Gasification of Agricultural Residues and Municipal Solid Waste (MSW) for CHP

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Introduction

Serbia generates an average of 2.5 millions of tons of MSW per year [1], and around 3.2 millions of tons of agricultural crops (residues for energy use) [2].

In Serbia, MSW is dumped in waste disposal sites, and small proportions of industrial waste are used [1]. Even though this waste contains a large percentage of organic waste, no composting is performed. In addition, waste is not incinerated, used as alternative fuel nor separated at the source. The situation regarding industrial waste is slightly better, but only 19% of it is treated [1]. The landfilling of MSW releases volatile organic compounds, along with leachable toxic heavy metals and greenhouse gases (GHGs) into the surrounding environment.

The field crops cultivation biomass (agricultural) is the largest potentially available biomass and it is contained in the residues obtained during the primary harvesting of the field products. The agricultural biomass residues are coming from cereals, mostly corn, wheat and barley, and from industrial crops mostly sunflower, soya, and rapeseed. Postharvest residue is mostly burned directly in the field, which is prohibited by law [3]. The accustomed burning of the postharvest residues means not only wastes of the organic substances and of considerable energetic value contained in it, but also the destroyment of humus and annihilation of microorganisms from the surface layer of soils. Also, the postharvest residues burning lifers not only carbon into the atmosphere, but also the other significant biogenic elements, such as nitrogen and phosphorus.

Energy recovery from waste can solve two problems at once: treating non-recyclable and non-reusable amounts of waste; and generating a significant amount of energy which can be included in the energy production mix in order to satisfy the consumers' needs.

Faced with the costly problem of waste disposal and the need for more energy, a growing number of countries are turning to gasification process, a time-tested and environmentally-sound way of converting the energy in MSW and agricultural crops into useful products such as electricity, fertilizers, transportation fuels and chemicals.

According to literature [4], on average, conventional waste-to-energy plants that use mass-burn incineration can convert one ton of solid waste to about 550 kilowatt-hours of electricity. With gasification technology, one ton of solid waste can be used to produce up to 1,000 kWh of electricity, a much more efficient and cleaner way to utilize this source of energy [4].

Gasification process

Gasification is an endothermic process, which converts carbon-based material (fossil fuels, MSW, agricultural residues, etc.) into useful gases and chemicals. Since gasification is an endothermic process, the energy needed to drive the chemical reactions forward are usually provided by feeding the reactor the necessary understoichiometric amount of oxygen [2, 5]. The process temperature of gasification is usually quite high (850 – 1500 ºC). The resultant mixture of gases produced during gasification process is called product gas, which contains CO, H_2, CO_2, CH_4, N_2 and is combustible [2].

Emissions of sulphur and nitrogen compound (mainly their oxides), particles, furans and dioxins are significantly reduced by use of gasification process [2]. The lack of oxygen during the gasification process prevents the formation of free chlorine from HCl [2]. Also, because of the same reason, the formation of dioxins is less than combustion. Emission of dioxins by this process is $0.2e^{-10}$ g/m^3 produced gas while burning the biogas produced in landfills through torches is 1.8 e^{-7} g/m^3 biogas [4]. This prevents contact of hydrogen chloride gas comes with moisture, and formation of hydrochloric acid, which is very corrosive substance.

According to Maya et al. [4] the main solid waste gasification advantages are: (a) a mass strong reduction of residue (about 70-80%) and volume (about 80-90%) [4, 6]; (b) drastic reduction in land use [4]; (c) the destruction of organic pollutants, such as halogenated hydrocarbons [4]; (d) the concentration and immobilization of inorganic contaminants so they can be used effectively and safely disposed [4, 6]; (e) the use of recyclable materials

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from the MSW (such as ferrous and non-ferrous metals from ashes and slags); (g) generating renewable energy from solid waste [4].
In this paper, basic principles of gasification process are presented and results of modelling of gasification CHP plant with use of corn cob (agricultural residue), plastic and waste tire (MSW).

Method for modelling of gasification CHP plant

In this study, the simulation of a small-scale gasification CHP plant was developed by means of the Equation Engineering Solver software (F-chart Software, LLC, Madison, WI, USA [7]).
Proposed configurations for the small-scale gasification plant contain the following components: a downdraft air-gasifier, an internal combustion (IC) gas engine (which is the prime mover of the system), heat exchangers for heat recovery and a gas clean-up section (Figure 1).
The chemical energy stored in solid waste (plastic, waste rubber and corn cob), in the downdraft gasifier at 950 °C, is converted into the energy of a producer gas (mixture of N_2, H_2, CO, CO_2 and CH_4). Part of the solid waste energy content is lost in the conversion process, both as heat loss and as energy stored in the charcoal. After gasification process, producer gas exit downdraft gasifier at temperature around 500ºC. Before entering the cleaning system, the producer gas needs to be cooled (up to 150ºC). The rejected heat can be used to pre-heat air and/or generate steam for the gasification, or to produce hot water for the DH. The cooled producer gas passes through a gas cleaning system (e.g. cyclone for large solid particles removal, catalytic tar cracker for tar reduction, a bag filter for small particles and condensed tar removal) where is additionally cooled to 25ºC. Afterwards, the cooled and cleaned producer gas is burned in IC gas engine to produce 330 kW of electrical power. Heat from exhaust gases and from the engine (oil and cooling water) is partially recovered and used to produce hot water for the DH.

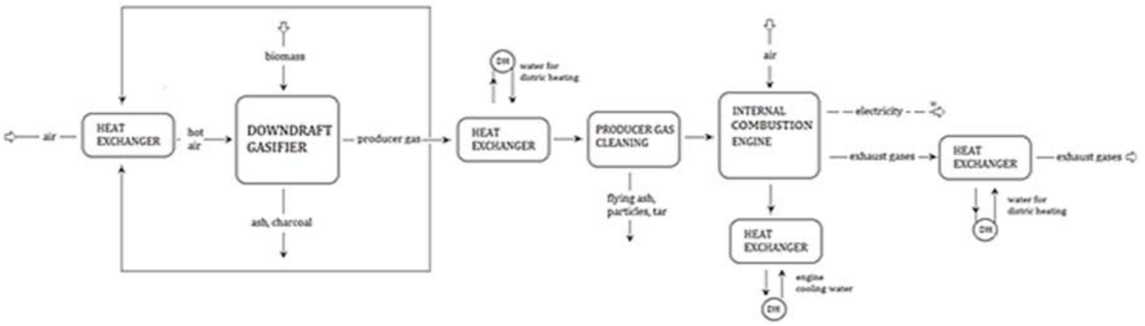

Figure 1 The block scheme of the typical components of a small-scale gasification plant

Model settings

Corn cob, as a form of solid agricultural residues is chosen as a feed into the downdraft gasifier. Proximate and ultimate analyses of corn cob were shown in works of Wang, Trninić et al. [8] and Trninić et al. [9] (Table 1). The proximate and elemental analysis of tire is presented in Table 2. The proximate and elemental analysis of plastic is presented in Table 3.

Table 1 Proximate and elemental analysis of corn cob [8, 9]

Elemental analysis (wt %)^a				
C	H	N	O^b	S
47.61	6.27	0.55	43.89	0.23
Proximate analysis (wt %)^a				
Moisture content^c	VM	fix- C	ASH	HHV ($MJkg^{-1}$)
5.18	81.08	17.47	1.45	18.63

a dry mass basis, b by difference and c as received.

Table 2 Proximate and elemental analysis of waste tire (Sorce: Adaptations of Refs. [10])

Elemental analysis (wt %)				
C	H	N	O	S
86.75	7.25	0.4	2.25	1.35
Proximate analysis (wt %)				
Moisture content	VM	fix- C	ASH	HHV ($MJkg^{-1}$)

1.25	63.5	28.5	5.25	34

Table 3 Proximate and elemental analysis of different plastic waste [11]

Elemental analysis (wt %)[a]						
Plastics sub-group	C	H	N	O	S	Cl
PE	85.59	14.15	0.12	0.07	0.07	0
PP	85.02	13.93	0.08	0.96	0.01	0
PVC	39.56	4.85	0.11	0.02	0.28	55.18
PET	62.30	4.43	0.09	33.13	0.05	0
Proximate analysis (wt %)[b]						
Plastics sub-group	Moisture content	VM	fix- C	ASH	HHV ($MJkg^{-1}$)	
PE		99.61	0.05	0.33	42.84	
PP		99.54	0.03	0.44	46.00	
PVC		83.47	10.67	5.86	20.84	
PET		92.27	7.53	0.20	23.09	

a - dry ash free, b - dry basis, Polyethylene (PE), Polypropylene (PP), Polyvinyl chloride (PVC) polyethylene terephthalate (PET)

The gasification model consists of a series of sub-processes, each containing one process (biomass drying, pyrolysis, gasification, air preheating, and steam generation). For prediction of pyrolysis products, empirical relationships between the product yield and pyrolysis temperature are used. The determination of empirical relationships between the product yield and pyrolysis temperature are explained in detail by Trninic et al. [12]. In addition to these correlations, the energy, mass, and molar balances for each element (C, H, O, and N) are set and used to calculate the gasification products. An initial gasification temperature is assumed in the iterative solution procedure. Model (operating) parameters (drying temperature, percentage of removed moisture, pyrolysis temperature, air inlet temperature, steam inlet temperature, gasification temperature and percentage of charcoal, tar and particles leaving the gasifier) can be directly introduced by the user. The model predicts the producer gas yield, composition (volume fraction in % of CO, CO_2, CH_4, H_2, N_2 and H_2O) and heating value for a particular biomass with a specific ultimate composition and moisture content.

The modelled characteristics of gasification plant coupled with IC gas engine is presented in Table 4. Table 5 shows the simulated results for produced gas for different input fuel (corn cob, waste tire, plastic)

Table 4 Technical specifications of the gasification plant

CPH power plant -downdraft gasification with IC gas engine specification			
System Characteristics			
Solid fuel	corn cob	waste tire	waste plastic(PE)
Solid fuel consumptions (kg/h)	227	137	107.80
LHV of solid fuel (MJ/kg)	18.045	34.00	42.845
Pyrolysis temperature (°C)		450	
Air (Nm^3/h)	250.2	509.1	437.1
Air Temperature (°C)		25	
LHV of produced gas (MJ/Nm^3)	6.95	5.086	5.511
Volume of produced gas[a] (Nm^3/h)	485.3	663.8	612.2
Gasification Temperature (°C)		950	
Ash (kg/h)	3.291	7.193	0.3557
Charcoal[b] (kg/h)	3.105	1.802	1.491
Tar[c] (kg/h)	3.402	1.974	1.634
CHP output			
Electric energy (kW)	336.0	336.4	336.0
Heat energy (kW)	393.20	393.7	393.3
Operating hours per year		7000 h	
Overall recoverable thermal energy, (kW)	468.03	488.6	483.47

Heat Block 1 (kW)	74.83	94.9	90.17
Heat Block 2(kW)	27.90	22.40	20.40
Efficiency of CHP system			
η_{cge} (%)	82.34	72.47	73.05
η_e (%)	29.52	25.99	26.19
η_t (%)	42.47	38.93	37.68
η_{CHP} (%)	71.99	64.92	63.87

a – dry gas, b- 5% of pyrolysis charcoal, c - 5% of pyrolysis tar

Table 5 Comparison of gas composition given by the downdraft gasification model for air first, second and third CHP configuration

	corn cob	waste tire	waste plastic
$T_{gasification}$ (°C)	955	955	955
λ	0.19	0.37	0.35
	Gas composition (vol%)[a]		
CO	24.03	24.81	20.73
CO_2	9.51	3.382	2.987
H_2	14.47	8.152	16.85
CH_4	2.50[a]	3	3
N_2	49.22	60.66	56.43
LHV of gas (MJ/Nm^3 dry)	5.52	5.086	5.511

a – dry basis

The use of agricultural waste and MSW to produce electricity and heat has several advantages. Energy recovery from MSW can solve two problems at once: treating non-recyclable and non-reusable amounts of waste; and generating a significant amount of energy which can be included in the energy production mix in order to satisfy the consumers' needs. Also, agricultural solid residues are a renewable energy with near-zero net CO_2 emissions. It was observed that, all three configurations, for adjusted same electrical output of 336 kW, gave similar values for cold gas efficiency, electric and thermal efficiency. However, the overall CHP efficiency is higher for cases when as a feedstock was used corn cob (71.99 %). Also, the case when waste tire and waste plastic was used as a feedstock, has the highest production of heating for the DH (488.6 kW and 483.47 kW).

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