Application of staged biomass gasification for combined heat and power production

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ABSTRACT: Multi-stage gasification combined with internal combustion gas engine is an efficient way of combined heat and power production (CHP) from woody biomass. In this work the performance of a multi-staged fix bed gasifier is reported. In this type of generator, all subsequent processes like pyrolysis, partial oxidation of volatile matter and gasification of char take place in different parts of the generator. The used multi-stage concept enables to increase cold gas efficiency over 80 % and produce a clean gas with low tar content. Another advantage is the possibility of controlled biochar production. The same multi-stage gasifier design was used in eleven cogeneration units built in the Czech Republic with an electrical output from 200 to 750 kW. This study presents the experience with operation of the largest CHP facility in the Czech Republic. The CHP facility consists of five generators with a maximum electrical power of 750kW each.

1 INTRODUCTION

Combined heat and power generation in small cogeneration plants is a promising approach to power production from biomass. Combination of woody biomass gasification with power production by an internal combustion (IC) gas engine coupled with power generator is an efficient way of power production in smaller units. To make the whole cogeneration process feasible and economically effective, it is necessary to efficiently transform the chemical energy of input fuel to power and maintain low capital and operating costs. Modern IC gas engines can transform chemical energy of producer gas to power with efficiency higher than 36 %. However, required gas purity has to be attained for steady long term operation. Particular attention should be given to tar content which should not exceed the limit. Multi-stage gasifiers are capable of producing gas with sufficiently low tar content and high cold gas efficiency. Therefore, it is possible to avoid expensive gas treatment technologies and only filtration of dust particles is needed.

Gasification is a thermochemical process transforming input fuel into flammable gas, generally called producer gas, which consists of CO, H_2, CO_2, H_2O, N_2 and C_xH_y. Gassification can be divided into three separated processes. Each of these partial processes has its own optimal reaction conditions. The first process, called pyrolysis, is slightly endothermic and takes place in zones without oxygen access at temperatures above 250 °C. Products of pyrolysis are carbon residue or charcoal and volatile matter, consisting of flammable and non-flammable gaseous compounds. The amount of volatile matter can be as high as 80 %wt. and it is the main source of tar. The second process, taking place during gasification, is partial oxidation (POX) of volatile matter. An amount of oxygen lower than the stoichiometric ratio reacts with the volatile matter during POX and the needed thermal energy for endothermic reactions is produced. The last process is reduction, also called gasification of charcoal by CO_2 and H_2O. This process is strongly endothermic and produces flammable gases like CO, H_2 (Bario 2002).

2 TWO-STAGED GASIFIERS IN THE CZECH REPUBLIC

The main advantage of staged gasification is the possibility to separate these partial processes into different sections of the generator. The most important aspect of tar destruction is to ensure that all of the volatile matter evolves in the pyrolysis section and then undergoes transformation in the partial oxidation zone and partially in the reduction zone.

2.1 *Two-staged gasifier design by Tarpo Ltd.*

In 2010, Czech company Tarpo Ltd. Patented a new biomass gasifier concept based on staged gasification. In Figure 1 the basic scheme of this type of gasifier is depicted. In this type of fixed-bed multi-stage gasifier all three partial processes take place in different sections of the same reactor body. Pyrolysis (Py) section, which is the biggest one, is in the upper part of the reactor. Pyrolysis section is separated from the partial oxidation (POX) zone and the reduction (RED) zone by an inner ceramic separator (in conus shape). The separator construction and used materials are „know-how“ of Tarpo Ltd. (Picek 2013)

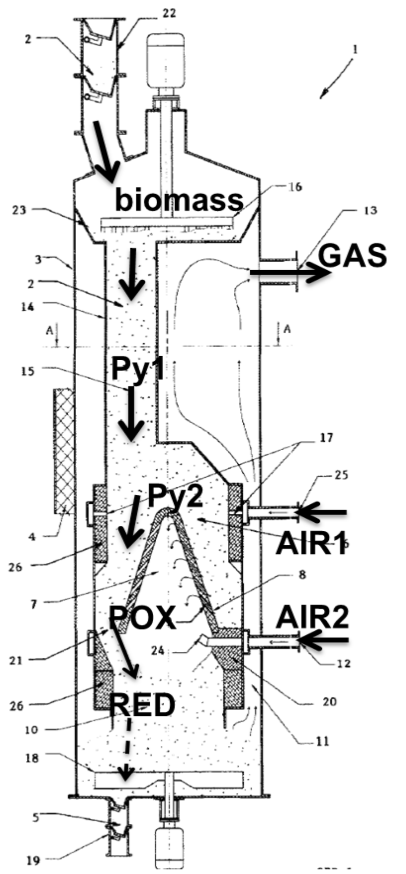

Figure 1: Scheme of two-staged gasifier designed by Tarpo Ltd.

Dried biomass chips are fed to the top of the generator where the pyrolysis zone is. Input fuel is heated up to temperature between 450 and 550 °C. Under this temperature input fuel transforms to charcoal and volatile matter. Heat necessary for complete pyrolysis of the fuel is gained partially by burning part of the fuel by primary air (A1) and partially by heat conduction through the inner wall of the generator and by radiation of the hot inner separator. Due to the separator all volatile matter flows to the partial oxidation (POX) zone inside the separator and tar free charcoal falls to the reduction zone in the bottom of the generator. Secondary air (A2) is added to the POX zone and due to oxidation reactions, temperature in this zone rises up to 1200 °C. Most of the volatile matter is decomposed in this zone and output gas contains mainly gaseous compounds (H_2, CO, CO_2, H_2O, CH_4). The hot gas then flows through the reducing bed of charcoal (RED). Gasification of tar free charcoal by endothermic reactions with H_2O and CO_2 takes place in this reduction zone and gas temperature drops below 700 °C. Producer gas then flows through the grates into a gas jacket and heats up the pyrolysis zone through the inner reactor wall. Conveyor dryer is an integral part of the whole technology, which reduces moisture content of raw wooden chips from 40-50 %wt. to less than 5 %wt. by using low potential heat of exhaust gases.

2.2 *Overview of installed units*

The first prototype of two-stage gasifier in the Czech Republic was GP200 with an electric output of 200 kW. It was built and successfully launched in 2012 and it replaced the previously used downstream gasifier GP300 (Skoblia et al. 2014). The overall electrical efficiency of existing power plant, using combustion engines CKD Hořovice (S160), increased from the initial 25 % to 27 %. Tar content in the producer gas decreased from approximately 2000 mg.m^{-3} for GP300 to a value below 25 mg·m^{-3} for GP200. Experiences from the operation of this prototype gasifier were implemented into numerous projects aimed to commercialize multi-stage gasifiers. Till now, several versions with a different power output (GP200 series, GP200XL, GP500 and GP750) were built in power plants in the Czech Republic and in one power plant in Slovakia. A brief list of gasifiers based on the two-stage design is summarized. in Tab. 2., including location and year of start-up, gasifier type, type of IC gas engine, nominal electric output and estimated overall efficiency.

Table 1: Two-stage gasifiers from Tarpo Ltd.

Location	Start up. Type of a gasifier	Type of engine	Nominal electric output/efficiency
Kněževes (CZ)	2012 GP200	ČKD, 2x6S160, 27l, R6	200 kW/27 %
Odry (CZ)	2012/201 2xGP500	Jenbacher 2xJ316, 48l, V16	2x500 kW/32 %
Olešnice (CZ)	2013/2014 GP200XL	ČKD, 2x6S160, 27l, R6	200 kW/27 %
Handlová (SK)	2014/2015 2xGP750	Guascor FBLD560, 56l	570+430 kW/32%
Dobříš (CZ)	2015 1xGP750	Guascor, FBLD560, (56l),	650 kW/32%
Kozomín (CZ)	2014/2015 5xGP750	Jenbacher, 3xJ320, (60l,	3x710kW/32% 5,1 MWt

2.3 *Operation of CHP plant in Kozomín*

The largest power plant using two-stage gasifiers in the Czech Republic is run by the company BOR Biotechnology Inc. in Kozomín (see Tab.2). This company operates technology for processing biomass, wood waste (chips) and other woody materials for pelletizing. Kozomín power plant consists of five separate units each with one gasifier GP750 and whole gas treatment line (see Fig 2.). Purified and cooled gas from all five lines enters one mix tank. Mixed gas is then used to power three modern IC gas engines Jenbacher J320 with power generators each with maximal electrical output of 710 kW. Currently three gasifiers GP750 are operated to produce gas for these three cogeneration units. The other two gasifiers were installed to produce gas and heat (steam) for a paper mill near the power plant. The technological part of the paper mill is not built yet, and the steam generator is not operating. For that reason, only three GP750 gasifiers are simultaneously operating to power the cogeneration units.

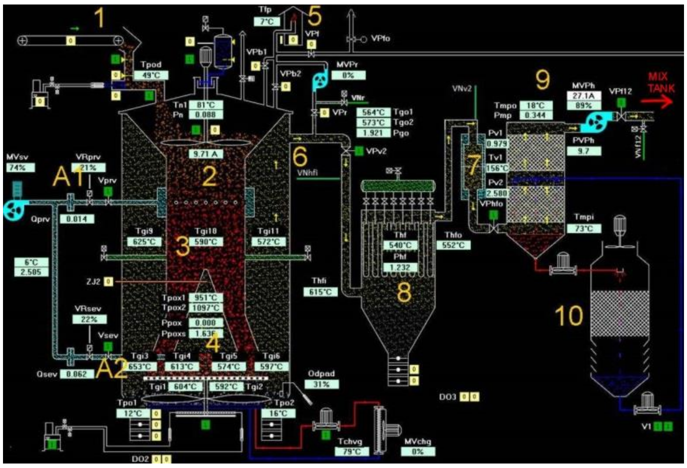

Figure 2: Operating scheme of GP750 in Kozomín

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,

Table 2: Basic parameters of Kozomín plant

Parameters	Value
Number of gasifier (GP750)	5
Number cogeneration(Jenbacher J320 GS)	3
Nominal electrical power output	3*710 KW
Fuel (wood chips)	5-60 mm
Consumption of fuel (abs. dry)	max. 550 kg/h
Gas production (0 °C, 101, 325 kPa),	1000-1200 m^3/h
Low Calorific value (LHV)	5,5-6,5 MJ/m3
Electrical efficiency	min. 27 %
Specific fuel consumption (abs. dry)	~ 0,75 kg/kWh
Char production rate	20-60 kg/h
Ash content in char	15-35 % wt

Kozomín power plant uses wood chips in the range of 5 to 60 mm for all five gasifiers. The first part of the whole technology is feeding wood chips to the system. Wood chips then enter a magnetic separator to separate ferrous metals. Then particles with size over 60 mm are separated to prevent arching inside the gasifiers. According to total load of the whole technology, wet chips are then fed to one or both conveyor dryers. During operation of three gasifiers only one of two dryers is operating, which is sufficient do decrease moisture content from up to 50 %wt. in input chips to below 10 %wt. Dried chips from both dryers then go through a sieve separating particles below 5 mm and then are transported by one feeding line to all five gasifiers. Producer gas from the gasifier is filtered by hot ceramic candle filters (550 – 650 °C) and flows to gas/water heat exchanger. The next parts of the gas treatment line are contact water cooling in spray tower and fine filters. After the final filtration, producer gas from all five lines enters the mix tank from which it is fed to Jehnbacher cogeneration units.

2.3.1 *Fuel parameters and efficiency*

Kozomín power plant is capable to use different types of wooden fuel. Commonly used materials are raw hardwood chips with moisture content about 40 %wt.

Table 3: Typical fuel composition after drying

Mass %	Raw	Dry
Water content	6,55	0,00
Combustible	92,36	98,84
Ash content	1,08	1,16
Volatile matter	71,05	76,03
Fixed carbon	21,31	22,81
C	46,33	49,58
H	5,89	6,30
O	39,65	42,43
N	0,48	0,51
S	0,02	0,02
Lower heating value, [$MJ.kg^{-1}$]	16,94	18,31

Currently the gasifiers are operated at average electric output of 650 kW each and each gasifier burns about 34,5 tons of biomass (abs. dry) per day. Overall efficiency is about 27 %. Moreover, the gasifiers produce about 1 tonne of biochar per day which is sold as fuel for briquetting. Due to textural properties of produced added value of produced biochar will likely be even higher in the future.

2.3.2 *Gas composition*

Detailed analysis of gas composition and tar content were carried out at the UCT, Prague and ICPF of CAS, to find out influence of different operational parameters on gas composition. In Figure 3 the gas composition from long term operation (30 days) is shown. The content of the main components (CO, CO_2 and CH_4) was measured by online infra-red analyzer URAS and H_2 content was measured by temperature conductivity analyzer Caldos, both from ABB. Several gas samples were also analyzed via gas chromatography (GC) to confirm that the online analyzers were working properly as well as to analyze minor gas components. From long term analysis can be concluded that the gas composition was mostly steady and the main gas component was CO with concentration about 25 %vol. The second flammable gas with high content was H_2 with typical content about 22 %vol. Producer gas also contained inflammable CO_2 and low amounts of CH_4 of about 1.5 %vol. Even though the gas composition was mostly steady, several fluctuations were observed. During these fluctuations of gas composition, content of CO dropped while content of H_2 and CO_2 rose. The fluctuations in gas composition were caused due to the water gas shift reaction (Equation 1), which shifted the reaction towards products (CO_2 and H_2) due to increased water content of the fuel. During these fluctuations, an increase in CH_4 content was observed, which also meant higher tar content.

Equation 1 $$CO + H_2O \leftrightarrow CO_2 + H_2$$

Long-term operation of the GP750 showed another advantage of the described process - biochar production, which was about 3-4% by weight, from the input fuel (dry basis). The ash content in biochar was between 15 and 35% wt. Biochar rate production can be controlled by regulating the intensity of the generator grating. Specific biochar features suggest wide possibilities of its usage such as high surface adsorbent material or complex fertilizer for soil quality improvement.

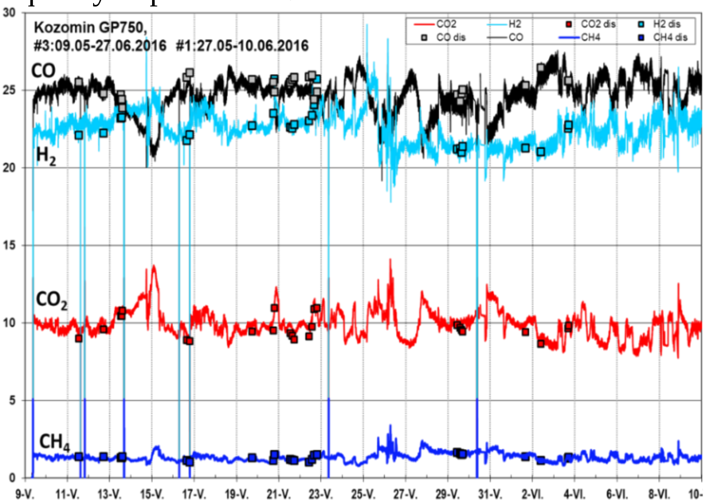

Figure 3: Producer gas composition in CHP plant in Kozomín

2.4 *Comparison of gas quality from different type of gasifiers*

Different gasifier constructions were designed to achieve high gasification efficiency and to decrease tar content in producer gas. In Table 4 in order to compare different gasifier types, approximate gas compositions and tar contents of different producer gases are listed. Two co-current gasifiers Imbert with electric output of 100 kW (Beňo et. all 2011) and stratified bed gasifier GP300 (Skoblia et all 2012) are enlisted for comparison with stage-bed gasifiers.

Table 4: Gas composition from different types of gasifiers

Gas comp., % vol.	Imbert[*1]	GP300[*2]	XW twin-fire	Viking	GP200[*]	GP500[*]	GP750
H_2O in Fuel, % wt.	<10	<10	<10	35 - 45	<10	<10	<10
CO	24,6	25,5	22,5	19,6	26,7	25,0	25,3
H_2	16,4	17,2	17,6	30,5	23,0	22,3	22,7
CH_4	*2,2*	*3,0*	*2,0*	*1,2*	*1,1*	*2,0*	*1,3*
CO_2	9,6	9,6	10,5	15,4	8,0	9,5	9,7
N_2	*46,1*	*43,5*	*45,1*	*33,3*	*40,6*	*41,1*	*40,9*
Rest	1,1	1,2	2,3	0	0,6	0,1	0,1
Tar content[**], mg/m³	1300-2000	1000-2000	<100	<5	0,5-2,0	5-40	20-200
Q_i (15°C), MJ/m³	5,7	6,3	5,4	5,6	5,9	5,9	5,8

[1] Modified „Imbert“ gasifier from BossEngineering Ltd.
[2] Co-current stratified gasifier from Tarpo Ltd. Used till 2012
[*] Air for gasification was preheated
[**] Determination of tar was carried out according to Tar Protocol. Given value does not contain toluene, xylenes and benzene

When using the same fuel and gasifying agent, in this case wooden chips and air, it is possible to approximately compare cold gas efficiency (η_{ce}) based on gas composition. Content of N_2 is directly proportional to the amount of air used for gasification. The most efficient gas production is achieved when a lower amount of air is used. The lowest content of N_2 in producer gas was observed in the case of the Viking gasifier (Brandt et all 200), which uses the waste heat of the flue gas from engine for pyrolysis and has the highest cold gas efficiency (η_{ce} = 95%). Low nitrogen content of the gas is also caused by high fuel humidity, which leads to an increase of total gas production (H_2, CO_2). It can be presumed that if moisture content of used wooden chips is less than 10 wt. %, content of nitrogen would increase to a value of about 37 vol.%. High efficiency and good gas composition were achieved in the experimental unit with electric output of 25 kW. The electrical output of the experimental unit is significantly lower than compared to the other presented gasifiers (Knoef 2012). The lowest cold gas efficiency has a twin fire gasifier from the company XyloWatt (www.xylowatt.com). Similar gas composition and cold gas efficiency can be achieved by the downstream generator GP300 from Tarpo Ltd., which has become obsolete and is out of order since 2012. In comparison with staged generators it can be concluded that according to available data depicted in the Table 4, two-stage gasifiers GP200, GP500 and GP750 have higher efficiency compared to all other concepts discussed above with the exception of the Viking gasifier.

The quality of producer gas can be assessed directly by tar content and indirectly by the content of methane or other hydrocarbons. The lower the content of hydrocarbons in the producer gas, the less tar content can be expected in the gas. Methane concentration in the producer gas from two-stage gasifiers is lower than in the case of co-current gasifiers. This is caused by partial oxidation of volatile matter in the POX chamber. Due to high temperatures in the partial-oxidation zone and the reactions of the flue gases (CO_2, H_2O) with the charcoal bed material, the CO_2 content is lower and CO content is higher. After comparison of gas composition from different types of gasifiers can be concluded that well-functioning multi-staged gasifiers produce lower amount of tar and CO_2 than co-current gasifiers. Moreover, CO and H_2 content is higher due to gasification of carbonaceous material (Skolia et al. 2016).

3 CONCLUSONS

Measurements carried out on different types of two-stage gasifiers showed that the composition of producer gas and tar content in producer gas greatly depends on the operating parameters of a gasifier. The main parameters are fuel properties and ratio of primary (A1) and secondary (A2) air. When operated improperly, volatile matter can flow throughout the POX zone without tar destruction, which may cause an increase in tar content in the producer gas. To avoid this negative effect, it is necessary to set optimal ratio of primary and secondary air in the range from 1:5 to 1:10. Ideal ratio of primary and secondary air depends especially on generator power, fuel moisture and intensity of grating.

Long term measurement conducted in CHP plant in Kozomín proved that gasifier GP750 produces gas with steady composition. During steady operation of GP750, main flammable gas components are CO and H_2 with concentration about 25 %vol. and 22 %vol. respectively. The average content of CH_4 is 1.5 %vol. and tar content is in the range from 20 to 100 $mg.m^{-3}$. It can be concluded, that this type of generator is suitable for gasification of woody biomass without the need of complex gas treatment. The tar content in producer gas rises with gasifier scale-up from 200 to 750 electric kW. But even in the case of the biggest gasifier GP750, tar content is suitable for steady operation of whole plant.

When compared to other types of staged and co-current gasifiers, the efficiency of two-stage gasifiers designed by Tarpo Ltd. is better than most of the known types of the gasifiers. Only complex multi-stage gasifier Viking is more efficient, which has an electric power output 25 kW compared to 200–750 kW in case of Tarpo gasifiers.

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5 RFERENCES

Beňo Z., et al. 2011 *Výroba elektrické energie z dřevní štěpky v komplexní kogenerační jednotce,* technical report. FT-TI1/219. Praha:VŠCHT

Brandt, P. et al. 2000. High Tar Reduction in a Two-Stage Gasifier. *Energy Fuels*.14 (4): 816–819

Knoef H.A.M. (2) 2012. *Handbook of Biomass Gasification*. Eschende: BTG

Picek I. *Equipment for multi-stage gasification*. UM: CZ26592U1, 2013

Skoblia S. et al. 2014. *Design and commercial application of two-stage fixed bed gasifier in Czech Republic, 6th International Freiberg Conference Coal Conversion and Syngas*, Dresden, 19-22 May

Skoblia S. et al. 2016. *Experience with Operation of Multi-Stage (Two-Stage) Fixed-Bed Gasifiers in the Czech and Slovak Republic, 6th International Freiberg Conference Inovative Coal Value Chain,* Cologne, 12-16 June

http://www.xylowatt.com/index.php/solutions/the-notar-gasifier.html

6 CONTACTS

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