# Mathematical Modelling and Performance Analysis of a Small-Scale Combined Heat and Power System Based on Biomass Waste Downdraft Gasification

Marta Trninic[1(✉)], Dusan Todorovic[1], Aleksandar Jovovic[1],
Dragoslava Stojiljkovic[1], Øyvind Skreiberg[2], Liang Wang[2],
and Nebojsa Manic[1]

[1] Faculty of Mechanical Engineering, University of Belgrade,
Kraljice Marije 16, 11020 Belgrade, Serbia
mtrninic@mas.bg.ac.rs
[2] SINTEF Energy Research, Postboks 4761 Sluppen, 7465 Trondheim, Norway

**Abstract.** The paper presents a simple mathematical model for designing, optimizing and simulating small–medium CHP scale plant with use of biomass waste downdraft gasification. A downdraft gasifier has been used as the starting point in the study, due to its low tar content and effective way of using heat in the engine's exhaust gases to dry and pyrolyze the different solid biomass waste. Hot water from the cooling circuit of the engine and from producer gas cooling is directly used for the district heating network, air or steam preheating. The mathematical model includes modelled components as a downdraft gasifier, an internal combustion engine using the characteristic equation approach method. The mathematical model enables the outputs of the plant to be evaluated and calculated for different types of biomass and operating conditions. The results demonstrate that it is a useful tool for assessing the performance of CHP plants using several types of biomass waste and enables comparisons to be made between operating conditions for real applications.

**Keywords:** Biomass · Downdraft gasification · CHP

## 1 Introduction

Gasification process is one of the most advanced and highly efficient processing routes to convert biomass into a useful gases and chemicals [1, 2]. The conversion is achieved, at high temperature (850–1500 °C), by reactions between a feed gas (air, enriched air, steam, oxygen) and biomass. The resultant mixture of gases (producer gas) formed during gasification process contains carbon monoxide (CO) and hydrogen ($H_2$), carbon dioxide ($CO_2$), methane ($CH_4$), water ($H_2O$), and a large panel of hydrocarbons including tars, and inorganic impurities in lower concentration [3–5]. Producer gas can be upgraded to synthesis gas (syngas) by adjusting the $H_2$/CO ratio and converted to any hydrocarbon [6]. It can be methanized or converted into other gaseous fuels (dimethyl-ether, hydrogen) or liquefied and upgraded to Fischer-Tropsch

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diesel, ethanol, or methanol [6]. Further, cleaned (free from tar, ash, alkali compounds) producer gas can be used in internal combustion engines, gas turbinesor fuel cells for power generation [7]. Integrating heating and electricity subsystems into a conventional plant could increase the plant's efficiency to 90% and to reduce its negative impact on the environment [4, 8].

One of efficient ways to integrate gasification with heating and electricity subsystems is by use of internal combustion (IC) gas engines. IC are best suited for small and medium scale plants from 1 to 10 MW [4, 9]. Also, IC gas engines have benefits like low capital cost, reliability, good part-load performance, high operating efficiency, and modularity and is quite safe to use [10].

The aim of this study is to develop simple and reliable simulation tools (mathematical model) to give a better understanding of the whole process of biomass gasification coupled with IC gas engine and to be used as preliminary tools to evaluate the characteristics of CHP biomass gasification plants. The mathematical model must be able to predict the performance of the whole system under varying operating conditions: different biomass characteristics, ambient temperature, gasifying agent, etc. This model should be useful, at a design stage, to evaluate the outputs of the plant for different types of biomass and operating conditions. In addition, the energetic performance of the CHP should be clearly stated.

This paper presents mathematical model development of a small-scale combined heat and power system, based on biomass waste downdraft gasification and IC gas engine, powered by corn cobs (as a form of waste biomass). With this model is possible to simulate how the heat from the producer gas and IC gas engine can be used to increase the performance of the system, for example by powering the gasification process (preheating air or generate steam) and heating water for district heating network (DH).

## 2 Development of Mathematical Models

Due to the inherent complexity of biomass gasification processes, modelling for simulation and prediction of performance of the processes is still an incipient activity [11]. In this paper, only description of gasification models is presented, as generally the simulation of equipment and processes after gasifier doesn't present a challenge. Different kinds of models have been proposed in order to explain the gasification process, with an interest towards the design, simulation, optimization, and process analysis of gasifiers. Regard to analysis of gasification process, the models can be divided into kinetic, thermodynamic equilibrium, artificial neural network models, Aspen Plus gasification models and computational fluid dynamics simulation models. In literature can be found a detailed review of recent biomass gasification models [2, 11–16]. In this paper, is presented the gasification model, part of developed downdraft CHP system model, which is no longer is considered as a black box. It involves main gasification sub-processes (drying, pyrolysis, gasification) and their products. The developed model, based on thermodynamic equilibrium calculations, has been validated with experimental published data of other authors. It, provides the opportunity to evaluate downdraft gasification processes as well as effects of variations in biomass properties and operating conditions. In further text, the development of whole gasification CHP system is presented.

## 3 Downdraft Gasification CHP System Description

Proposed configurations for the small-scale gasification plant contain the following components: a downdraft 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 (Fig. 1).

The chemical energy stored in biomass, 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 biomass energy content is lost in the conversion process, both as heat loss and as energy stored in the charcoal [17]. After gasification process, producer gas exit downdraft gasifier at temperature around 500 °C [18]. Before entering the cleaning system, the producer gas (at 500 °C) needs to be cooled (up to 150 °C). 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 [17–19]. 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 25 °C [18]. Afterwards, the cooled and cleaned producer gas is burned in IC gas engine to produce 320 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.

## 4 CHP System Modelling

### 4.1 Process Model Simulator

The "Engineering Equation Solver (EES)" [20] has been found to be very suitable for modeling this kind of system, because it contains all of the necessary thermodynamic functions and it is possible for the model builder to make a user interface [2, 18].

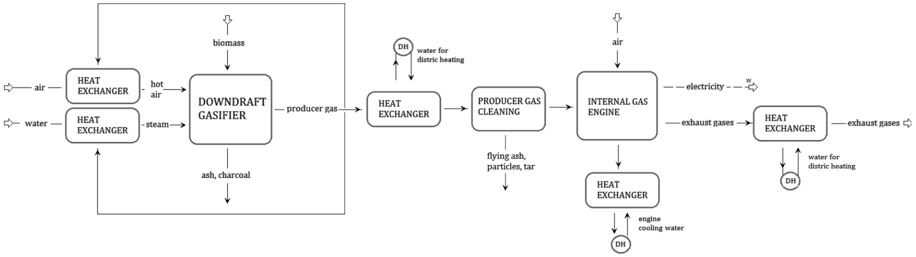

**Fig. 1.** The block scheme of the typical components of a small-scale gasification plant

## 4.2 Model Settings

### Biomass Fuel

Corn cob, as a form of biomass waste 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. [21] and Trninić et al. [22]. The proximate and elemental analysis of corn cob composition is presented in Table 1.

**Table 1.** Proximate and elemental analysis of corn cob

| 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 (MJ $kg^{-1}$) |
| 5.18 | 81.08 | 17.47 | 1.45 | 18.63 |

a - dry mass basis, b - by difference, c - as received

### General Assumptions

The following assumptions were made:

1. Heat losses in pyrolysis and gasification units are estimated by the user as a percentage of biomass energy input to the system [2].
2. Corn cobs are assumed to enter the CHP plant at 25 °C and 1 atm.
3. The air for the gasification process is considered as dry, containing only: 21% $O_2$, 78% $N_2$ (volume fraction).
4. Modelling of the IC gas engine was carried out without consideration of the thermodynamic cycle and mechanical aspect analysis.
5. The gasification consists of a series of sub-processes:
    - Drying unit, that predicts the removal of moisture from raw biomass. The percentage of removed moisture can alternatively be set by the user.
    - Pyrolysis unit that, using empirical correlations, predicts the formation of pyrolysis products (charcoal and volatiles, including tar).
    - Gasification unit, that predicts the formation of gasification products (gas, including small amount of charcoal and tar).
    - Air preheating, and steam generation units.
6. All sulphur and nitrogen in biomass, during pyrolysis, is converted into the tar and charcoal.
7. Tar and charcoal leaving the gasifier as a percentage of tar and charcoal produced in the pyrolysis unit [2].
8. Particles leaving the gasifier are set by the user as mg/Nm3 in the producer gas. These particles are considered to consist only of carbon.
9. Gas products consists of $CO_2$, CO, $H_2$, $CH_4$, $N_2$, and $H_2O$.
10. Setting the amount of $CH_4$ produced.

11. All Sulphur in biomass is converted into the ash.
12. The model considers that producer gas completely cleaned from particles, tar and organic and inorganic impurities (through a water scrubber cyclone, bag filter etc.).

### 4.3 Model Description of the Different CHP Units

**Gasifier Model**

The gasification model consists of a series of sub-processes, each containing one process (biomass drying, pyrolysis, gasification, air preheating, and steam generation), see Fig. 2.

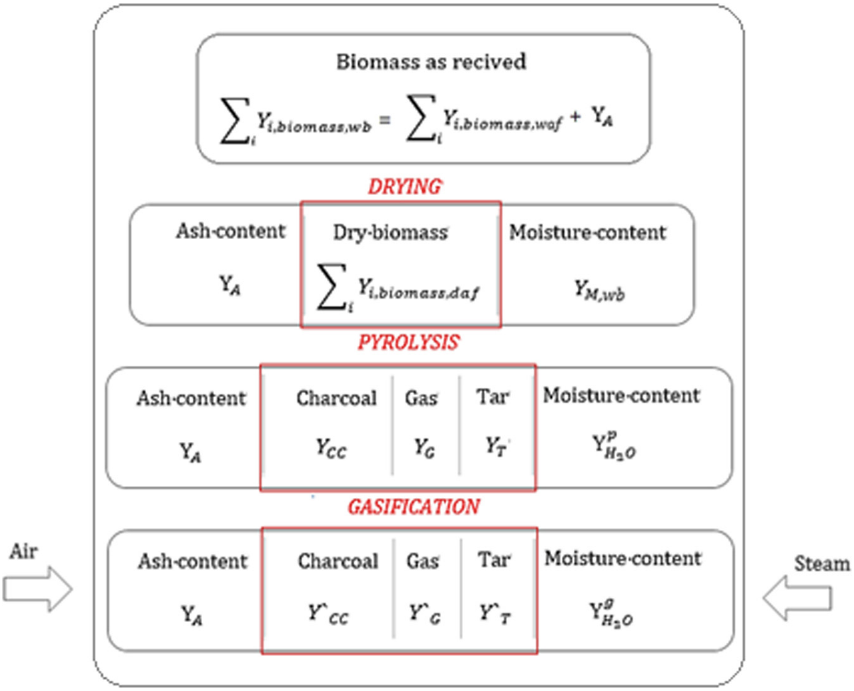

**Fig. 2.** Overall mass balance for the biomass gasification process

Gasification sub-processes can be described with the equations:

Drying:

$$\sum_i Y_{i,biomass,waf} + Y_A \underset{drying}{\rightarrow} \sum_i Y_{i,biomass,daf} + Y_{M,wb} + Y_A \tag{1}$$

Pyrolysis [23]:

$$\sum\nolimits_i Y_{i,biomass,daf} + Y_{M,wb} \underset{pyrolysis}{\rightarrow} \sum\nolimits_i Y^p_{j,products,daf} + Y^p_{H_2O} + Y_A \tag{2}$$

Gasification:

$$\sum\nolimits_i Y^p_{j,products,daf} + Y^p_{H_2O} + Y_A + Y_{AIR} + Y_{STEAM} \underset{gasification}{\rightarrow} \sum\nolimits_i Y^g_{j,products,daf} + Y_A + Y^g_{H_2O} \tag{3}$$

where:

$\sum_i Y_{i,biomass,waf}$ is the mass fraction of the ith element (carbon, hydrogen, oxygen, nitrogen) in wet biomass on an ash free basis.
$\sum_i Y_{i,biomass,daf}$ is the mass fraction of the ith element (carbon, hydrogen, oxygen, nitrogen) in dry biomass on an ash free basis.
$Y_A$ is the ash content in biomass on dry basis.
$Y_{M,wb}$ is the moisture content of biomass on dry ash free basis.
$\sum_i Y^p_{j,products,daf}$ is the mass fraction of the jth pyrolysis product (charcoal, tar and gas) on a dry ash free basis.
$Y^p_{H_2O}$ is the moisture content in the gas obtained in the pyrolysis process.
$Y_{AIR}$ is the mass fraction of air.
$Y_{STEAM}$ is the mass fraction of steam.
$\sum_i Y^g_{j,products,daf}$ is the mass fraction of the jth gasification product (charcoal, tar and gas) on a dry ash free basis.
$Y^g_{H_2O}$ is the moisture content in the gas obtained in the gasification process.

For prediction of pyrolysis products, empirical relationships between the product yield and pyrolysis temperature are used (Eqs. 4–12). The determination of empirical relationships between the product yield and pyrolysis temperature are explained in detail by Trninić et al. [23]. In addition to these correlations, the empirical equations, which describe the general trends of product distribution as a function of temperature, are set and used.

$$\sum\nolimits_i Y^p_{j,products,daf} = Y_{cc} + Y_T + Y_G \tag{4}$$

$$Y_G = Y_{CO2} + Y_{CO} + Y_{CH4} + Y_{H_2} \tag{5}$$

Temperature dependent charcoal, tar and gas yields are given by [23].

$$Ycc = 7.97T^2 \cdot 10^{-5} - 0.125 \cdot T + 68.87 \tag{6}$$

$$Y_T = -1.38T^2 \cdot 10^{-4} + 0.12 \cdot T + 12.64 \tag{7}$$

$$Y_G = 1.12T^2 \cdot 10^{-4} - 0.058 \cdot T + 30.77 \tag{8}$$

Dependence of gas yield on pyrolysis temperature is described by:

$$Y_{CO} = -2.65T^2 \cdot 10^{-4} + 0.27 \cdot T - 32.71 \tag{9}$$

$$Y_{CO2} = -2.85T^2 \cdot 10^{-5} - 0.029 \cdot T + 70.89 \tag{10}$$

$$Y_{CH4} = 6.69T^2 \cdot 10^{-5} - 0.037 \cdot T + 4.28 \tag{11}$$

$$Y_{H2} = 7T^2 \cdot 10^{-5} - 0.0371T + 5.11 \tag{12}$$

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 results provided by this model were validated by comparison of results given by variation of different parameters with the experimental results from Senelwa [24] and Da Silva [25]. The results form model validation showed that the model is accurate (RMSD = 0.026 [5]) enough to predict the behavior of downdraft gasifiers and it is proved to be sensitive enough to evaluate the influence of equivalence ratio, air preheating, steam injection, oxygen enrichment and biomass moisture content on the quality of producer gas.

### Producer Gas Cooling

The producer gas cooling is modelled with a Heater block 1. The temperature is lowered from 500 °C to 150 °C. It is assumed that producer gas after passing the gas cleaning unit is additionally cooled to 25 °C. The exhaust gas cooling is modelled with a Heater block 2. The temperature is lowered from 180 °C to 85 °C.

### Internal Combustion Engine Model

The exhaust gases from IC gas engines are complex mixtures consisting principally of the products of complete combustion, small amounts of the oxidation products of sulphur and nitrogen, and compounds derived from the fuel and lubricant [26].

The exhaust gas composition is calculated based on the combustion stoichiometry. In the analytical model presented for the adiabatic combustion in this section it is assumed that all gases are ideal gases and their enthalpies and specific heats only change with temperature.

The electricity and heat generated by the IC gas engine are calculated based on the electrical ($\eta_{el}$) and thermal ($\eta_{th}$) efficiencies of a GE's Jenbacher JMS 208 GS-B.L gas engine ($\eta_{el} = 35.8\%, \eta_{th} = 41.9\%$) [27]. Electrical and thermal efficiencies are defined as follows [4]:

$$\eta_{el} = \frac{W}{LHV_{gas} \times V_{gas}} \tag{13}$$

$$\eta_{th} = \frac{Q}{LHV_{gas} \times V_{gas}} \tag{14}$$

The amount of corn cob supplied to the CHP plant is adjusted to have an electrical output of 320 kW. Exhaust gas temperature at full load is 500 °C [27]. A heater block is placed on the exhaust gas stream to recover heat from 500 °C to 85 °C for district heating.

**The Efficiency of CHP System Performance**

The energetic performance of the CHP plant can be evaluated, according to Francois et al. [4], from cold gas efficiency and electrical, thermal and CHP efficiencies.

The cold gas efficiency ($\eta_{cge}$) is defined as the ratio of the energy contained in producer gas ($Q_{pgas}$) to the energy contained in biomass fuel ($Q_{biomass}$) [4]:

$$\eta_{cge} = \frac{Q_{pgas}}{Q_{biomass}} = \frac{V_{pgas} \times LHV_{pgas}}{m_{biomass} \times LHV_{biomass}} \tag{15}$$

The electrical ($\eta_e$), thermal ($\eta_t$) and overall efficiencies ($\eta_{CHP}$) of a CHP plant are calculated as follows [4]:

$$\eta_e = \frac{W_e}{Q_{biomass}} \tag{16}$$

$$\eta_t = \frac{Q_{DH} + Q_{steam} + Q_{AIR}}{Q_{biomass}} \tag{17}$$

$$\eta_{CHP} = \frac{W_e + Q_{DH} + Q_{steam} + Q_{AIR}}{Q_{biomass}} \tag{18}$$

where, $W_e$ (kW) is the electrical output of the IC gas engine, $Q_{DH}$ (kW) is the heat provided to the District heating, $Q_{steam}$ (kW) the heat provided for steam generation and $Q_{AIR}$ (kW) the heat provided for the air preheating.

## 5 Results and Discussion

In the present paper, a scenario analysis of the gasification CHP plant configuration is presented.

## 5.1 Configuration

The modelled characteristics of gasification plant coupled with IC gas engine is presented in Table 2. The input was considered to be 239 kg/h of dry corn cob with 5.8% of moisture. The air is not preheated. In the model, the pyrolysis and gasification unit temperature has been adjusted to 450 °C and 950 °C respectively. Percentage of charcoal and tar leaving the pyrolysis and gasification unit is given to the model. It was assumed that after gasification, 5% of pyrolysis charcoal and 5% of pyrolysis tar leaves the gasifier. Also, the CH4 percentage leaving the gasifier is also given to the model (3%). The temperature of the producer gas leaving the gasifier is considered to be 500 ° C. Table 3 shows the simulated results for produced gas. It can be seen that the model results are in good agreement with those reported by Senelwa [24] and Da Silva [25]. For the validation of the model, the temperature of the gasification process is settle to be 930 °C and 955 °C. Also, the percentage of CH4 is settle to be 2.5% and 3%. Heat is recovered from producer gas, exhaust gas and IC gas engine. Heat from producer gas is first used for possible air or steam preheating. Producer gas enters the Heater block 1, where temperature of the gas is lowered from 500 °C to 150 °C. The 83.75 kW of heat is used to heat water from 70 °C to 85 °C for District heating. Heat for District heating is also recovered from IC gas engine with 316.36 kW and exhaust gas cooling, Heater block 2, with 35.63 kW. The CHP plant provides 329.70 kW of electricity and 449.08 kW of heat for DH.

In the configuration studied, the cold gas efficiency ($\eta_{cge}$) is 85.35% when considering the energy content of clean producer gas. With reference to the corn cob energy content, the electrical ($\eta_e$), thermal ($\eta_t$) and overall ($\eta_{CHP}$) efficiencies of the CHP plant are 28.73%, 39.13% and 67.86% respectively.

## 5.2 Configuration

The modelled characteristics of gasification plant coupled with IC gas engine is presented in Table 2. The input was considered to be 222 kg/h of dry corn cob with air is preheated up to 400 °C. Other input is set up like in pervious case (temperature of pyrolysis and gasification process, percentages of charcoal and tar etc.). The temperature of the producer gas leaving the gasifier is considered to be 500 °C. Table 2 shows the simulated results for produced gas.

The CHP plant provides 330.40 kW of electricity and 423.56 kW of heat for District heating. Heat from producer gas, exhaust gas and IC engine is used for air preheating and water heating for DC. After leaving air preheating unit, temperature of the producer gas is lowered from 500 °C to 325 °C. Cooled producer gas enters the Heater block 1, where temperature of the gas is lowered from to 150 °C. The 39.62 kW of heat is used to heat water from 70 to 85 °C for District heating. Heat for District heating is also recovered from IC gas engine with 317.03 kW and exhaust gas cooling, Heater block 2, with 32.44 kW. In the configuration studied, the cold gas efficiency ($\eta_{cge}$) is 86.89% when considering the energy content of clean producer gas. With reference to the corn cob energy content, the electrical ($\eta_e$), thermal ($\eta_t$) and overall ($\eta_{CHP}$) efficiencies of the CHP plant are 29.69%, 39.07% and 68.76% respectively.

**Table 2.** Technical specifications of the gasification plant

| CPH power plant-downdraft gasification with IC gas engine specification | | | |
|---|---|---|---|
| Fuel characteristics | | | |
| Fuel | Corn cob | | |
| Size | Do = 10–20 mm | | |
| System characteristics | #1 | #2 | #3 |
| Biomass consumptions (kg/h) | 239 | 222 | 229 |
| Pyrolysis temperature (°C) | 450 | 450 | 450 |
| Air ($Nm^3/h$) | 293.60 | 240.90 | 249.6 |
| Steam (kg/h) | – | – | 10 |
| Air temperature (°C) | 25 | 400 | 400 |
| Steam temperature (°C) | – | – | 400 |
| LHV of produced gas ($MJ/Nm^3$) | 6.39 | 6.97 | 6.87 |
| Volume of produced gas[a] ($MJ/Nm^3$) | 575.9 | 499.30 | 530.40 |
| Gasification temperature (°C) | 950 | 950 | 950 |
| Ash (kg/h) | 3.47 | 3.22 | 3.32 |
| Charcoal[b] (kg/h) | 3.27 | 3.04 | 3.13 |
| Tar[c] (kg/h) | 3.58 | 3.33 | 3.43 |
| CHP output | | | |
| Electric energy (kW) | 329.70 | 330.40 | 330.50 |
| Heat energy (kW) | 316.36 | 317.03 | 317.13 |
| Operating hours per year (h) | 7000 | 7000 | 7000 |
| Overall recoverable thermal energy (kW) | 449.08 | 423.56 | 453.59 |
| Air preheating (kW) | – | 34.47 | 34.77 |
| Steam generation (kW) | – | – | 35.25 |
| Heat block 1 (kW) | 83.75 | 39.62 | 32.88 |
| Heat block 2 (kW) | 35.63 | 32.44 | 33.50 |
| Efficiency of CHP system | | | |
| $\eta_{cge}$ (%) | 85.35 | 86.89 | 88.20 |
| $\eta_e$ (%) | 28.73 | 29.69 | 28.80 |
| $\eta_t$ (%) | 39.13 | 39.07 | 39.52 |
| $\eta_{CHP}$ (%) | 67.86 | 68.76 | 68.32 |

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

## 5.3 Configuration

The modelled characteristics of gasification plant coupled with IC gas engine is presented in Table 2. The input was considered to be 229 kg/h of dry corn cob with air is preheated up to 400 °C. Other input is set up like in pervious case (temperature of

**Table 3.** Comparison of gas composition (vol.%) given by the downdraft gasification model, literature review

| | Model (in this study) steady state model for downdraft | | Da Silva [25] downdraft gasification of corn cob | Senelwa [24] downdraft gasification of P. tomantosa with bark |
|---|---|---|---|---|
| $T_{gasification}$ (°C) | 930 | 955 | 930 | 955 |
| λ | 0.25 | 0.19 | 0.25 | 0.19 |
| CO | 24.21 | 24.03 | 19.00 | 24.10 |
| $CO_2$ | 9.68 | 9.51 | 10.30 | 9.50 |
| $H_2$ | 14.84 | 14.47 | 15.90 | 12.90 |
| $CH_4$ | 3.00[a] | 2.50[a] | 3.00 | 2.50 |
| $N_2$ | 48.27 | 49.22 | 49.51 | 51.10 |
| LHV of gas (MJ/Nm$^3$ dry) | 6.22 | 5.52 | 5.66 | 6.11 |

a - add by user

**Table 4.** Comparison of gas composition (vol. % db) given by the downdraft gasification model for air first and second CHP configuration

| | Air preheating Tair = 400 °C | Air and steam Tair/steam = 400 °C |
|---|---|---|
| $T_{gasification}$ (°C) | 955 | 955 |
| λ | | |
| Gas composition (vol.%)[a] | | |
| CO | 26.94 | 25.78 |
| $CO_2$ | 8.13 | 8.95 |
| $H_2$ | 17.03 | 17.61 |
| $CH_4$ | 2.5 | 2.5 |
| $N_2$ | 45.41 | 45.17 |
| LHV of gas (MJ/Nm$^3$ dry) | 6.13 | 6.05 |

a - dry basis

pyrolysis and gasification process, percentages of charcoal and tar etc.). The temperature of the producer gas leaving the gasifier is considered to be 500 °C. Table 2 shows the simulated results for produced gas.

The CHP plant provides 330.50 kW of electricity and 453.59 kW of heat for District heating. Heat is recovered from producer gas, exhaust gas and IC gas engine. Heat from producer gas is first used for air and steam preheating. After leaving air preheating unit, temperature of the producer gas is lowered from 500 °C to 292 °C.

Cooled producer gas enters the Heater block 1, where temperature of the gas is lowered to 150 °C. The 32.88 kW of heat is used to heat water from 70 to 85 °C for District heating. Heat for District heating is also recovered from IC gas engine with 317.13 kW and exhaust gas cooling, Heater block 2, with 33.50 kW.

In the configuration studied, the cold gas efficiency ($\eta_{cge}$) is 88.20% when considering the energy content of clean producer gas. With reference to the corn cob energy content, the electrical ($\eta_e$), thermal ($\eta_t$) and overall ($\eta_{CHP}$) efficiencies of the CHP plant are 28.80%, 39.52% and 68.32% respectively (Fig. 3).

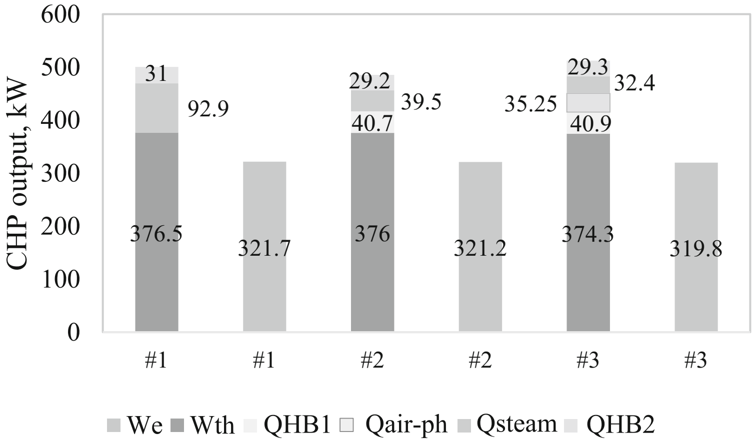

**Fig. 3.** Comparison of CHP output for different configurations

All three configurations, for adjusted same electrical output of 330 kW, gave similar values for cold gas efficiency, electric and thermal efficiency. However, the overall CHP efficiency is higher for cases when as a gasifying agent is used preheated air and air/steam mixture (around 63%). The use of preheated air and air/steam mixture achieves downsizing of the plant [28, 29]. Downsizing is achieved due to reduced volume of gasifying agent (air or air/steam mixture) which bring the gasifier to the required operating temperature. This also reduced the size of the reactor and gas clean-up system needed [28]. However, according to Puig et al. [5] the air temperature has a significant influence on composition only up to a certain level. It is limited by the effectiveness of the heat-exchange equipment and the operating temperature constraints of the reactor. Mixture of air and steam injected in biomass gasification increases slightly the $H_2$ content of producer gas. Also, the characteristics of produced gas are better in case of preheated air and steam/air mixture gasification (LHV of approximately 6.9 $MJ/m^3$). Also, the case where steam/air was used as a gasifying agent at 400 °C, has the highest production of heating for the DH (Fig. 4).

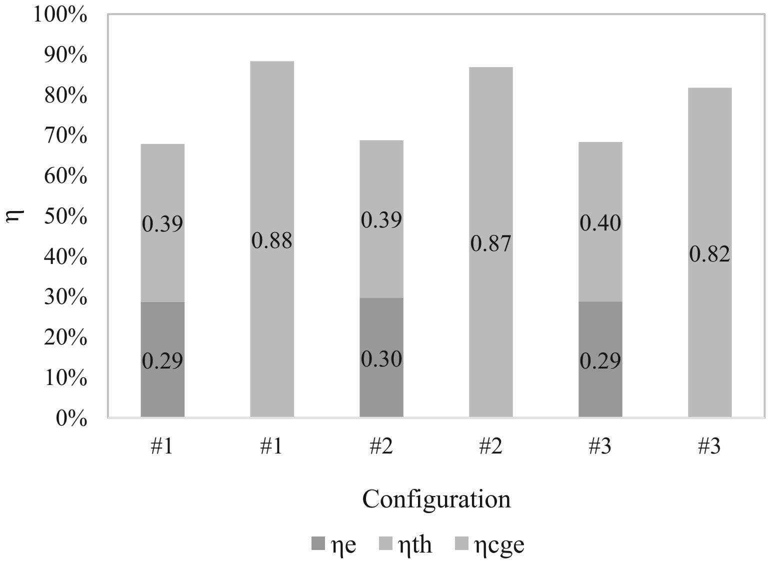

**Fig. 4.** Comparison of efficiencies for different configurations

## 6 Conclusions

In the present paper, a scenario analysis of the CHP biomass gasification plant with use of different gasifying agent characteristics is presented.

Model can be used to predict the final producer gas composition and its main characteristics, such as the heating value, for a certain biomass with a defined ultimate composition and moisture, and to predict influence of different gasifying agent characteristics on CHP plant performance. The use of preheated air and air/steam mixture achieves downsizing of the plant [28, 29]. Downsizing is achieved because a smaller volume of gasifying agent (air or air/steam mixture) is needed to bring the gasifier to the required operating temperature, which in turn reduces the size of the reactor and gas clean-up system needed [28]. Mixture of air and steam injected in biomass gasification increases slightly the $H_2$ content of producer gas. Also, the model has proved to be effective at simulating electricity generation and the composition and gas production. All three configurations generate the same electricity. The third case, with steam/air as gasifying agent at 400 °C, has the highest production of heating for the DH. Nevertheless, all the configurations have similar values for cold gas efficiency (around 82%). The overall CHP efficiency is for 10% higher for cases when as a gasifying agent is used preheated air and air/steam mixture (around 63%). However, all these configurations can be considered to be "high efficiency systems". Choose of suitable configuration depends on user requirements (e.g. production of heating for the DH).

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