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Energy Performance of CHP System Integrated with Citrus Peel Air-Steam Gasification: a Comparative Study

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Abstract

The aim of this work is to exploit the potential of residual biomass, different from the traditional wood feedstock, by thermochemical gasification process. In particular, citrus peels waste of the juice extraction process, was selected since it is a typical local Sicilian residue. The citrus peel conversion performances in air-steam gasification process were evaluated and compared with those obtained with pinewood as feedstock. Experimental activities of air-steam gasification were carried out in a bench-scale fluidized bed reactor at 1023 K, for both citrus peel and pinewood, varying the steam to biomass ratio (S/B). A simulation model of the experimental facility was developed in order to find a useful tool to realize the virtual scale-up of the system with downstream syngas utilization. The cold gas efficiency (CGE) and the net cold gas efficiency (CGE_{net}) were calculated to define the best gasification conditions. Results showed that using pinewood a very low reactivity can be observed, showing a very low net CGE. The highest net CGE for citrus peel was observed at S/B = 0.5, while for pinewood the addition of water did not improve the net CGE. Finally, an integration of the citrus peel gasification system with a commercial CHP unit was proposed and the efficiencies were evaluated.

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Keywords: Citrus Peel; Air-Steam Gasification; Fluidized Bed Gasification; Combined Heat and Power; CHP;

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1. Introduction

Combined heat and power (CHP) systems demonstrated to be very reliable and effective solutions for efficient decentralized energy production. However, these systems often rely on fossil fuels as feedstocks. The need of renewable feedstocks for CHP systems (e.g. SOFC CHP systems [1]) is one of the main challenges for the reduction in fossil fuel dependence and increasing the energy security of importing countries. Among renewables primary energy sources, biomasses are promising candidates that are able to ensure programmable and constant energy production [2] [3]. Biomass fuels available for gasification in Mediterranean countries include, in addition to wood, agricultural waste and by-products [4] [5] [6] [7]. In many cases, such as in the Italian economic network, most of the agricultural waste (both lignocellulosic and bio-residues) are produced by small and medium enterprises. Despite the potential of feedstocks availability and the above-mentioned scenario, the installation of small-scale CHP plants in the Italian territory is still underexploited. In this way, the production of citrus peel (CP) residues in Sicily is estimated in more than 30.000 ton/year (solid in dry basis) [8]. In scientific literature, it is possible to find various works on CP pyrolysis [9] [10], but there is a lack of information about the potential of exploiting CP in gasification processes. The authors of this paper presented preliminary results of CP gasification using a batch fixed bed reactor [11] [12] [13], which is useful in order to obtain preliminary information but it does not replicate a real continuous process. Thermochemical gasification of carbon based materials, which allows obtaining a product gas consisting of H_2, CO, CO_2, CH_4 and some light hydrocarbons, has been used and developed for nearly two hundred years [14]. Nevertheless, studies on various biomass feedstock and the influence of the gasification parameters process on the energy efficiency, reported that the biomass composition has remarkable effects on syngas and thus in its exergy content [15] [16] [17]. Chemical-physical characteristics (i.e. elemental composition, lower heating value, ash content, moisture content, volatile matter content, bulk density, size and contaminants: N, S, Cl, heavy metals, etc.), are so decisive that pre-treatments of the feedstock are often applied before most of the prevailing gasification technologies [18] [19].

Among the existing types of gasifiers, the fluidized bed gasifier has many advantages, such as easy scale-up, flexibility regarding feedstock type and size, uniform temperature distribution and high carbon conversion efficiency; therefore, it is suitable for the gasification of biomass [20]. The same authors presented a preliminary study on CP gasification in a continuous fluidized bed gasifier at different working conditions, without comparing the results with a traditional woody biomass at the same conditions [21].

Aim of this work is to compare the potential of CP with a woody biomass, which is a typical feedstock for thermochemical gasification, at relatively low temperature. In particular, citrus peel conversion performances in an air-steam gasification process were evaluated and compared with those obtained with pinewood. Experimental activities of air-steam gasification were carried out in a bench-scale fluidized bed reactor, for both citrus peel and pinewood, varying steam to biomass ratio. A simulation model of the experimental facility was developed in order to realize a virtual scale-up of the system and integrate the gasification process with a CHP system. Then, the plant CHP efficiencies were evaluated, as well as the potential of exploiting citrus peel for the combined production of heat and power.

2. Fluidized bed gasifier

2.1. Mathematical model

A zero-dimensional and steady state model was developed in order to simulate the gasification process of citrus peel and white-pinewood in a bench scale fluidized bed reactor. In this work, the gas cleaning section was neglected. The principal input stream of the model is the biomass, which is considered as a “non-conventional” component, described by its ultimate and proximate analysis that are reported in section 2.2 for both the investigated biomasses.

The simulation model shown in Fig. 1 describes the various steps of the gasification process using different approaches. During the drying step (323 – 393 K), biomass loses its moisture content (max 20%). This phenomenon was described with a “RYield” block (EVAP) and a “Separation” block (EVAPSEP), in which the water is separated from the biomass stream according to the proximate analysis. The next step, the pyrolysis one, was modeled using a regressive approach by a “RYield” block (PYROYIELD). Indeed, the yields of the pyrolysis products were obtained from previous experimental tests of pyrolysis conducted at 873 K, for both citrus peels and pinewood. The experimental results of the pyrolysis tests were reported in previous works [21] [22]. Then, the pyrolysis products were directed with the gasifying agents (air and steam) in a “RGibbs” block (GASIFIC) at 1023 K. The gasifying agents flow rates were calculated in order to ensure the proper air equivalence ratio (ER) and steam to biomass ratio (S/B). In this step, the Gibbs free energy is minimized and the output stream corresponds to the gasification products. The condensable products were removed from the gas stream cooling the syngas at ambient temperature. The simulation model aimed to replicate the experimental gasification conditions in order to make a virtual useful tool that allows carrying out feasibility studies about scaled-up processes with downstream applications.

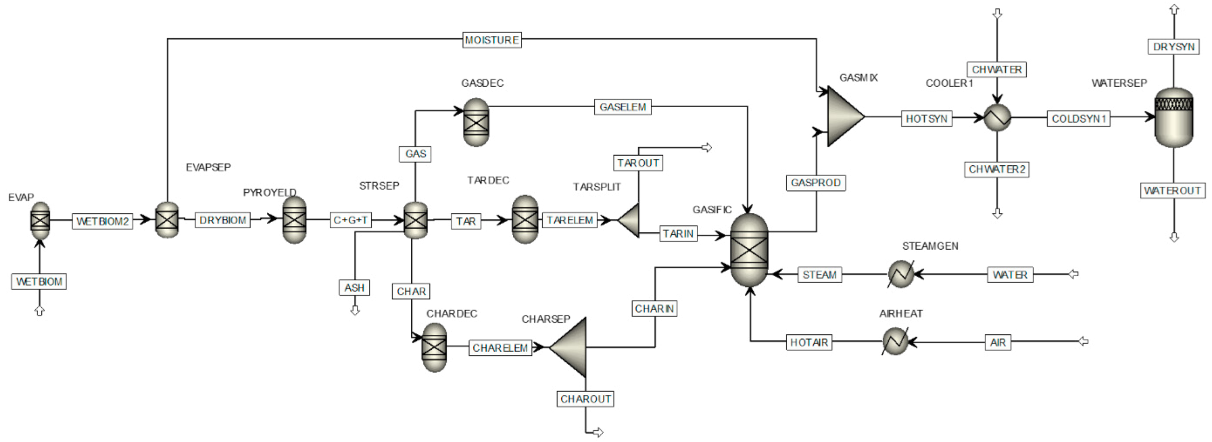

Fig. 1. Gasification process model

2.2. Materials and samples characterization

The biomass characterization was experimentally performed on the samples previously treated. The pinewood sample was air-dried at 383 K for 6 h, while citrus peels were dried at 353 K for 16 h. Biomasses were shredded and sieved into a size range of 0.4<d<1 mm, successively samples were conserved in an electric oven at 80°C in order to assure a dried feedstock.

Ultimate and proximate analysis were performed to determine chemical-physical characterizations of the samples (Table 1). In particular, the ultimate analysis were performed through a CHNS analyzer (CHNSO Thermo Fisher Scientific, Flash EA 1112) while the thermogravimetric analysis (TGA) was adopted for the proximate analysis.

Table 1. Ultimate and proximate analysis of biomass

	Ultimate analysis [%wt$_{db}$]					
	C	H	N	S	O^{a}	Ash
Pinewood	49.2	5.8	0.2	0.05	43.9	0.8
Citrus peel	43.0	6.3	1.3	0.1	40.8	8.5
	Proximate Analysis [%wt$_{db}$]				HHV$_{db}$*	LHV$_{db}$*
	Moisture	VM	FC		(MJ/kg)	(MJ/kg)
Pinewood	7.6	74.2	17.4		19.4	18.2
Citrus peel	8.0	71.9	19.6		18.0	16.6

a. by difference;

*HHV = 0.3491C + 1.1783H + 0.1005S – 0.1034O – 0.015N – 0.0211A [23]

2.3. Air-steam gasification measurements

Experiments were carried out in an atmospheric bench-scale bubbling fluidized bed (BFB) reactor (i.d. 27 mm, H=475 mm), that was described in detail elsewhere by the authors [21].

Qualitative and quantitative analysis of the syngas was determined by a Pollution Vega micro-GC. In particular, the syngas composition was determined as the average composition of five measurements, which started about 20 minutes after that the input streams reached the specific set points.

The biomass feeding rate was 0.69 g/min (dry matter) for pinewood and 0.98 g/min (dry matter) for citrus peels.

All experiments were performed with an equivalence ratio (ER) equal to 0.3, in order to ensure the gasification and fluidization conditions, while the steam to biomass ratio (S/B) investigated were 0, 0.50, 0.75 and 1.00 by weight. In order to reduce particles agglomeration and de-fluidization, due to the high ash content of citrus peel, it was decided to avoid gasification experiments at a high temperature. Hence, the reactor was operated at 1023 K.

3. Results and discussions

3.1. Model validation

In order to evaluate the reliability of the gasification model, experimental data from citrus peels and pinewood air-steam gasification were compared with the simulation model results. Principal syngas components (H_2, CO, CO_2, CH_4, N_2) obtained from simulations (lines) and experimental tests (dots) in terms of volume percentage were reported in Fig. 2. For both samples, a good agreement between experimental and simulated data was obtained. Specifically, when using steam as gasification agent, the best fit between experimental and simulated data were obtained at high steam to biomass ratios. This behavior may be correlated to the enhanced kinetics of the experimental process at high steam partial pressures that are achieved at high S/B ratio.

The main limitation of the proposed simulation model is correlated to the difficulty to obtain methane when steam is added into reactor. Indeed, at the investigated conditions and with a thermodynamic approach, hydrocarbons are converted in hydrogen, carbon monoxide and carbon dioxide.

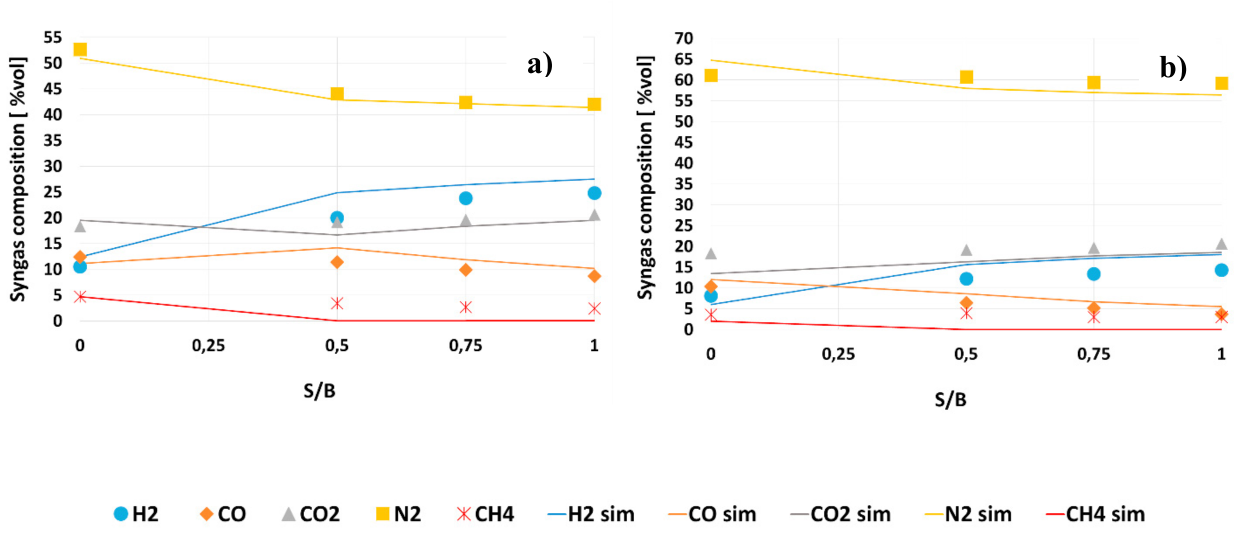

Fig. 2. Syngas composition for Citrus Peel (a) and Wood (b)

As expected for both samples, the carbon monoxide decreases, while carbon dioxide and hydrogen increase at higher S/B ratio, according to the progress of the water gas shift reaction. The experimental and simulated syngas yields were determined for both samples using the nitrogen mass conservation equations.

Considering the nitrogen content in the air as inert during the gasification process, the equation (1) can be formulated for the syngas yield determination (α_{syn}):

$$\alpha_{syn} = \frac{\dot{V}_{air}\ x_{N_2air}}{x_{N_2syn}\dot{m}_{biom}} \quad [Nm^3/kg_{biom}] \qquad (1)$$

where $\dot{V}_{air}$ x_{N2air} and x_{N2syn} are the air flow rate [Nm^3/s], the nitrogen volume fraction in air and in producer gas, respectively, and $\dot{m}_{biom}$ is the dry biomass flow rate [kg/s].

Fig. 3 (a) and Fig. 3 (b) show the effect of the S/B ratio on the syngas yields, calculated for both biomass. It is worth noting how in air gasification conditions the syngas yield is almost the same for both samples and it differs when steam is introduced into the reactor. Indeed, the effect of steam is an evident increase of the syngas yield for the citrus peels, while it is almost constant for the pinewood. This means that, at 1023 K for the wood sample, the heterogeneous reactions involving formed char and steam are so slow that are not able to compensate the negative effect (from a thermal point of view) of introducing a steam stream at a relatively low temperature [24].

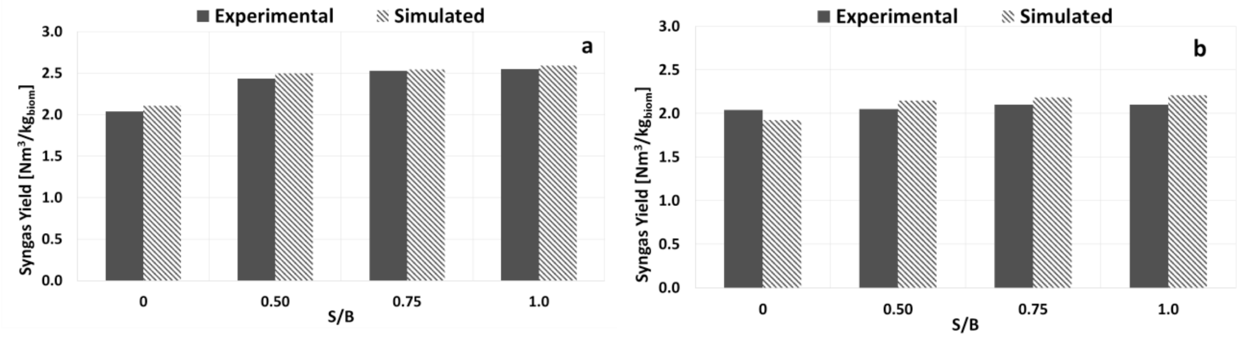

Fig. 3. Syngas Yield obtained from experimental and simulated data: Citrus Peel (a), Wood (b)

On the contrary, the introduction of steam in the gasification process using citrus peels as feedstock showed a progressive increase of the syngas yield, as the steam to biomass ratio increased. The highest yield (2.55 Nm^3/kg_{biom}) was obtained for the citrus peel at S/B = 1. Furthermore, a good agreement between simulated and experimental data was found, confirming the reliability of the proposed simulation model. The lower reactivity of wood, at the investigated conditions, was also evidenced by the weak effect of steam on the hydrogen concentration in the producer gas (Fig. 2 b), with a maximum value of 14.3 %vol at S/B = 1.

The different behavior of the two biomasses can be further underlined observing the conversion efficiencies analyzed from an energetic point view. The cold gas efficiency (η_{CGE}) is an index of the capacity of the gasification system to convert the chemical energy of the biomass into syngas, without considering optional thermal energy recovery from the hot syngas stream. The cold gas efficiency was calculated according to Eq. (2). Analyzing also the effect of steam on the gasification process, the thermal power request to produce steam should be taken into account. For this purpose, net cold gas efficiency (η_{CGE_net}) was calculated according to Eq. (3).

$$\eta_{CGE} = \frac{LHV_{syn}\,\dot{m}_{syn}}{LHV_{biom}\,\dot{m}_{biom}} \qquad (2)$$

$$\eta_{CGE\_net} = \frac{LHV_{syn}\,\dot{m}_{syn}}{LHV_{biom}\,\dot{m}_{biom} + \dot{Q}_{steam}} \qquad (3)$$

where LHV_{syn} and LHV_{biom} are the lower heating values of syngas and feedstock, respectively, $\dot{m}_{\text{syn}}$, $\dot{m}_{\text{biom}}$ indicate the mass flow rate of the produced gas and the mass flow rate of the dry biomass fed, respectively, and $\dot{Q}_{\text{steam}}$ is the input thermal power required to produce steam. Fig. 4. (a) and Fig. 4. (b) show the CGE and the net CGE for both samples at different S/B ratio. It is evident that the introduction of steam has a relevant effect on the efficiency of citrus peels gasification. Indeed, the CGE increases from 0.56 to 0.67 when S/B increases from 0 to 0.5. The latter is also the working point that showed the highest net CGE, which decreases at higher S/B ratio. For pinewood the addition of steam does not lead to an increase of the efficiency at the investigated temperature. The CGE trend for the pinewood showed in Fig. 4. (b) confirms the lower reactivity of wood, compared to citrus peels. It follows that co-gasification of pinewood with citrus peel, if operated at 1023 K, should be restricted at low percentage, in order to avoid low efficiencies of the process. The highest syngas LHV is obtained, for citrus peel, at S/B = 0.5, resulting equal to 4.47 MJ/Nm^3 (4.14 MJ/kg).

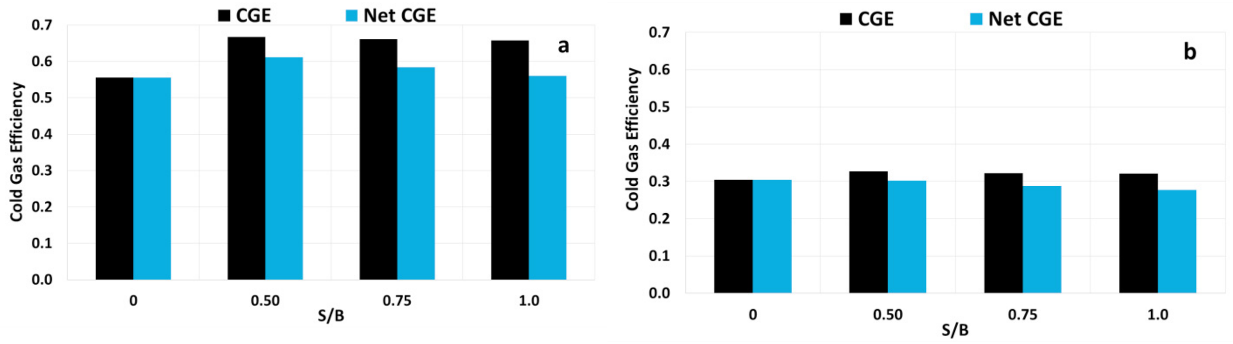

Fig. 4. Cold Gas Efficiency (CGE) and net CGE at different Steam to Biomass (S/B) ratios: Citrus Peel (a), Wood (b)

3.2. CHP application

In order to evaluate the potential applications of citrus peel gasification, for decentralized power production, a commercial combined heat and power (CHP) unit, based on internal combustion engine optimized for low-grade syngas, was considered. In particular, the CHP unit produced by General Electric (JMS – 316) was selected, whose rated electrical output is 516 kW. The main information from the data sheet are reported in Table 2.

Table 2. CHP unit data.

Combined Heat and Power production unit	
Rated thermal output [kW]	639
Rated electrical output [kW]	516
Rated electrical efficiency	0.36
Rated thermal efficiency	0.45
Spec. fuel consumption of engine electric [kWh/kWh$_{el}$]	2.75
Spec. fuel consumption of engine [kWh/kWh$_{th}$]	2.66
Hot water flow rate [m^3/h]	27.4
Exhaust gas temperature at full load [°C]	455
Exhaust gas mass flow rate, dry [kg/h]	3.563

The rated electrical and thermal efficiencies of the proposed CHP system at full load are 0.36 and 0.45, respectively. For this case study, it was decided to consider the gasification process working at 1023 K and S/B=0.5 where the citrus peel showed the highest cold gas efficiency. Moreover, at the above conditions, the producer gas composition (reported in the previous section) is in the range admitted by the CHP unit constructor.

According to the gasification efficiencies reported in section 3.1 and considering the electrical efficiency of the CHP unit, it is possible to calculate the amount of dry citrus peel that is needed to feed the proposed gasification-CHP system.

$$\dot{\mathrm{m}}_{\mathrm{dry\_biom}} = \frac{P_{el}}{\eta_{el}\,\alpha_{syn}\,LHV_{syn}} \qquad [kg/s] \tag{4}$$

where P_{el} is the electrical power output [W], η_{el} is the electrical efficiency of the CHP system, α_{syn} is the syngas yield [Nm^3/kg_{biom}] reported in Fig. 3, and LHV_{syn} is the lower heating value of syngas, expressed in J/Nm^3. From the above equation, the resulting dry biomass rate is about 469 kg/h. Furthermore, the syngas is available at high temperature and it is possible to recover heat from it (P_{syn} = 473 kW). It was considered to cool the syngas from 873 K to ambient temperature (298 K) neglecting the efficiencies of heat exchange and any heat losses (strongly dependent on plant conditions). Therefore, the global maximum efficiency [25] of the system at the considering operative conditions was calculated according to the Eq. (5):

$$\eta_{global} = \frac{P_{el} + P_{th} + P_{syn} - P_{steam}}{\dot{m}_{dry\_biom}\,LHV_{biom}} \tag{5}$$

where P_{th} is the CHP thermal power output that is recovered from the internal combustion engine and P_{steam} is the thermal power needed for steam production as gasification agent (about 365 kW_{th}). At the considered conditions, the global maximum efficiency of the system is about 57.5%.

In this work, citrus residues are considered as renewable sources of primary energy, and its exploitation for power production reduces the dependences from non-renewable primary energy sources. The non-renewable primary energy savings (PES_{NR}) were calculated as follow [26]:

$$PES_{NR} = E_{el} f_{ep-nren} + \frac{E_{th} f_{gp-nren}}{\eta_{boiler}} \tag{6}$$

where E_{el} and E_{th} are the electrical and thermal energy production of the gasification-CHP system in 8,000 h/year, respectively, $f_{ep-nren}$ and $f_{gp-nren}$ are the non-renewable primary energy factors for electrical energy (from the grid = 1.95) and for natural gas (1.05), respectively [27], and η_{boiler} is the efficiency of an industrial methane boiler (91%). In the proposed case study, PES_{NR} can be calculated using eq. 6 considering the same amount of electrical energy and hot water (produced by the gasification-CHP unit) obtained from the grid and with an industrial methane boiler. It results that the non-renewable primary energy savings were about 53,800 GJ/year.

4. Conclusion

A preliminary comparative study was developed for the gasification of citrus peels and pinewood in a fluidized bed reactor, using air and steam as gasification agents. A simulation model of the gasification system was also developed in order to obtain a reliable virtual tool for the development of future system scale-up of the plant. The model was validated comparing the syngas composition and syngas yields between experimental and simulated data, at different steam to biomass ratios (S/B). Both experimental and simulated gasification units were run at 1023 K, ER = 0.3 (air equivalence ratio) and variable S/B values (0, 0.5, 0.75, 1). The simulation model showed good fitting with experimental data for both biomass considered. At the selected operative conditions, the comparison of the gasification efficiencies (CGE) between pinewood and citrus peels. Can be noticed that the conversion in syngas is ineffective if the pinewood gasification process is carried out without steam, showing a net cold gas efficiency of about 30%. Furthermore, the addition of steam as gasification medium did not enhanced the gasification efficiency of pinewood. As opposite, citrus peels showed good reactivity both in air and air-steam atmosphere, reaching the highest net CGE = 0.61 at S/B = 0.5. However, the CGE could be further improved through the optimization of the air flow rate and temperatures. After model validation and the selection of the best operative condition, the potential of the combination of citrus peel gasification with a CHP unit was evaluated considering an internal combustion engine produced by

General Electric(model JMS – 316), whose rated electrical output is about 516 kW. The analysis of the global maximum efficiency of the gasification-CHP system was calculated and it is equal to 57.5%.

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