GASIFIKACIJA OSTATAKA BIOMASE ZA POTREBE PROIZVODNJE ELEKTRIČNE ENERGIJE

GASIFICATION OF BIOMASS WASTES AND RESIDUES FOR ELECTRICITY PRODUCTION

Marta TRNINIĆ[1],
University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia

Tehnologija gasifikacije predstavlja jednu od obećavajućih opcija za pretvaranje energije biomase u električnu energiju. Proces gasifikacije predstavlja process konverzije biomase (uglja itd.) u mešavinu gorivih gasova (ugljen-monoksid, vodonik, ugljen-dioksid i gasovite ugljovodonike). Proizvodni gas se može koristiti kao gorivo za motore sa unutrašnjim sagorevanjem i mikro turbine u cilju proizvodnje električne energije. Da bi se maksimalizovala efikasnost konverzije biomase, proizvodeni gas treba koristiti ne samo za proizvodnju električne energije, već i za proizvodnju toplotne energije. U ovom radu su prikazani rezulatati simulacije gasifikatora povezanog sa motorom sa unutrašnjim sagorevanjem i mikro turbinom. Rezultati pokazuju odnos snage od 0,788 kWh/Nm^3 za unutrašnji gasni motor i 0,553 kWh/Nm^3, za mikroturbinski sistem.

Ključne reči: *biomasa; električna i toplotna energija, motori sa unutrašnjim sagorevanjem, mikro – gas turbine*

Gasification technology presents one of promising option for converting biomass energy into electricity. Gasification process converts carbonaceous materials into carbon monoxide, hydrogen, carbon dioxide, and gaseous hydrocarbons (producer gas). Producer gas can be supplied as fuel to internal combustion engines and micro turbines for electricity generation. In order to maximize the efficiency of biomass conversion, producer gas should be utilized not only for power generation but also for thermal production from the producer gas' sensible heat. In this paper, gasification techniques have been reviewed in depth and the main factors to be considered in the design of a gasification plant have been outlined. It is observed that there are a great number of factors involved in design and operation of a gasification plant, and many of them are critical. Additionally, modeling results for two power generation processes are analyzed. One power generation process include downdraft gasifier coupled with internal combustion engine, and other include downdraft gasifier coupled with micro gas turbine. The results show a power ratio of 0.788 kWh/Nm^3 for the internal gas engine and 0.553 kWh/Nm^3, for the micro turbine system.

Key words: *Biomass, gasification; electricity and heat energy; internal combustion engine; micro gas turbine*

1 Introduction

Ever increasing energy demand and the climate change problem caused by anthropogenic greenhouse gas emissions have resulted in the worldwide effort to find a sustainable and environmentally friendly alternative to today's fossil fuel-dominated energy supply. There is potential for biomass waste (agricultural residues, forest residues and food processing waste) to be useful in solving some of the world's energy and environmental problems, as it is widely recognized as an environmentally friendly and renewable energy source.

Agricultural waste is one of the main renewable energy resources available especially in an agricultural country such as Serbia. It is estimated that every year in Serbia, a total amount of 4.24 million tons of agricultural residues is produced, which is equivalent approximately to 1.71 million tons of oil equivalent (toe) [1].

---

[1] Author, email: mtrninic@mas.bg.ac.rs

Several thermochemical techniques, such as pyrolysis, gasification and combustion processes, have been proposed for biomass conversion into hydrocarbon fuels, power and thermal energy. Among the different thermochemical paths, biomass gasification is continuously receiving attention due its advantages compared to other conversion paths. A gasification process is a partial thermal oxidation, which results in mainly gaseous products (carbon dioxide, hydrogen, carbon monoxide, water vapor, methane and other gaseous hydrocarbons), and small quantities of charcoal, ash, and condensable compounds-tars [2]. The quality of produced gas from gasification, called producer gas, vary as a function of gasifying medium (air, oxygen, steam, carbon dioxide or a mixture of these) and the operating conditions. Installation of small, low-cost and efficient gasifier-engine systems can be an attractive alternative to direct combustion, considering achievable electric efficiency and costs related to storage and transport of biomass fuels [3]. The producer gas, after cleaning and conditioning, can be used as a fuel in gas engines and turbines owing to its acceptable thermochemical combustion properties (flame speed and knock tendency) [4]. Gasification is also considered as a cleaner and more efficient technology than combustion, since it enables higher electric performances at smaller scales and due to its very acceptable combustion properties coupled to a conventional Rankine cycle, giving lower NO_X and SO_X emissions, and possibilities for CO_2 capture [5].

Although gasification is widely considered as a more efficient and less polluting initial thermochemical upstream process of converting biomass to electricity than direct solid fuel combustion processes, the performance of the gasification process is highly unpredictable especially small-scale biomass gasification [6]. The major culprits are unpredictable fuel behavior[7] and unreliable operating conditions partly due to the inhomogeneous nature of biomass feedstock and the complex phenomena of a gasification process. Gasification process modeling has been suggested as a way to handle the prediction of operation behavior during normal gasification with electricity and/or heat production [7]. Furthermore, modeling can guide the preparation and optimization of experiments to be undertaken in a real system. The objective of the present article is to assess and compare the performance of electricity generation systems integrated with fixed–bed downdraft biomass gasifiers for distributed power generation. A model for estimating the electric power generation of internal combustion engines and micro gas turbines powered by syngas was developed. For model development and process simulation the Aspen Plus software was used. In this analysis, corn cob was used as a biomass feedstock (Table 1).

Table 1 Ultimate and Proximate analysis of corn cob (wt % db) [1, 7]

Ultimate analysis					
C	*H*	*O*	*N*	*S*	*ASH*
47.60	6.30	43.90	0.55	0.60	1.45
Proximate analysis					
MC	*VM*	*A*	*fC*	*HHV* [MJ/kg]	
5.18	81.08	1.45	17.47	18.63	

2 Model Formulation

2.1 Description of the system

Two different pathways for electricity generation is analyzed. The first one is the central biomass gasification and production of electricity with internal gas engine. The second one is the central gasification of biomass and production of electricity with micro turbine.

The main components of *"the downdraft – internal combustion engine system"* include: the gasifier, cyclone, producer gas heat exchanger, internal gas engine and heat recovery unit. The cycle involves air gasification of corn cob in a fixed bed downdraft gasifier and the producer gas obtained is then led to a cyclone in order to remove impurities such as dust and uncracked tar [1, 7]. After cleaning, the gas is fed into the heat exchanger and thereafter gas is fed into the engine to generate electricity. The exhaust gases from the internal gas engine are led to a heat recovery where drops it temperature. Process heat or district heating or hot water heat exchange can be installed to further extract energy from the exhaust gases [7].

The main components of "*the downdraft - micro gas turbine system*" include: the gasifier, producer gas combustor/heat exchanger, indirectly fired micro-gas turbine and heat recovery unit [7]. The cycle involves air gasification of corn cob in a fixed bed downdraft gasifier and the producer gas obtained is then led to a combustor. Compressed air (to 3-5 bars) is heated up in the high temperature heat exchanger and thereafter preheated air enters the combustor where the fuel is combusted (temperature reaching 900 – 1000 °C) [8]. Hot flue gases expand through the micro turbine where mechanical work is produced. The exhaust gases from the turbine are led to a heat recovery where drops it temperature. Process heat or district heating or hot water heat exchange can be installed to further extract energy from the exhaust gases [7-9].

Plant capacity at which this technology is used ranges from 1kW$_{el}$ – 10MW$_{el}$ [7, 8, 10]. The efficiency is seen to be averagely 30% for 100 kWel size, 35-45% for more than 1 MW$_{el}$ [11] [12]. Also, internal combustion engines are high flexibility, long lifecycle, reliability, low cost, etc. However it should keep in mind that internal gas engines requires emission control systems because its operation produces high quality of NO_x and CO pollutants [7, 8]. In developing countries, internal combustion engine technology is used for generating electricity for small industries, residential buildings and etc. [7].

2.2 Process model simulator

Aspen Plus[2] is one of the sophisticated processes modeling softer package that gives a complete integrated solution to chemical processes and reactors. Aspen Plus is a steady state chemical process simulator, which uses unit operation blocks, which are the models of specific process operations (mixture, reactor, heat exchanger etc.) [7, 13]. The user places these blocks on a flow sheet, specifying material, and energy streams. An extensive built-in physical properties' database were used for the simulation calculations [7, 13].

The simulations of two proposed CHP systems were based on the mass-energy balance and chemical equilibrium for the overall process.

2.3 Model description

Regarding to Keche A.J. et al. [13] the following assumption were considered in modeling the gasification process:

1. The whole process is in steady state and the reactions reach chemical equilibrium.
2. The heat exchange in a fixed bed is ideal and it is isothermal in the same section.
3. The heat exchange occurs instantaneously at equilibrium with volatile products including chiefly H_2, CO, CO_2, CH_4, and H_2O.
4. Tars are assumed to be negligible in the producer gas.
5. Charcoal only contains carbon and ash; ash is inert and does not participate in chemical reactions.

For the microturbine option the Capstone C200 model was chosen to be considered in calculations, while for internal gas engine Jenbacher JMS 208 GS-B.L. [7]

Figure 1 shows the modeled flowsheet for corn cobs downdraft gasification micro gas turbine system. Dry feed of corn cobs, specified as a non-conventional solid is first converted into its constituting elements (C, H, O, N, S, and ash) (block DECOMP in Figure 1) [7]. This is done by RYield model with calculations that are based on the component yield specifications. A Fortran[3] statement is used to specify the yield distribution according to the ultimate and proximate analysis of corn cobs and determines the mass flow rate of each component in the blocks outlet stream [14]. The outlet stream from the block DECOMP is fed to the gasification reactor (block GASIFIER in Figure 1) where selected possible products were H_2, CO, CO_2, CH_4, and H_2O. The RGibbs was used to simulate the gasification of biomass. The RGibbs reactor calculates the producer gas composition by

---

[2] Aspen - Advanced System for Process Engineering

[3] A drawback of using Aspen Plus is the lack of a library model to simulate fixed bed unit operations. However, it is possible for users to input their own models, using Fortran codes and reactions nested within the Aspen Plus input file, to simulate the operation of a fixed bed.

minimising the Gibbs free energy and assumes complete chemical equilibrium. The gasification reactor outlet enters a cyclone, which separates the ash from the produced gas. The clean product gas is cooled and combust in the Rstoic reactor (block COMB in Figure 1) with the compressed air, before the produced gas from the reaction expand through the turbine.

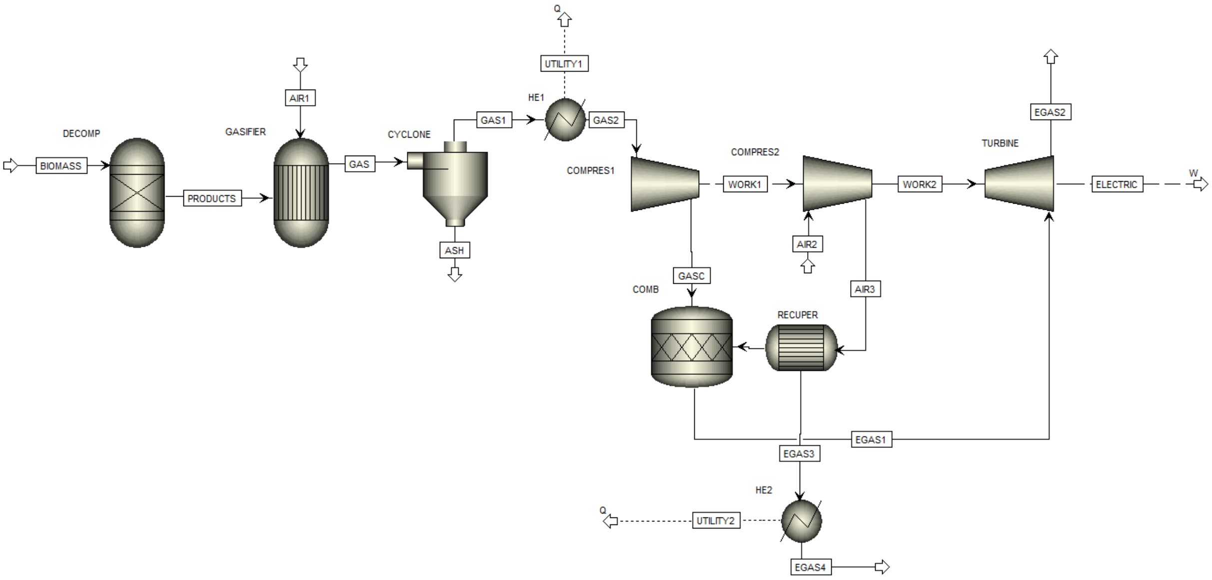

Figure 1 Corn cob downdraft gasification micro gas turbine simulation flowsheet

Figure 2 shows the modeled flowsheet for corn cobs downdraft gasification internal gas engine system. The part regarded to corn cob gasification is same as for the downdraft - micro gas turbine system, except that at the end of producer gas cooling, gas is mixed with air and compressed before entering the internal gas engine (block ENGINEIC in Figure 2) [7].

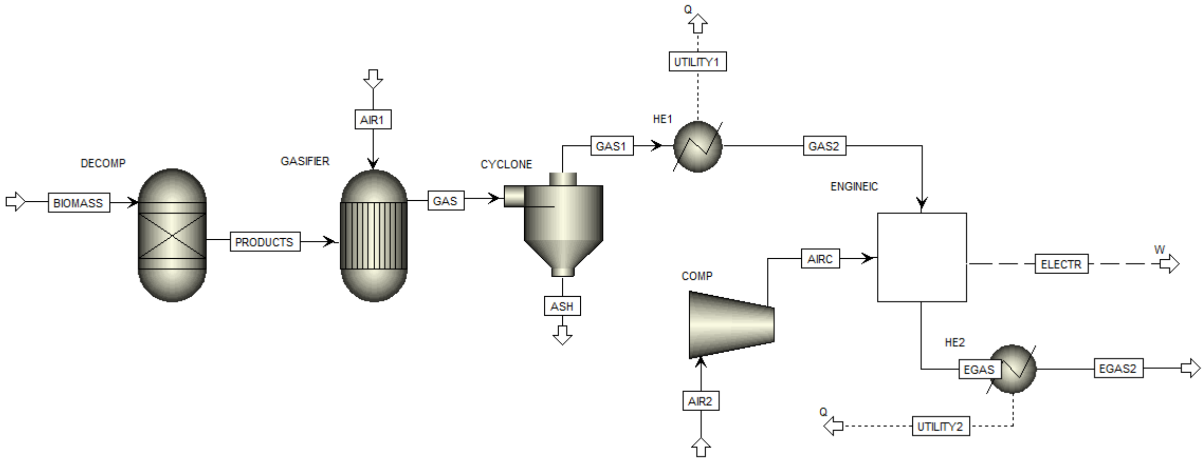

Figure 2 Corn cob downdraft gasification internal combustion engine simulation flowsheet

3 Results and Discussion

The overall process parameters are shown in Table 2.

The gasifier is fed with 100 kg/h of corn cob (HHV=18.63 MJ/kg). This yields 253.6 Nm^3/h (dry basis) of producer gas with estimated low heating value of 6 MJ/Nm^3 and components (by volume): H_2-16.82%, CO-21.48 %, CH_4-2.74 %, CO_2-9.63 %, N_2-40.67 and H_2O-8.66 %. Presence of water vapor and carbon dioxide molecules is due to the water-gas shift reaction during the gasification phase.

When comparing the electricity output of the two systems running, at gasification temperature of 850 °C, the power with internal combustion engine (208 kWe) is slightly higher than for the micro gas turbine (200 kW). The electrical efficiency obtained for internal combustion engine was 37.65 % and the efficiency obtained for micro turbine was 36.20 %. Also, the systems also demonstrate higher value for thermal energy of internal gas engine (234 kW) than for micro gas turbine (135 kW). Further, the maximum attainable electricity ratio of internal gas engine (0.821 kWh/Nm^3) is higher than that of micro turbine for biomass gasification (0.789 kWh/Nm^3).

Simulation output result of NOx formation in kg/kWh from all process, indicate that internal combustion engine (500 mg/Nm^3) lead the chart in the production of NOx. The micro gas turbine gave a low emission of 18 mg/Nm^3 of NOx.

Despite, higher NOx emission compared to micro gas turbine, based on literature data, internal combustion engines are economically feasible in small scale (decentralized power investment) than that of micro gas turbine.

Table 2 Process parameters [7]

Unit	*Value*
Gasifier	
Reactor for gasification	Gibbs equilibrium reactor
Gasification media	air
Gasifier operating pressure	1 [bar]
Air entering conditions	25 [°C[, 1 [bar]
Biomass LHV	17.13 [MJ/kg]
Biomass input conditions	25 [°C], 1 [bar]
Corn cob feed rate	117 [kg/h]
Thermal power input of the gasifier ($m_{bio}LHV_{bio}$)	552.5 [kW[
air/feedstock ratio	0.3 [kg/kg]
Gasification Zone	850 [°C]
Producer gas exit	253.6 [Nm^3/h], 700 [°C]
CHP with micro turbine	
Micro turbine	
Gas inlet turbine temperature	950 [°C]
Inlet Pressure	5.5 [bar]
Turbine exhaust	1 [bar]
Nominal electricity output	200 [kW]
Electricity output	135 [kW]
Exhaust Gas Temperature	280 [°C]
Heat exchanger	1 [bar]
Pressure loss across heat exchanger	5 [%]
Efficiencies	
Electrical	33 [%]
CHP with internal combustion engine	
Internal combustion engine	
Electrical output	208 [kW]
Total recoverable thermal output	234 [kW]
Engine speed	1500 [rpm]
Exhaust gas flow	883 [Nm^3/h]
Exhaust gas temperature	471 [°C]
Combustion air volume	742 [Nm^3/h]
Efficiencies	
Electric efficiency	35.8 [%]

4 Conclusion

The results show that the proposed two CHP systems are feasible with self-sustaining heat generation and recovery to satisfy the process goals. The systems also demonstrates the potential of obtaining relatively high electrical efficiency. However, the maximum attainable electricity ratio of internal gas engine (0.821 kWh/Nm^3) is higher than that of micro turbine for biomass gasification (0.789 kWh/Nm^3). While on other hand, the micro gas turbine gave a low NO_X emission (18 mg/Nm^3) compared to internal combustion engine (500 mg/Nm), but are more expensive than internal combustion engines.

Unfortunately, CHP systems still characterises technical uncertainties namely operational difficulties, poor reliability and low overall efficiency that requires considerable technical advances prior to commercial viability. Therefore, there is a research need to overcome the existing technical obstacles, and to demonstrate energy-efficient biomass-fuelled CHP systems.

5 References

[1] **Trninić, M.**, *Modeling and Optimisation of corn cob Pyrolysis*, Ph.D. thesis, Belgrade University Faculty of Mechanical Engineering, Belgrade, Serbia, 2015.

[2] **Puig-Arnavat, M., J.C. Bruno, A. Coronas,** Modified Thermodynamic Equilibrium Model for Biomass Gasification: A Study of the Influence of Operating Conditions, *Energy & Fuels, Volume 26* (2012), issue 2, pp. 1385-94.

[3] **Chanphavong, L., Z.A. Zainal,** Characterization and challenge of development of producer gas fuel combustor: A review, *Journal of the Energy Institute, Volume 92* (2019), issue 5, pp. 1577-90.

[4] **Gautam, G.,** *Parametric Study of a Commercial-Scale Biomass Downdraft Gasifier: Experiments and Equilibrium Modeling*, MSc thesis, The Graduate Faculty of Auburn University, Auburn, Alabama – USA, 2010.

[5] **Burgt C.H.M.,** *Gasification*, Gulf Professional Publishing, 2008.

[6] **Musinguzi, W.B., M.A.E. Okure, A. Sebbit, T. Løvås, I. da Silva**, Thermodynamic Modeling of Allothermal Steam Gasification in a Downdraft Fixed-Bed Gasifier, *Advanced Materials Research, Volumes 875-877* (2014), pp. 1782-93.

[7] **Trninić, M., A. Jovović, D. Stojiljković, G. Jankes, T. Simonović, N. Tanasić, M. Stanojević**, Process Simulations of Small scale Biomass Power plant, Proceedings *V Regional Conference Industrial Energy and Environmental Protection in South Eastern Europe - IEEP 2015,* The Society of Thermal Engineers, Zlatibor, Serbia, 2015.

[8] **Megwai, G.U.**, *Process Simulations of Small Scale Biomass Power Plant*, MSc thesis, University of Borås, Borås, Sweden, 2014.

[9] **Lymberopoulos, N.,** *Microturbines and their Application in Bio-energy,* Centre for Renewable Energy Sources, 2004.

[10] **Carrara, S.**, *Small-scale Biomass Power Generation*, Ph.D. thesis, University of Bergamo, Bergamo, Italy, 2010.

[11] **Goldstein. L., B. Hedman, D. Knowles, S.I. Freedman, T. Schweizer**, *Gas-Fired Distributed Energy Resource Technology Characterizations*, National Renewable Energy Laboratory NREL, 2003.

[12] ***Technology Data for Energy Plants, available at https://www.energinet.dk/. 2020.

[13] **Keche, A., A. Gaddale, R. Tated**., Simulation of biomass gasification in downdraft gasifier for different biomass fuels using ASPEN PLUS, *Clean Techn Environ Policy, Volume 17* (2015), Issue 2, pp. 465-73.

[14] **Nikoo, M.B., N. Mahinpey**, Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS, *Biomass and Bioenergy, Volume 32* (2008), Issue 12, pp. 1245-54.

[15] **Mavukwana, A.E., K. Jalama, K. Harding**, Simulation of South African Corncob Gasification with Aspen Plus: A Sensitivity Analysis, *Applied Mechanics and Mat*erials, *Volume 92* (2014), pp. 386-91