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Conventional and advanced biomass gasification power plants designed for cogeneration purpose

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Abstract

In this paper conventional and advanced biomass gasification power plants designed for small cogeneration application are defined. The CHP plants consist of a gasification unit, that employs a downdraft gasifier, and a power unit based on a microturbine in the case of conventional configuration, and on a solid oxide fuel cell module, in the case of advanced configuration. The plants are sized to supply about 100 kW of electrical power.
In order to investigate and to analyze the performances of the two plant configurations, in terms of thermal and electrical efficiencies, numerical models have been developed by using thermochemical and thermodynamic codes.

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Keywords: Biomass gasification, externally fired microturbine, SOFC, cogeneration

1. Background and scope

The biomass using in decentralised CHP systems is expected to increase in the future, because these plants allow to avoid the cost associated with biomass transportation. Efficient power producing technologies for small scale production typically include gas engines, micro gas turbines and fuel cells, all of which require gaseous fuel that can be obtain by biomass gasification [1-7].

Mathematical models are certainly helpful for the development of power systems based on gasification technology. In fact, the use of numerical simulation in product development is becoming increasingly important, since prototyping is expensive, time-consuming and not able to investigate a greater number of design points and operating conditions.

In this paper conventional and advanced biomass gasification power plants designed for small cogeneration application (~100 kW_{el}) are defined. The CHP plant consist of a gasification unit and a power unit based, on a microturbine (μ-TG) plant, in the conventional configuration, and on a solid oxide fuel cell module, in the advanced configuration. The plants are sized to supply about 100 kW of electrical power. In order to investigate and to analyze the performances of the two plant configurations, in terms of

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thermal and electrical efficiencies, numerical models have been developed by using thermochemical and thermodynamic codes.

2. Plant Lay-outs Description

Figure 1 shows the schematic of the CHP plants. The gasification unit consists of a downdraft reactor, based on Ankur Scientific technology [8], fed by biomass (Wood Chips or Pellets) and air as gasifying medium and a clean-up system (Venturi scrubber and dry filters). In the case of conventional plant configuration, the power unit is an externally-fired micro gas turbine (EFμGT) based on the Turbec T100, whereas, in the case of advanced plant configuration, a SOFC power module based on Westinghouse technology is the power generation system.

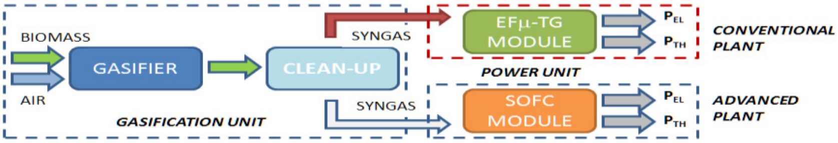


Fig. 1. Schematic of the conventional and advanced CHP configurations.

The biomass characteristics are as follow [9]. Proximate Analysis (dry basis wt%): Ash 0.2, VM 83.3, FC 16.5, Moisture 10; Ultimate Analysis (dry basis wt%): C 50.5, H 5.9, O 43, N 0.3, S 0.2. The higher and lower heating values, on dry basis, are equal to 20.14 and 18.85 MJ/kg, respectively, whereas, with a moisture of 10%, they are equal to 18.13 and 16.72 MJ/kg, respectively.

3.System Modeling

3.1 The gasification unit

The gasification modeling techniques include the application of thermodynamic equilibrium, chemical kinetics, diffusion controlled, diffusion–kinetic approach and CFD tools [10-16]. Pure equilibrium approach has thermodynamic limitations, but the advantage of being generic, relatively easy to implement and rapid convergence. Researchers have successfully demonstrated the application of equilibrium chemistry in downdraft gasifiers [11,12,14,16]. The overall gasification process can be separated into four different reaction zones stratified along the reactor height: drying, pyrolysis, oxidation and reduction, characterized by different operating temperatures [14-16]. By following this approach, the gasification process is performed by (see figure 2a): i) Drying zone. Biomass is introduced into the downdraft gasifier at the top. Due to the heat transfer from the lower part of the gasifier, drying of biomass takes place and water vapour flows downwards to the oxidation zone. The temperature is about 200°C; ii) Pyrolysis zone. The biomass is thermochemically decomposed in char, tar and light hydrocarbons without external gasifying agent. The heat needed for the pyrolysis reactions is provided by the oxidation zone. The temperature reached in this zone is close to 600°C; iii) Oxidation zone. The pyrolysis gases are partially burnt with air under sub-stoichiometry conditions to supply the heat needed to sustain the pyrolysis and gasification reactions. The temperature can vary between 800 °C and 1300 °C, depending on the set air mass flow rate; iv) Reduction zone. In this zone the gasification, shift and methanation reactions occur. Because the main reaction (gasification) is endothermic the temperature reduces, so the exothermic reactions (shift and methanation) are favored. The syngas leaves the reactor at the bottom, with temperatures ranging from 300 °C to 500°C. In figure 2b the flowsheet of the gasifier model, developed by AspenPlus^{TM}, is depicted.

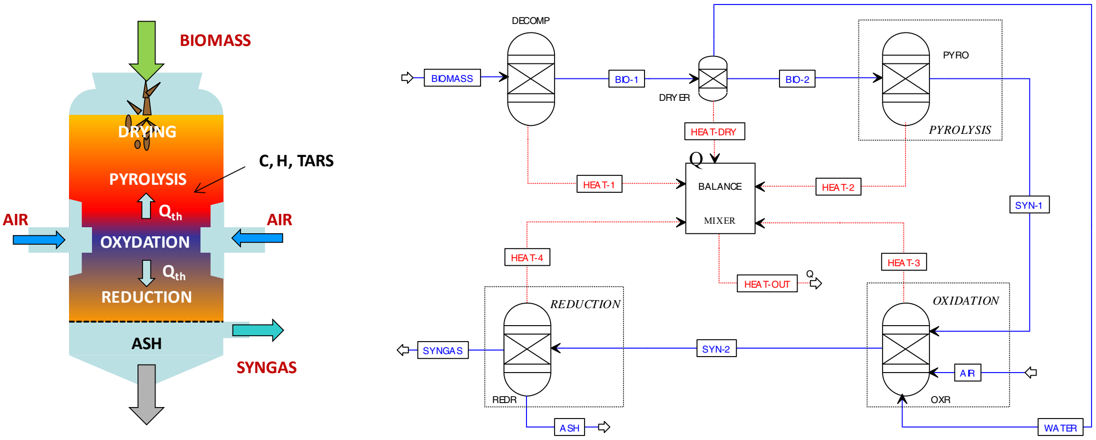


Fig. 2. a) Regions of downdraft gasifier; b) Flowsheet of the downdraft gasifier model

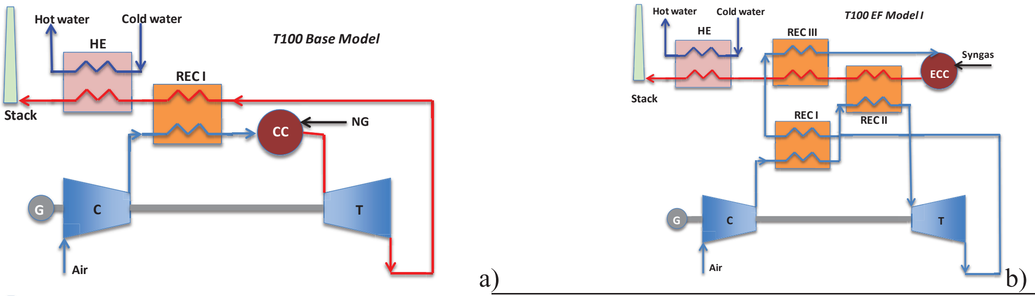
The operation blocks are:

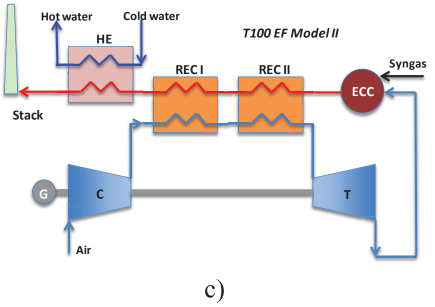
- DECOMP (RYield): in this block the non-conventional solid component (BIOMASS) is converted to its constituent elements by specifying the yield distribution. The heat of reaction associated with the biomass decomposition is considered in the energy balance as a “heat stream”, HEAT-1.
- DRYER (Separator): the drying of the biomass is simulated by separating the water content in the stream BIO-1 from the other components. The heat needed for water evaporation is the thermal flux HEAT-DRY. The temperature of the streams exiting this operation block is assumed equal to 200°C;
- PYRO (RGibbs): in this reactor the pyrolysis process, that occurs at 600°C, is simulated by assuming the chemical equilibrium, solved by the minimization of the Gibbs free energy. This hypothesis is justified because of the high residence time typical of the downdraft gasifiers. The species considered at the chemical equilibrium are H2, CO, char (solid carbon), CH4, CO2, H2O, H2S;
- OXR (RGibbs): the stream SYN-1 is partially burnt by the gasifying agent (AIR) to generate the heat needed for the pyrolysis and gasification reactions. In this reactor, that simulates the oxidation zone, the temperature is up to 1100°C, so the chemical equilibrium is reached. The stream WATER, coming from the DRYER block, also reacts with the streams SYN-1 and AIR.
- REDR (RGibbs): in this block the reduction zone is simulated by assuming the chemical equilibrium due to the sufficiently long residence time. The temperature is equal to 450°C and the unreacted char is assumed to consist only of carbon and to be 1 % of the total fuel carbon content.
- BALANCE (Q-Mixer): this block calculates the thermal balance of the gasifier by considering the thermal fluxes from the other blocks that work under isothermal conditions.
- The clean-up unit is modeled as a black box unit that calculates the mass and energy fluxes by assigning a removal efficiency of 100%. The Peng-Robinson equation of state has been applied.

3.2 The micro turbine power module

Externally-fired cycles have been studied in the past [17-20] because they represent a valid option for the exploitation of low-calorific and mostly-unclean fuels. Figure 3 shows the plant lay-outs.

Micro gas-turbine Turbec T100 with a 100 kW electric output is chosen as the base case. In order to allow the external combustion of the low-calorific syngas produced by the biomass gasification, the micro gas-turbine configuration has been modified according to the T100 externally-fired proposed in ref. [17] fed directly by biomass. The modified plant layout is the scheme T100 Model I. It can be noted that a new type of combustor ECC (External Combustor Chamber) is needed and the combustion gases do not pass through the turbine. The heat transfer is carried out by three heat exchangers: i) REC I is the commercial recuperator provided with the microturbine package, that allows to realize the first air temperature increasing; ii) REC II is the high-temperature heat exchanger in which the air reaches the required TIT; iii) REC III is used to increase the combustion air temperature by recovering the thermal content of the exhaust gases.





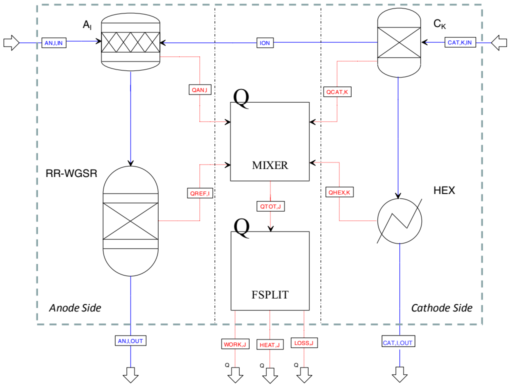
Microtubine model	T100 [17] Base Model	T 100 EF Model I	T 100 EF Model II
Fuel type	Natural gas	Syngas	Syngas
Mass flow air (kg/s)	0.7833	0.7833	0.7833
Pressure ratio/ TIT (°C)	4.5/950	4.5/850	4.5/850
Exhaust Gas temperature after REC I (°C)	270	-	-
Turbine/Compressor isentropic efficiency (%)	82.6/76.8	82.6/76.8	82.6/76.8
Water IN/OUT HE (°C)	50/70	50/70	50/70

Fig. 3. Microturbine plant configurations; a) T100 base model; b) T100 EF Model I; c) T100 EF Model II

Furthermore, in order to optimize the plant configuration of the EFμTG, the authors have proposed a new layout, T100 EF Model II. This configuration allows to use only two heat exchangers: a) REC I is the commercial recuperator provided with the microturbine package; b) REC II is the high-temperature heat exchanger. In this configuration, the air coming out the expander is directly used as combustion air in the ECC. Moreover, the HE used for cogeneration purpose is the component provided by the T100 package. In the table the operating data used as inputs for the proposed models are listed. With respect to the base case model, the other configurations have been realized assuming the same data (air flow rate, turbomachineries efficiencies, etc.).

3.3 The Solid Oxide Fuel Cell power module

The numerical model, based on a novel system-level approach and developed by using the Aspen Plus^{TM} code, is able to predict the behavior and performance of high temperature fuel cells systems under different operating conditions, flow arrangements and configurations. The single cell is discretized in N-elements along both the anodic and cathodic flow directions and each J-element consists of anode, cathode and electrolyte. The model solves mass and energy balances by considering both the electrochemical (i.e. electro-oxyreduction of hydrogen and oxygen) and thermochemical reactions (i.e. reforming and shifting reactions). Figure 4 shows the flowsheet of the J-element. A detailed description of the model and its validation is reported in ref. [21].



Anode side:
Stoichiometric reactor (A_I)
Gibbs reactor (RR-WGSR)
Cathode side:
Separation unit (C_K)
Heat exchanger (HEX)
Energy balance:
Thermal Mixer block (QMIXER)
Thermal Splitter block (QFSPLIT)

Fig. 4. J-element flowsheet

4.Results and discussion

4.1 Gasifier performance

The validation of the gasifier model has been performed by using the technical data of commercial downdraft gasifiers manufactured by Ankur Scientific and fed by the biomass previously characterized. Table 1 shows the comparison between the numerical results and the operating data of the WBGs [8].

Table 1. Biomass derived syngas: comparison of gasification model and operating data

Syngas (mol %, dry basis)		Model	Data [8]
H_2		18.59	18±2
CO		18.98	19±3
CH_4		3.06	>3
CO_2		12.97	10±3
N_2		46.40	50
HHV/LHV	MJ/kg	5.40/4.96	>n.a./4.4

Table 2. Main streams characteristics of gasifier model

Mole Frac	**BIO-1**	**BIO-2**	**SYN-1**	**WATER**	**AIR**	**SYN-2**	**SYNGAS**
H_2	0.345	0.346	4.76E-03	0	0	0.180	0.186
CO	0	0	0.637	0	0	0.288	0.190
CH_4	0	0	0.344	0	0	0	0.031
CO_2	0	0	1.39E-04	0	0	0.041	0.130
H_2S	0	0	1.48E-03	0	0	4.95E-04	5.27E-04
H_2O	6.54E-04	0	0	1.00	0	5.24E-02	3.19E-04
O_2	0.159	0.159	0	0	0.210	9.04E-03	9.63E-03
N_2	1.26E-03	1.26E-03	2.53E-03	0	0.790	0.426	0.454
S	7.35E-04	7.35E-04	0	0	0	0	0
C	0.493	0.494	9.91E-03	0	0	3.32E-03	0
Temperature (°C)	25	200	600	200	25	1100	450
Molecular Weight	11.77	11.77	23.62	18.02	28.85	23.45	24.93

The A/F ratio (defined as the ratio between the air mass flow rate and the biomass mass flow rate) is equal to 1.96. It is worth noting that the model is in good agreement with the declared data. Table 2 summarizes the main characteristics of the gasifier streams calculated by the thermo-chemical model (see figure 2b).

The energy balance of the gasifier has allowed to estimate that the heat loss from the system to the surroundings is equal to 7% of the energy input, according with the literature data [22].

4.2 Power modules performance

The models of the power units, microturbine and SOFC, allowed to calculate the operating data and the performance in the nominal working conditions. In table 3 the main numerical results are listed. The data of the micro-turbines refer to the plant configurations illustrated in figure 3.

Table 3. Power Units modeling results

	Conventional CHP configurations					Advanced CHP configuration	
Power Unit	T100		T100 EF Model I		T100 EF model II	SOFC	SOFC
	[17]	Model	[20]	Model	Model	Model [21]	Model
Air temperature compressor outlet (°C)	214	215	-	205	206	-	-
Gas temperature turbine outlet (°C)	650	650		584	580	-	-
Fuel Mass flow (kg/s)	0.0067^{a}	0.0067^{a}	0.023^{b}	0.066^{c}	0.073^{c}	0.0056^{a}	0.048^{c}
Fuel Input (kW)	333	335	395	330	362		237
Net electric output (kW)	100	101	70	68	74	107^{d}	68^{d}
Thermal power (kW)	167	168	-	197	224	-	113
Net electric efficiency (%), LHV	30.0	30.0	17.7	20.6	20.5	50.2	28.6
CHP efficiency, (%) LHV	80.0	80.0	-	80.0	82.0	-	76.2

^{a}natural gas; ^{b} biomass; ^{c} syngas; ^{d}the DC/AC inverter efficiency is assumed equal to 95%

It can be noted that the electric efficiencies of the plant configurations fed by the syngas produced by the gasifier (T100 EF model I and model II) are lower than the electric efficiency obtained by using natural gas (the difference is about of 10 percentage points) but the CHP efficiency is comparable (or higher).

The SOFC module is similar to the SPGI 120 kW-DC. The anode gas is obtained from a pre-reforming reactor in which the syngas reacts with steam (S/C=1) at 535°C. Contrary to natural gas fuelled SOFC configurations no recirculation of depleted anode gas is considered, due to high nitrogen content of the fuel gas that would significantly dilute the anode gas [6]. Therefore, the anode off-gas is burnt with the cathode off-gas to produce useful heat for the cathode air pre-heating (820°C) and to generate the steam for the pre-reforming reactor. The SOFC module is operated at thermoneutrally conditions (I= 104 A which corresponds to 0.125 A/cm^2, V=0.645 V) at 910°C. In these conditions the electric efficiency is equal to 28.6 % and the CHP efficiency achieves 76.2 % (the thermal energy is obtained from the cooling of the catalytic burner exhausts). With respect to the natural gas feeding the electric efficiency is greatly reduced due to the nitrogen dilution that impacts on reactants partial pressures. The CHP efficiency of the conventional configuration is higher than that of the advanced configuration because of the higher thermal efficiency.

4.2 Integrated power systems performance

By applying the developed numerical models for each module (gasification and power modules) and by integrating the calculated data, the overall performance has been determined as summarized in table 4.

It can be observed that the advanced configuration based on SOFC power module allows to obtain an electric efficiency that is about 8 percentage points higher than that achieved by using the micro-turbine.

Table 4. Integrated WBG-Power units results

Biomass gasification power plant	Conventional CHP configuration	Advanced CHP configuration
	WBG/T100 EF	WBG/SPGI 120
Biomass energy input (kW)	427	267
Electric output (kW)	74	68
Thermal power (kW)	224	113
Electric efficiency (%), LHV	17.3	25.3
CHP efficiency, (%) LHV	69.7	67.6

However, further performance improvements can be obtained by optimizing both the plant architecture and the operating data, such as the temperature, the pressure and the gasifying agent.

From a techno-economic point of view, it is important to underline that the SOFC system needs to be proved in terms of commercial implementation because the capital cost is still high to justify this power plant solution with respect to conventional technologies. Otherwise, thanks to the cogeneration application, it is possible both to obtain interesting performance, also by using low quality fuels, and to achieve economic benefits by selling the thermal power; these aspects permit to sustain the feasibility of advanced biomass gasification plants based on SOFC technology [23].

5. Conclusion

The aim of the present research is to provide an analysis on the performance of small-scale power plants integrated with a biomass gasifier, in order to recognize the most promising configurations from thermodynamic point of view.

The calculated performance indicate that if the syngas from the gasification process is used in a SOFC system better performance can be obtained, even if improvements have to be introduced in order to reach electric an efficiency higher than 30%.

From economic point of view, the capital costs of the gasifier/SOFC systems are still high to justify this power plant solution with respect to conventional technologies. However, the cogeneration application (with economic benefits due to the thermal power selling) and the low pollutants emissions (thanks to fuel pre-treatment) of these renewable power plants can help to sustain their application in the field of the distributed generation.

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