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Coupling of biomass gasification and SOFC – Gas Turbine Hybrid System for small scale cogeneration applications

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Abstract

In this study the performances of small cogeneration power plants fed by biomass and based on conventional and advanced technologies are presented. Three system configurations have been considered and analyzed. They are characterized by: a) a biomass gasification (G) unit, based on down-draft technology; b) a power unit, based on the SOFC technology or on the micro gas turbine (MGT) technology or on a hybrid configuration SOFC-MGT; c) a thermal recovery unit.
The energy analysis of the proposed power plants has been conducted by using thermochemical/thermodynamic models able to study the integrated systems and each unit in terms of operating and performance parameters.

1. Introduction

The share of biomass in CHP production is expected to increase in the future and decentralized CHP plants are of interest to avoid the costs associated with biomass transportation. Efficient power producing technologies for small scale production typically include gas engines, micro gas turbines (MGT) and fuel cells – all of which require gaseous fuel. Gasification can deliver biomass-based gaseous fuel with a heating value in the range 5-15 MJ/kg [1-4]. Therefore, the coupling of biomass gasification and efficient syngas conversion systems may enable the design of a sustainable and efficient CHP plants.
In this paper the energy assessment of small CHP plant configurations (electric power < 500kW) based on conventional (MGT) and/or advanced (SOFC) technologies, integrated with a biomass gasification (G) unit, is presented.
The energy assessment is conducted by means of mathematical models, based on thermodynamic/thermochemical approaches and validated by using available experimental data.
A reasonable number of studies are available in the literature about integrated biomass gasification and solid oxide fuel cell systems or on hybrid configurations with SOFC and MGT fueled with gasified biomass [2,3]. All of them confirm the interest in the development of these systems.
This study aims to propose novel analysis tools developed in AspenPlus^{TM} environment that can easily be used for investigating complex systems and can efficiently support the different steps of the development of these systems, reducing the costs linked to the design, experimental and prototyping.

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2. Description of the CHP configurations

The CHP plant configurations are illustrated in Figure 1. The gasification unit, based on the Ankur Scientific's technology, consists of a down-draft gasifier and a clean-up system. Its operating conditions and performance have been studied by experimental activities, carried out on a small scale prototype (WBG15 model) installed at the Renewable Energy Lab of the Cassino and Southern Lazio University [4]. The power units are a microturbine (fig.1a), based on T100 ECC (External Combustion Chamber) model manufactured by TURBEC and a SOFC module (fig. 1b).
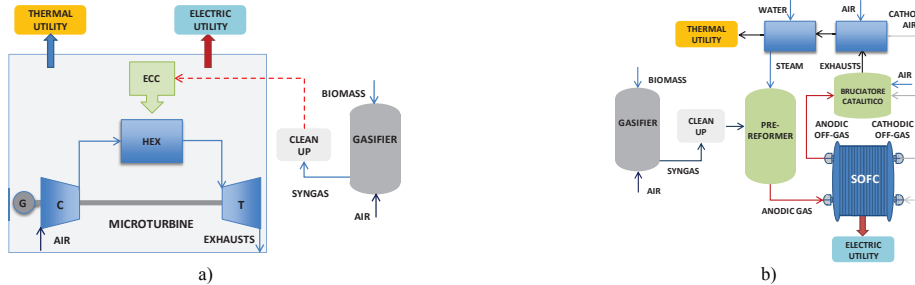

Fig 1. Cogeneration plants lay-out: a) Conventional (CHP G-MGT), b) Advanced (CHP G-SOFC)

An advanced hybrid configuration (G-SOFC_MGT), based on the integration between the fuel cell and the microturbine, has been also studied (figure 2). The characteristics of the biomass used are summarized in table 1.
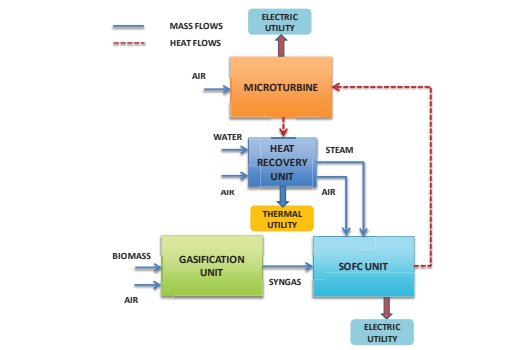

Fig 2. Hybrid advanced cogeneration plant G-SOFC_MGT

Table 1. Biomass Characteristics		
Proximate Analysis, dry basis (wt %)		
Moisture		10
Volatile Matter		83.2
Fixed Carbon		16.5
Ash		0.3
Ultimate Analysis, dry basis (wt %)		
N		0.1
C		50.4
H		6.1
S		0.01
O		43.1
Ash		0.3
Heating Values		
LHV (dry basis)	MJ/kg	17.3
LHV (wet basis 10%)	MJ/kg	15.4

2. Numerical Model

The energy analysis of the proposed power plants has been conducted by using thermochemical/thermodynamic models able to study the integrated systems and each unit in terms of operating and performance parameters. The models, developed for each unit in AspenPlus^{TM} environment, are described in the following.

2.1 Down-draft gasifier

Theoretical models used in the scientific literature to investigate the gasification processes can be classified in thermodynamic equilibrium, chemical kinetics, diffusion controlled, diffusion–kinetic approach and CFD tools [4]. Several researchers have successfully demonstrated the application of equilibrium chemistry in downdraft gasifiers [4,6,7]. In order to take into account the temperature change inside the gasifier, Ratnadhariya and Channiwala [7] suggest to separate the gasification process into four different reaction zones, stratified along the reactor height and characterized by different operating temperatures. By following this approach the gasification process is performed by i) the drying zone where, thanks to the heat transfer from the lower part of the gasifier, the biomass drying takes place and water vapour flows downwards to the oxidation zone (the temperature is about 200°C), ii) the pyrolysis zone where biomass is thermochemically decomposed in char, tar and light hydrocarbons (the temperature is close to 600°C), iii) the oxidation zone where 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) and iv) the reduction zone where the gasification, shift and methanation reactions occur (the temperature is about 600°C).
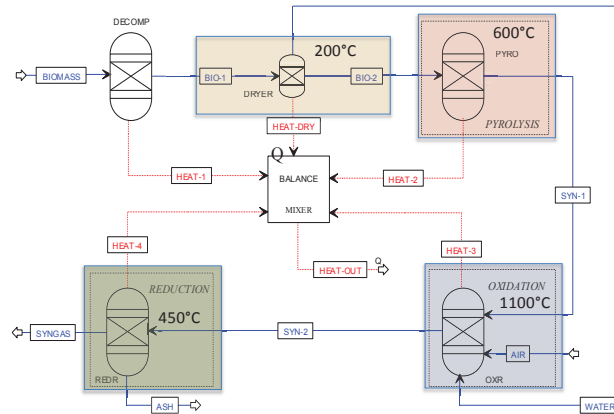
Fig. 3. The gasifier unit model flowsheet (continous lines indicate the mass fluxes, dashed lines the thermal ones)

Fig. 4. WBG 15 gasifier

Table 2. Model validation of the Gasification Unit

		Model	Data [4]	Model	Data [5]
A/B		2	2	2.6	2.6
Syngas Composition					
H_2	Vol %	16	16±4	11.1	9.5±1.5
CO	Vol %	19.4	21±3	13.0	13.5±1.5
CH_4	Vol %	2.5	1.75±0.75	2.3	3±1
CO_2	Vol %	12.2	11±3	15.2	15.5±1.5
N_2	Vol %	49.6	50	58.0	57.5±1.5
O_2	Vol %	0.3	0.55±0.35	0.4	nd
LHV	MJ/Nm³	4.6	~4.3	3.4	~3.5
LHV	MJ/kg	4.5	>n.a.	3.0	3.1

By following this approach, the model flowsheet, shown in figure 3, consists of the following operation blocks:

• DECOMP (*RYield*): this block is used in Aspen Plus to convert the non-conventional solid component (BIOMASS), that cannot be accepted as reactant in the chemical reactor blocks, to conventional components. A Fortran calculator block interacts with it by calculating the constituent elements of the non-conventional fuel by using the proximate and ultimate analyses. The heat stream HEAT-1 represents the energy required to this conversion.

• DRYER (*Separator*): Once the biomass moisture content is convert to liquid water in the DECOMP block, 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;

• PYRO (*RGibbs*): in this reactor the pyrolysis process (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 are H_2, CO, char, tar (C_6H_6O), CH_4, CO_2, H_2O, H_2S;

• 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. The temperature is up to 1000°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.

The validation of the gasifier model has been performed by using the technical data of commercial downdraft gasifiers manufactured by Ankur Scientific and experimental data (table 2) carried out from the Renewable Energy Lab of the University of Cassino and Southern Lazio on the WBG15 (fig.4).

2.2 Micro-gas turbine

Externally-fired cycles have been studied in the past [4,8] because they represent a valid option for the exploitation of low-calorific and mostly-unclean fuels. In a previous paper, the model of the microturbine T100 (by Turbec) with an external combustion chamber (ECC) has been developed and validated by using the available nominal data [4,8].

The model is realized considering a new plant configuration of the microturbine, as proposed by the authors (figure 5), that consists of: a) a low temperature heat exchanger (REC I), that is the commercial recuperator provided with the nominal natural gas microturbine package (T100); b) a high temperature heat exchanger (REC II), in which the compressed air (the compression ratio is equal to 4.5) is heated at the assigned turbine inlet temperature (TIT) before entering in the turbine; c) an external combustion chamber (ECC), in which the air coming out from the turbine is directly used as combustion air; d) a heat exchanger for cogeneration purpose (CHP1); e) a compressor (the isentropic efficiency is equal to 78.6%) and a turbine (the isentropic efficiency is equal to 82.6%) as provided by the T100 model manufactured by Turbec. Thus, with respect to the base case model (T100), in this configuration, the same working data have been assumed (air flow rate, turbomachineries efficiencies, etc.). Figure 5 shows the plant lay-out and, in table 3, the calculated input and out data are summarized. These data refer to two different TIT values and, as a consequence, to different configurations: i) MGT-ECC_LT (low temperature); ii) MGT-ECC_HT (high temperature).
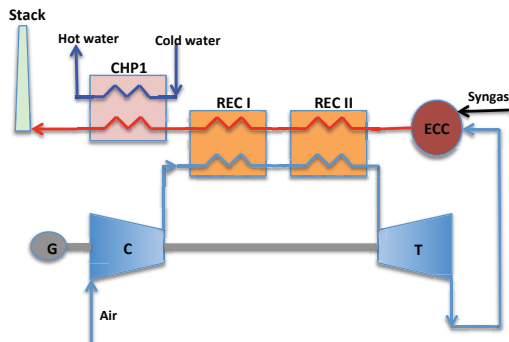

Fig. 5. MGT-ECC configuration

Table 3. Operating data and performance of MGT-ECC plant

Configuration		MGT-ECC_LT	MGT-ECC_HT
Input data			
Turbine inlet temperature	°C	800	900
Exhaust gas temperature (inlet RECII)	°C	850	950
Air mass flow rate	kg/s	0.783	0.783
Output data			
Chemical power (LHV)	kW	368*	412*
Temperature outlet turbine	°C	523	606
Electric power(AC)	kW	70	92
Thermal power	kW	168	176
Electric efficiency (LHV)	%	19	22
Cogeneration efficiency (LHV)	%	65	65

*Syngas A/B=2

2.3 SOFC

The numerical model of the SOFC unit, based on a novel approach detailed in [9], is able to predict the behavior and the performance of a solid oxide fuel cell under different operating conditions, fuel cell designs and flows arrangements. 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 taking into account both the electrochemical (i.e. electro-oxidation of hydrogen) and thermochemical reactions (i.e. reforming and shifting reactions). Figure 6 shows the flowsheet of the J-element.

The anode is simulated by a stoichiometric reactor *RStoich* in which the electro-oxidation reaction takes place and a *RGibbs* reactor (SR-WGS) in which the reforming reaction and/or the water gas shift reaction that can occur during the fuel cell operation are considered. According with scientific literature, in this study, the electrochemical oxidation of CO at the anode side is neglected because of the dominating of H_2 over CO in the charge transfer chemistry. It is estimated that about 98% of current is produced by H_2 oxidation in common situations, while CO seems to play a minor role [9,10]. Therefore CO mostly participates in the WGS reaction (the nichel-based catalyst that covers the anode speeds up this reaction), rather than in the electrochemical process so that it is possible to assume that the whole CO in the anode feeding stream is converted into hydrogen.

The cathode side is modeled by a *Separator* block in which the oxygen is separated from the incoming cathode flow and sent to the anode side according to the assigned utilization factor.

The energy balance of the J-element is performed by using the *QMIXER* block, while the *QFSPLIT* block is used to separate the energy output streams of the J-element, in terms of power (W_J), heat, ($Q_{NET,J}$) and losses ($Q_{HTRF,J}$).

In order to estimate each of these energy fluxes, a Fortran block calculator is implemented. It results:

$$E_{TOT,J} = \Delta H_{A,J} + \Delta H_{C,J} = Q_{A,J} + Q_{CRA,J} + Q_{C,J} \qquad (1)$$

where $\Delta H_{A,J}$ e $\Delta H_{C,J}$ are the enthalpies change of anodic and cathodic streams which are the sum of $Q_{A,J}$ (ΔH of reaction and sensible heat change) and $Q_{CRA,J}$ (the net thermal energy due to the steam reforming e water gas shift reactions) in the anode side and $Q_{C,J}$ in the cathode one.

The term W_J is defined, once the voltage (V) and the current (I) are determined:

$$W_J = V_J \cdot I_J \qquad (2)$$

The voltage of the J-element at different current values is calculated by the potential losses to the $_{OCV}$ (open circuit voltage):

$$V_J = OCV - (\eta_{act,A} + \eta_{act,C} + \eta_{ohmic} + \eta_{conc,A} + \eta_{conc,C})_J = OCV - \left(\sum_i \eta_{i,k}\right)_J \qquad k=A,C \qquad (3)$$

The term $Q_{NET,J}$ is calculated by:

$$Q_{NET,J} = E_{TOT,J} - W_J - Q_{HTRF,J} \qquad (4)$$

where $Q_{HTRF,J}$ (the convective and radiative fluxes to the surrounding) is calculated as follows:

$$Q_{HTRF,J} = h \cdot S_{cell,J} \cdot (T_{cell} - T_{room}) + \sigma \cdot \epsilon \cdot S_{cell,J} \cdot (T_{cell})^4 \qquad (5)$$

where $S_{cell,J}$ is the surface no insulated, T_{cell} is the cell temperature (K), T_{room} (K) is the ambient temperature, h is the convective heat transfer coefficient, σ the Stefan-Boltzmann constant and ε the emissivity of material [9]. The cell performances in terms of voltage (V), current (I), electric power (W) and net thermal power (Q_{NET}) are calculated as:

$$V = OCV - \frac{1}{N}\sum_{J=1}^{N}\left(\sum_i \eta_{i,k}\right)_J \qquad (6)$$

$$I = \sum_{J=1}^{N} I_J \qquad (7)$$

$$W = \sum_{J=1}^{N} WORK,J \qquad (8)$$

$$Q_{NET} = \sum_{J=1}^{N} QNET,J \qquad (9)$$

The SOFC model has been validated and calibrated by means of experimental data on a planar cell tested (figure 7) at the Fuel Cell Research Center of KIST (Korea Institute of Science and Technology) and on the data reported in [11]. Figure 8 shows the comparison between the polarization curve obtained from simulation and the available experimental data.
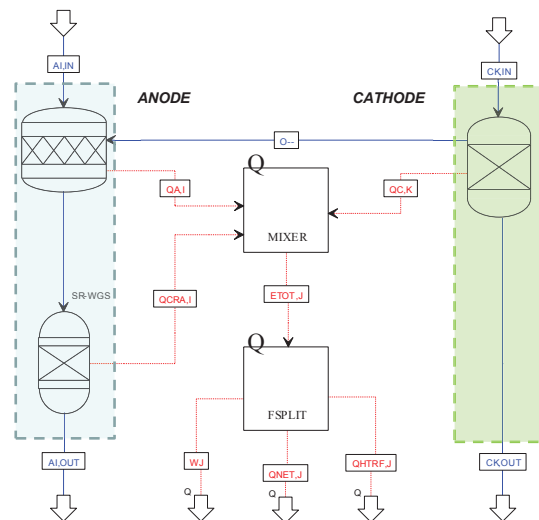

Fig. 6. Flowsheet of the SOFC model
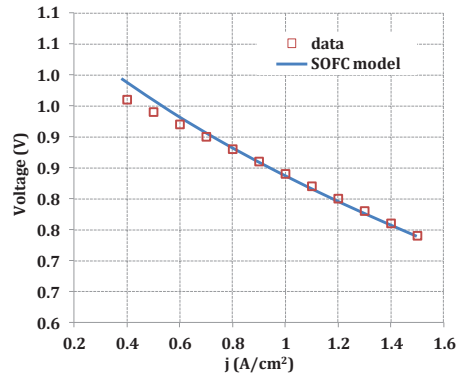
Fig. 7. SOFC test bench at the KIST

Fig. 8. SOFC model validation

3. Results and Discussion

3.1 SOFC and Gas turbine configurations

Considering the operating conditions and the performance calculated for the gasification unit (G) and for the power unit (MGT-ECC_HT and SOFC), it has been possible to estimate the performance of the integrated small scale cogeneration configurations (CHP G-MGT and CHP G-SOFC), described in figure 1. Table 4 shows the results of the numerical analysis. As it can be noted, the configuration based on the gas turbine has lower performance in terms of electric and cogeneration efficiencies and the difference with respect to the SOFC configuration is high (about 10 percentage points). Thus, the advanced plant configuration is more attractive.

3.2 Hybrid configuration SOFC-MGT

The hybrid configuration CHP G-SOFC_MGT has been studied by using a new model developed by combining the models of each sub-unit according with a modular architecture, as proposed in figure 2. The flowsheet of the novel hybrid model is illustrated in figure 9. It is worth noting that the SYNGAS from the gasification unit is sent to the SOFC unit as the anodic stream; a catalytic burner (CB) is fed by the anodic and cathodic exhaust gasses and the burned gases, before being separated into two streams, are used to supply the heat needed for the pre-reforming reactor (PRE-REF). The first stream (EXH3CB) is sent to the high temperature heat exchanger (REC II) of the microturbine in order to supply the heat needed to increase the temperature of the compressed air (3MTG) at 800°C (TIT), while the second one (EXH4CB) allows to preheat the cathodic air (AIRSOFC2) before entering the cell (C-IN). The heat for cogeneration is recovered in CHP1 and CHP2 heat exchangers. In table 5 the main streams characteristics are listed. The calculated performance of the CHP G-SOFC_MGT is summarized in table 4.

The G-SOFC_MGT plant shows better performance in terms of electric efficiency (it is 18 and 9 percentage points higher than the G-MGT plant and G-SOFC plant, respectively), but the heat available for cogeneration purpose results to be smaller. Moreover, the electric power supplied by the microturbine is the 25% of the total electric power (88 kW vs. 360 kW).

Table 4. Performances of the CHP plants

Configuration		CHP G-MGT	CHP G-SOFC	CHP G-SOFC_MGT
Chemical power (LHV)	kW	499[a]	246[a]	986[a]
Electric power (AC)	kW	92	67	360
Thermal power	kW	176	82	240
Electric efficiency (LHV)	%	18.4	27.4	36.5
Cogeneration efficiency (LHV)	%	53.7	61.0	60.8

[a] The heating value refers to wet basis (moisture 10%)

Fig. 9. Flowsheet of the CHP G-SOFC_MGT Model

Table 5. Streams data

Stream	Mass flow (kg/s)	T (°C)	p (bar)
BIOMASS	0.064	25	1
SYNGAS	0.18	25	1.08
AIRSOFC	0.78	25	1.08
AIRSOFC1	0.78	300	1.08
A - IN	0.24	536	1.08
C – IN	0.783	780	1.08
AIRMTG	0.80	25	1
1MTG	0.80	230	4.5
2MTG	0.80	400	4.5
3MTG	0.80	800	4.5
EXH3CB	0.57	915	1
EXH4CB	0.57	915	1
EXH5CB	0.57	318	1
EXHCB,A	0.57	50	1
EXH1MTG	0.80	518	1
EXH2MTG	0.80	353	1
EXH3MTG	0.80	121	1
EXHMTG	0.80	50	1
STEAMREF	0.06	340	1

4. Conclusions

In this study the results of a numerical analysis on the performances of small-scale cogeneration (European Directive 2004/08/CE) systems, fed by biomass and based on conventional and advanced technologies, are presented.

The analysis has been performed by means of numerical models based on a thermochemical and thermodynamic approach. The experimental activities, carried out on the system sub-units, have allowed to calibrate and validate the developed models. Results show that the hybrid configuration is a very interesting option to produce electric and thermal power from biomass with high efficiency.

The proposed models, developed by following a modular architecture, can support the design and sizing of these systems considered very interesting for clean power production as demonstrated by the EU framework program Horizon 2020.

Acknowledgements

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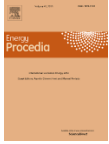
Biography

Mariagiovanna Minutillo is Associate Professor in Energy Systems at University of Naples "Parthenope". She has authored over 90 papers in referred international journals and conference proceedings in the fields of high efficiency power plants, fuel cell systems, hydrogen production technology, electric energy storage systems, renewable sources.