasification 2012, 18-19.10.2012,Stockholm

Requirements for Tar contents in gas IC engines

Gas Composition (after gas cleaning) CHP-PLANT GÜSSING (Jenbacher J620, 1970 KW_e)

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/Nm³	~200
Mercaptans	mgS/Nm³	~30
Thiophens	mgS/Nm³	~7
HCl	ppm	~3
NH3	ppm	500-1000
Dust	mg/Nm³	< 20



„Tar Protokol“ tar = ~ 0,5 +2+ 0,03=2,53 g/m^3 =

= 2530 mg/m^3

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 !!!)

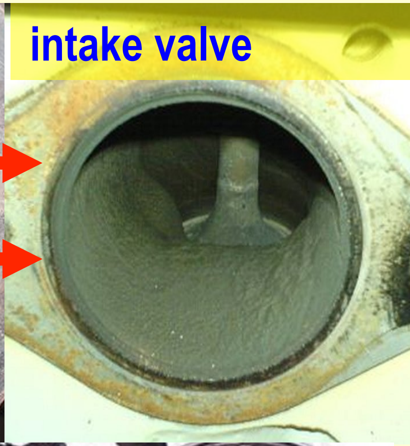
Higher contents of particles (> **50** mg.m^{-3})

- ✓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.

The efficiency of electricity generation by various processes

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

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

Type of generation	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. Fluidized bed gas./dual-fuel diesel,180/110kW_e** BURKHARD GMBH,	-	**MAN D26,** 12,4 dm^3, 6 Cyl.	**31,6**	high
5. Prototype of Two Stage gasifier (200kW_e) Tarpo ltd, Kněževes, 2011/2012	min. 85	**~32** (see 3) **max. 36** (see 6)*	**~ 27,2** **~ 30,6**	80-90 **80-100**
6. Two Stage gasifier (2x530kW_e) Tarpo Ltd, Air Technic Ltd Odry, 2012	**~ 90**	**~ 36***	**~ 32,4**	**80******
7. Model: Two Stage gasifier, 3,5-8 MW_e	max. 95	42-44 ***	**~ 40**	????

* Jenbacher AB, J316 GC (J320GC)

** Wood Gasifier with cogeneration unit, BURKHARD GMBH, calculation on 110 kg/h pelets and 3,7 kg/h oil

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

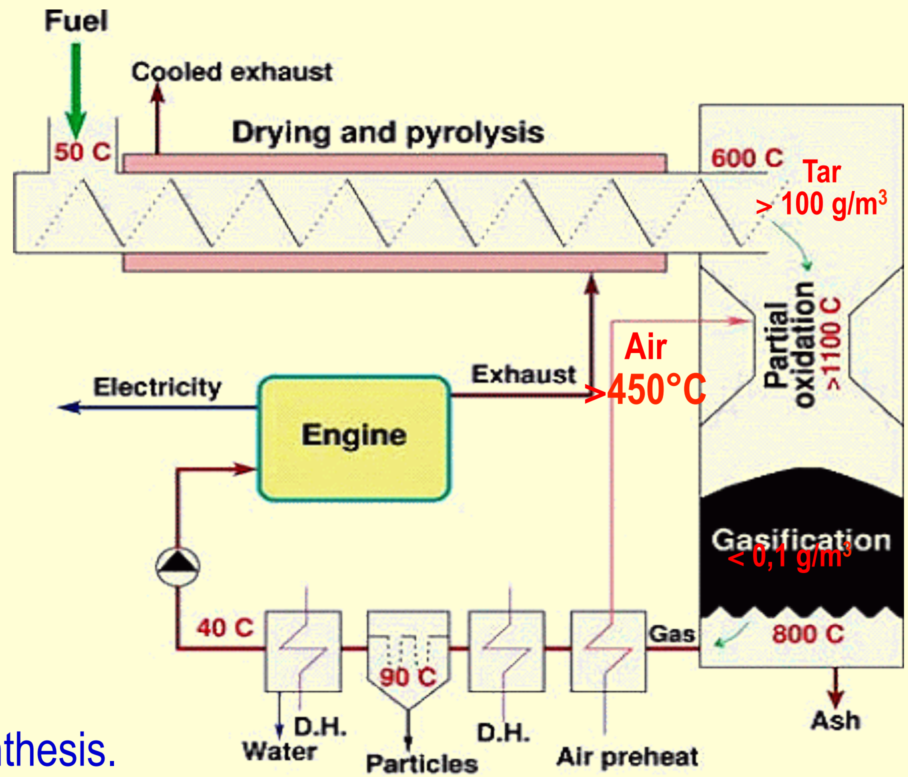
**** The first commercial implementation in CR

Two Stages gasifiers

The basic principle of the generator is the spatial separation pyrolysis zone from oxidation and reduction zones to reduce tar and use additional external heat to increase the efficiency.

Advantages of Viking gasifier

- **low tar content in gas < 0,1 g/m^3**
- high degree of heat utilization
- high cold gas efficiency (**η_{ce}=95 %**)
- effective control of the individual processess
- lower proportion of ballast in gas (N_2, CO_2), ↑ Q_s,



Disdvantages of Viking gasifier

- **scale up without major structural re-design is not possible and is a major problem to widespread application of the technology in practice**

Generators of higher performance

- **CHOREN Carbo-V** production of **tarfree** gas for F-T synthesis.

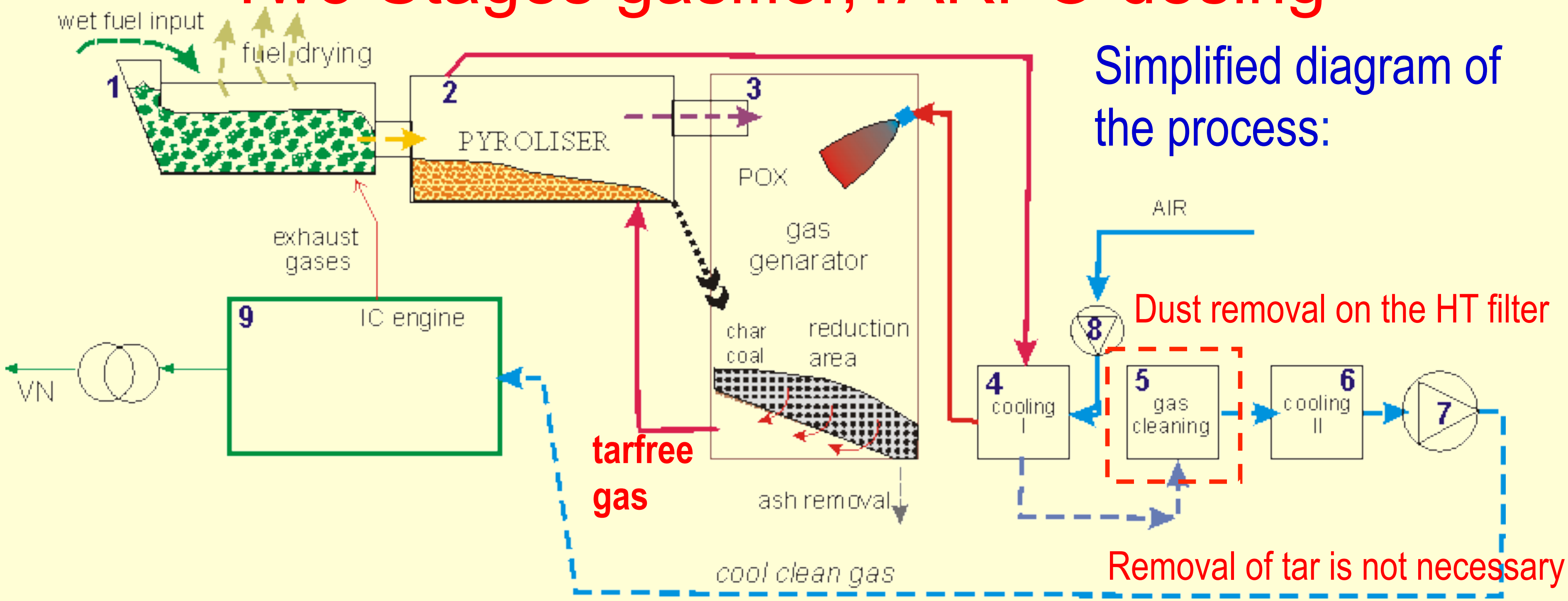
low-temperature pyrolysis (500 °C), volatile matter is carried out in the steam-oxygen burner (1400 °C), which is also sprayed by solid char residues, due to endothermic gasification reactions gas cools to a temperature below 800 °C.

- **TK Energy A/S, Thomas Koch**

biomass is pyrolysed by partial oxidation (λ<0,1) with preheated air (600 °C), partial oxidation of volatile matter and reduction on the charcoal bead, reduction of efficiency (**η_{ce}=85 %**)

- **Low-Tar BIG,Low-Temperature Circulating Fluid Bed**
- **FICFB** (concept)

Two Stages gasifier,TARPO desing

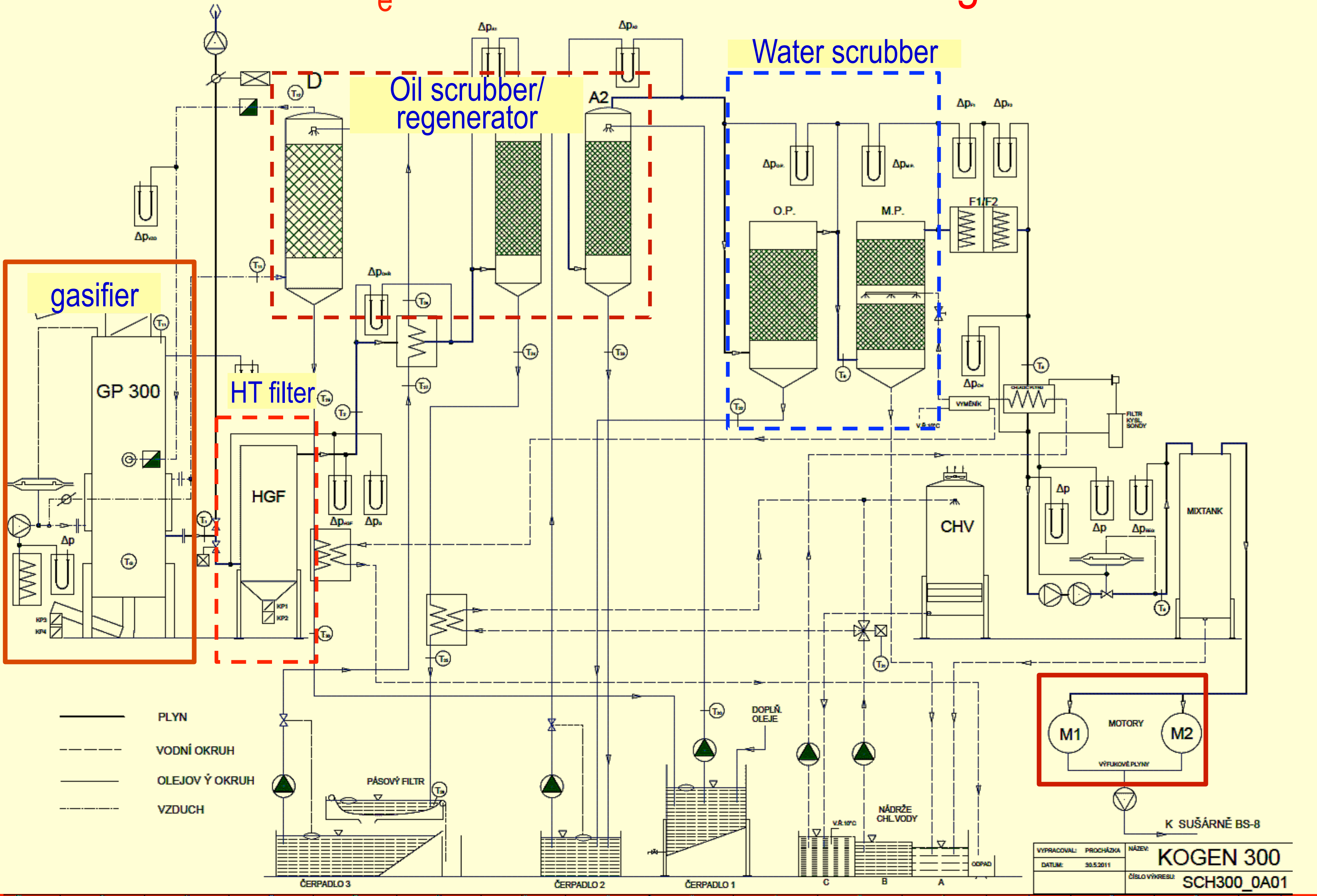


Simplified diagram of the process:

The current implementation of the Two Stage system in the Czech Republic:

- **prototype of Two Stage generator,200kW$_e$(TSG200), TARPO Ltd. Knezeves,**
  construction in 2011, launching in March 2012,
  TSG200 replaced the older type of co-current generator GP300,
- **Reconstruction and extension of power plants for biomass (2011),** Odry (2x 550kW$_e$)
  start operation (end of 2012), trial operation (2013), modification of auxiliary equipment
  (solid particles collection system for HT filter, reactor grate modification)
- **Other implementation of Two Stage generator,** cogeneration and heat production
  Kozumín, 3x710 KW$_e$ (4x2500 kW$_t$) paper Industry, 2014

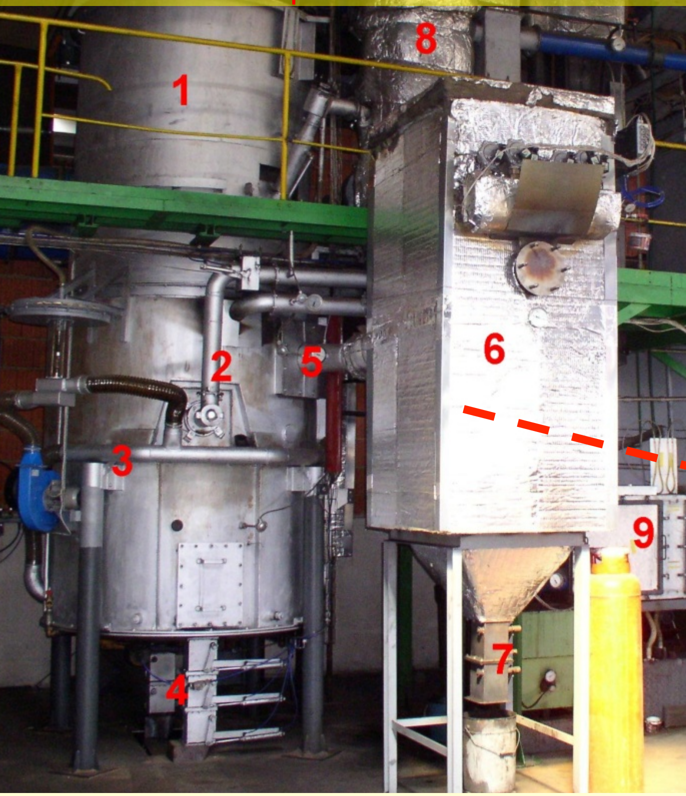
Scheme of 200 kW$_e$ Power station with downdraft generator GP300



12.-14.6.2013

Prototype of Two Stage gasifier

In March 2012 GP300, has been replaced by a two-stage gasification generator with an output of 200kW



Basic parameters of 200kW$_e$ power plant , TARPO ltd. Kneževes:

Fuel:	wood chips
Gas generator:	200kW$_e$, (before, old version, downdraft GP300 -replacemen in march 2012)
Tar removal:	org. liquid scrubber: 6**0°C**/reg.at **120°C** by air (from march 2013 – disconected)
Dust removal:	**ceramic candle filters**, **390-550°C**
Final gas treatment:	water washing/cooling tower,
Gold gas efficiency:	~85 %
Gas to electricity efficiency:	~32 %
El. účin. elektrarny:	**~27,2 %**

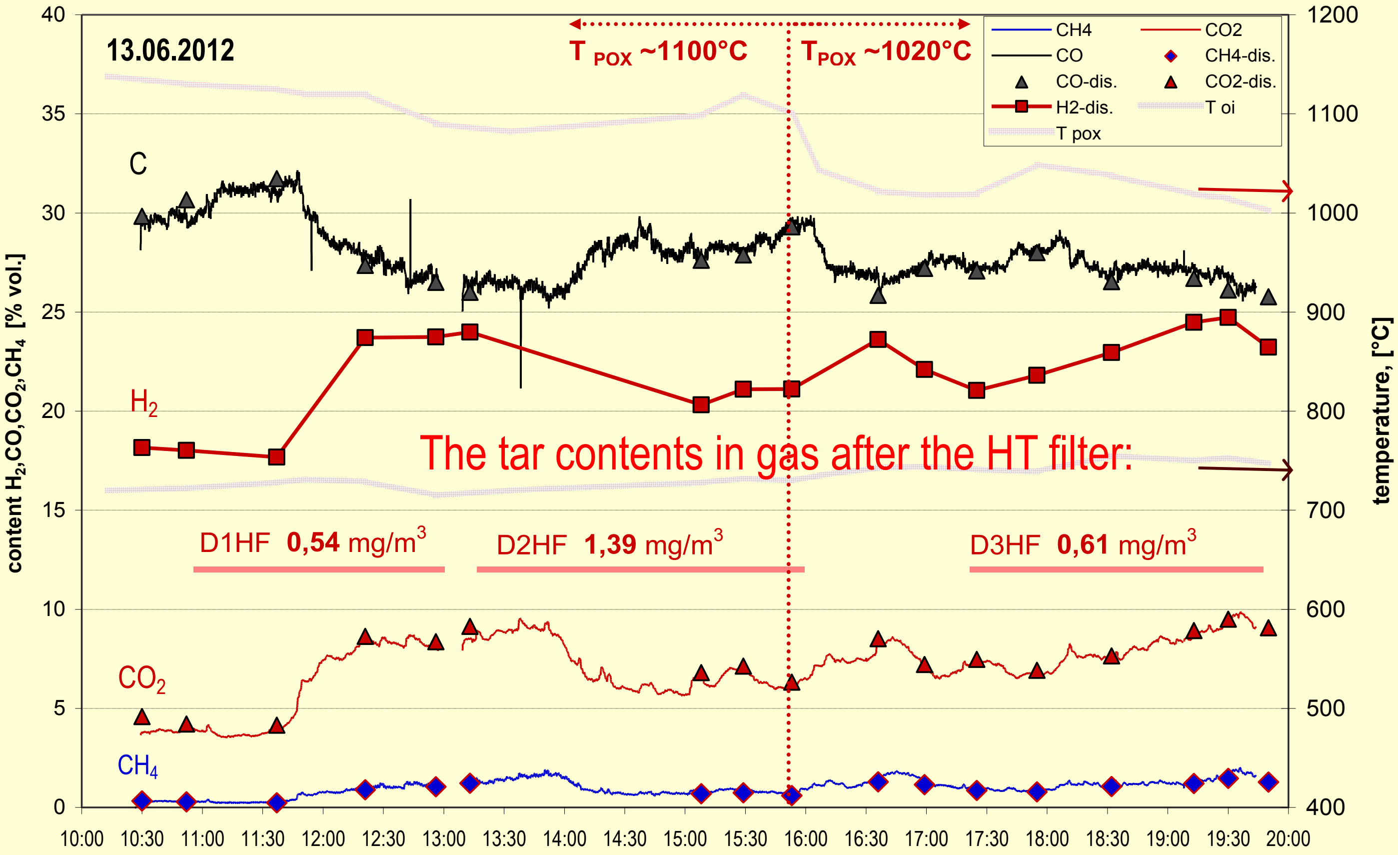
S160 ČKD Hořovice

Electrical output:	100 kW$_e$
Engine vol.:	27 dm^3
Cylinder nuber:	6
Compression ratio:	11,5 (CI-17,5)

Skoblia S., Picek I, Beňo Z., Pohořely M., Vývoj malých a středních kogeneračních jednotek na biomasu a jejich aplikace v praxi, Energie z biomasy XIII – odborný seminář, s. 103-120, VUT BRNO, 2012, ISBN 978-80-214-4685-4

Prototype of Two Stage gasifier 200kW$_e$, gas composition

Selected gas components record



Average gas composition

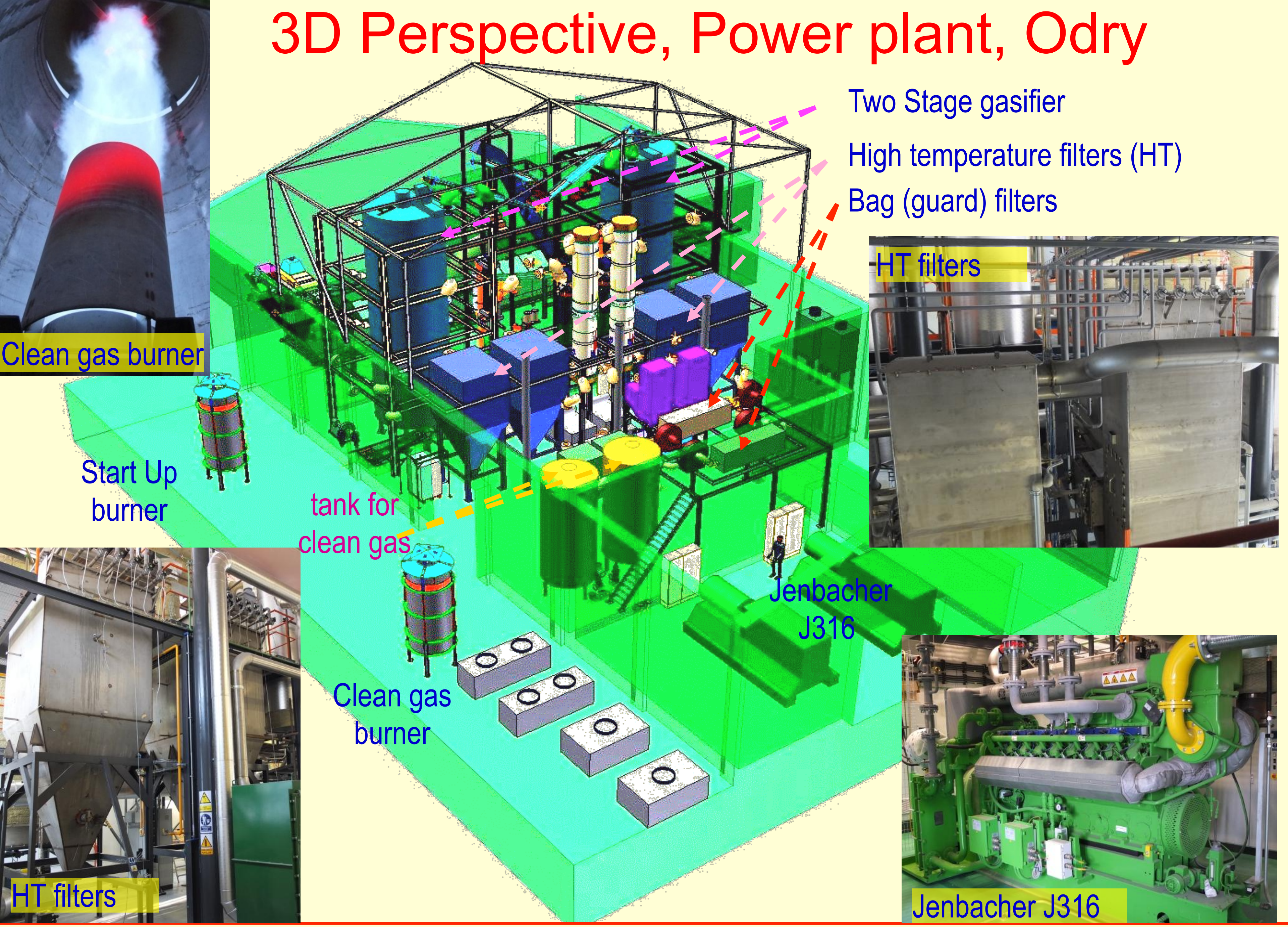
components	Conc. % vol.
O_2 in sample *	**0.84**
CO_2	7.72
H_2	22.37
CO	27.31
CH_4	0.97
N_2	41.14
Ar**	0.48
ethane	0.0017
ethylene	0.0018
acethylene	0.0002
propene	0
benzene	0.0005
toluene	0.00003
Other	0.0002
Sum	100
LHV**(15/15C)**, MJ/m^3	**5.89**
LHV **(0/0C)**, MJ/m^3	**6.21**

POX chamber temperature: 1000-1150°C. Raw gas contain minimum amount of tar and hydrocarbons (BTX). After a few weeks of operation, the gas from two stage gasifier still purge a dirty scrubber oil previously used for tar removal (Downdraft, GP 300), therefore higher levels of "tar" was obserwed in „cleaned“ gas.

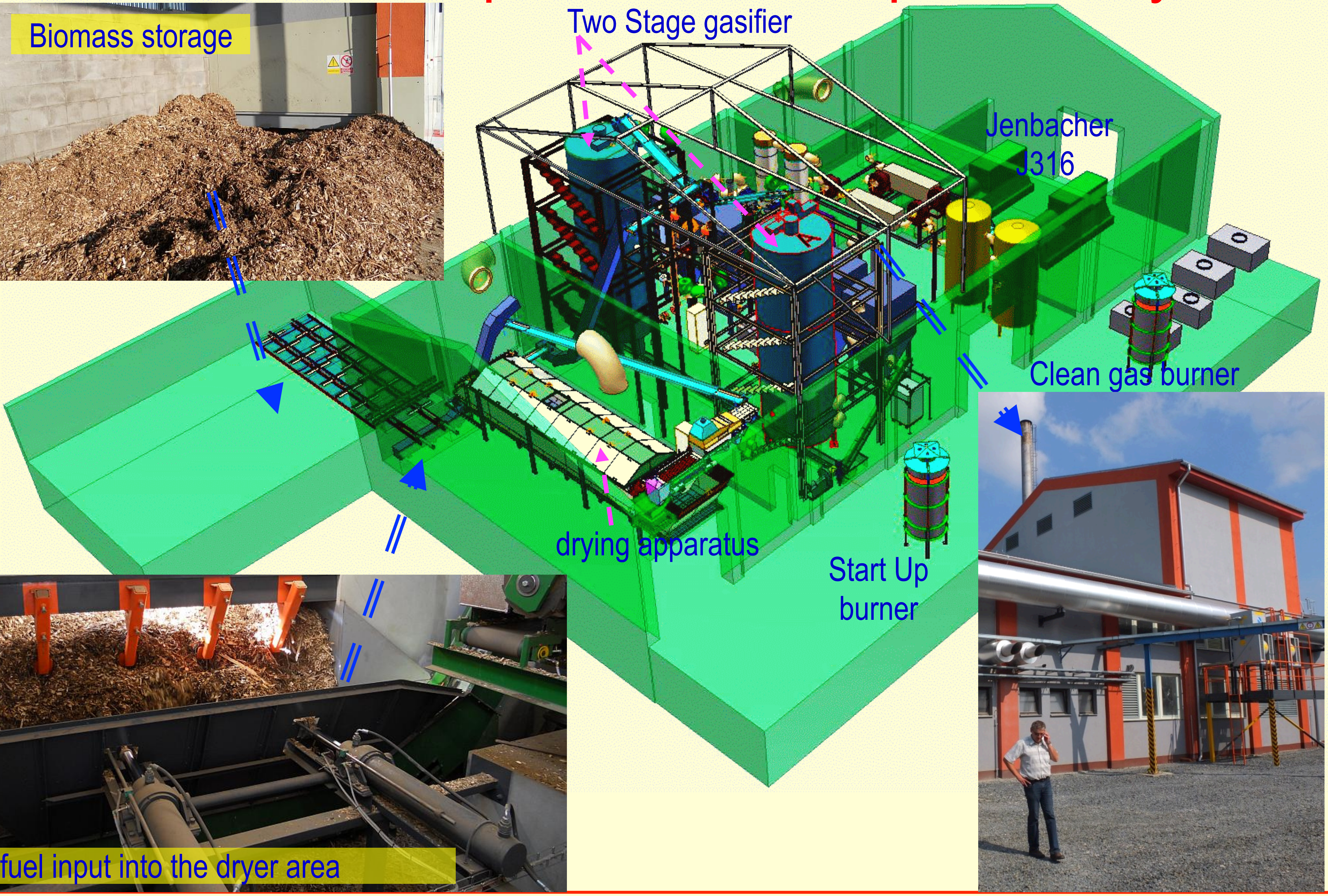
The basic parameters of the Power plant, Odry

Number of units:	2
Gas generator	
maximum power output (good quality fuel)	1700 (2500) kW_t
temperature in pyrolysis chamber	500-650°C
temperature in POX chamber	1000-1100°C (max. 1250°C)
exit temperature of the reducing zone	<750°C
Calorific value of gas (LHV)	5,5-6,5 MJ/m^3
Cogeneration unit (engine with el. generators)	
Manufacturer	Jenbacher AG (GE)
Type	J316 GS (LEANOX)
Number of cylinders/capacity	$16/48dm^3$
Rated el. Power	**500 (550) kW_e**
Fuel	
Consumption of wood chips (abs. dry)	360 (400) kg/hod
Chip size	20 až 80 mm (0,1-50 mm)
Ash content (dry basis)	< 2 % mass (<5 mass)
Maximal moisture content, before drying	50 %
Moisture content, after drying	<10 hm. (20 hm. %)
The waste heat of cooling water (80°-90°C)	650 kW_t
The electrical efficiency	**min. 32%**
Specific fuel consumption (abs. dry)	**~ 0,7 kg/ kWh_{el}**
Specific el. output	**~ 1,43 kWh_{el} /kg**

3D Perspective, Power plant, Odry

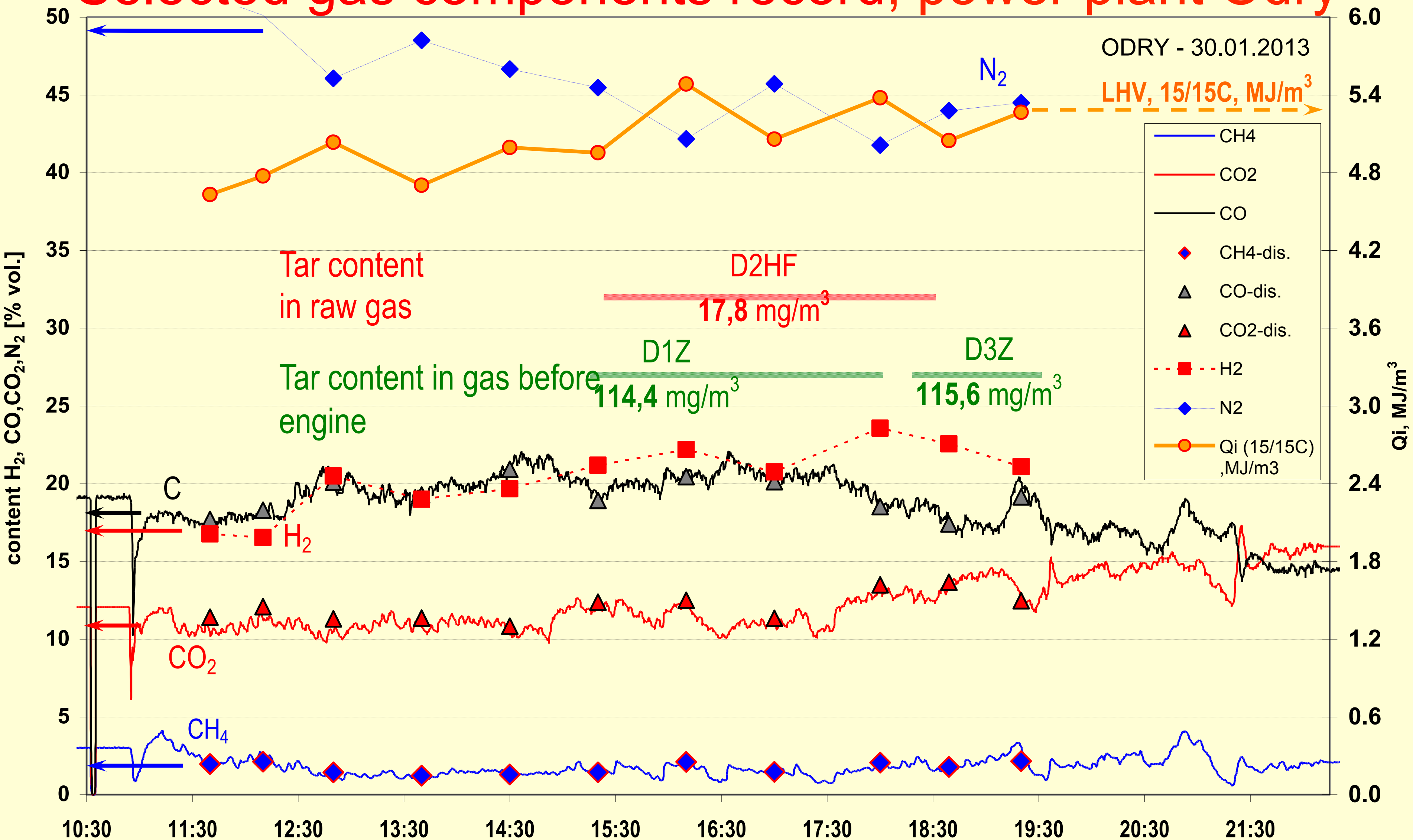


3D Perspective, Power plant, Odry



Power plant, Odry (november 2012)

Selected gas components record, power plant Odry



engine power output: 300 kW_e

Temperatures in POX chamber around 1000°C allow to produce gas with low-tar and hydrocarbons contents (BTX).

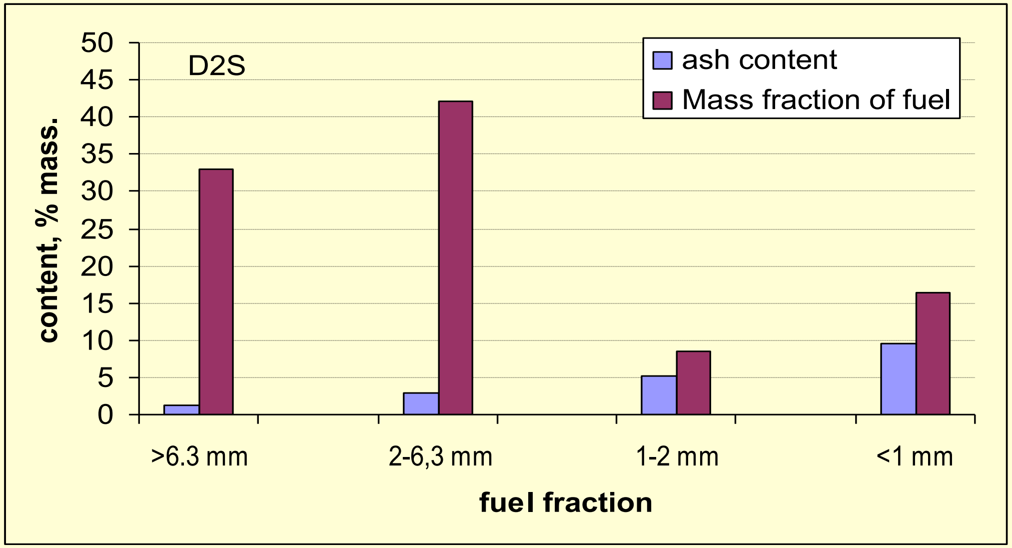
Tar composition (% mass.): 80-90% naphthalene, 3% 1-MN+2-MN, 3-4% acenaphthene, < 1% fenatren + anthracene

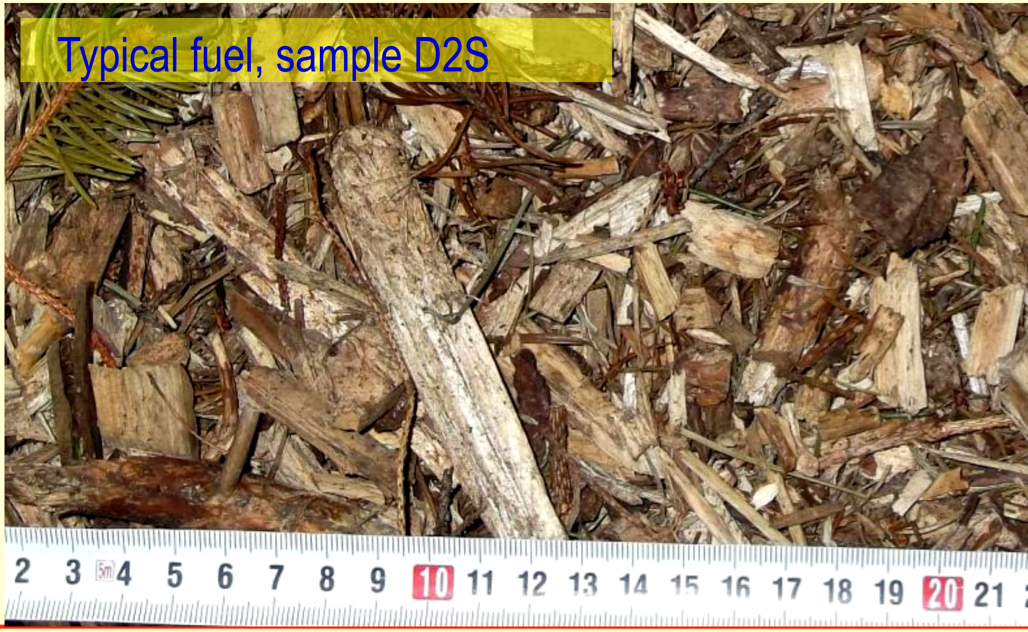
Properties of fuel

Typical fuel composition (sample D2S)

fuel properties	value		dry	daf
moisture,W	% mass.	30.11	**0.00**	**0.00**
combustible	% mass.	67.35	**96.36**	**100.00**
ash, A	% mass.	2.54	**3.64**	**0.00**
volatile,V	% mass.	54.39	**77.82**	**80.75**
fixed carbon, FC	% mass.	12.96	**18.54**	**19.25**
Q_s	$MJ.kg^{-1}$	13.73	**19.64**	**20.38**
Q_i	$MJ.kg^{-1}$	12.85	**18.39**	**19.06**
C	% mass.	34.28	**49.05**	**50.90**
H	% mass.	4.22	**6.03**	**6.26**
N	% mas.	0.18	**0.26**	**0.27**
O*	% mass.	28.67	**41.02**	**42.57**
$S_{tot.}$	% mass.	-	-	-

Fuel size distribution and ash content in the fraction





Acknowledgement

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Questions ?
Thank for you attention