Biomass blend effect on energy production in a co-gasification-CHP system

Cite as: AIP Conference Proceedings **2191**, 020082 (2019); https://doi.org/10.1063/1.5138815
Published Online: 17 December 2019

A. Galvagno, M. Prestipino, V. Chiodo, S. Maisano, S. Brusca, and R. Lanzafame

Biomass blend effect on Energy Production in a Co-Gasification-CHP System

A. Galvagno[1,a)], M. Prestipino[1], V. Chiodo[2], S. Maisano[2], S. Brusca[1] and R. Lanzafame[3]

[1]*Department of Engineering, University of Messina, C.da Di Dio, Messina, 98166, Italy.*
[2]*Institute CNR-ITAE, via Salita S. Lucia sopra Contesse 5, Messina, 98126, Italy.*
[3]*Department of Civil Engineering and Architecture, University of Catania, Viale A. Doria, Catania, 6 - 95125, Italy.*

[a)] Corresponding author: agalvagno@unime.it

Abstract. Biomass is recognized as a reliable renewable energy source because its supply can be planned and it overcomes the problems related to the intermittency of other renewables. Furthermore, sustainable biomass supply chain allows considering this primary energy source as carbon neutral. To this regard, the use of local bio-residues from agro-industries can have a significant impact on the local economies and the local production of renewable energy. In a previous research study, the authors investigated the impact of the energy integration of citrus peel gasification in a citrus juice factory. The study showed that using citrus peel waste to produce heat and power through the biomass gasification-CHP system, the whole factory's energy demand cannot be covered. Also, due to the high ash content of citrus peel, it is recommended to operate the gasifier at moderated temperatures. In order to increase the production of electricity through the gasification-CHP system, it was decided to integrate the orange peel waste of the factory with a different kind of biomass. To this aim, this work studies the effects of citrus peel-woody biomass co-gasification on the process efficiency, using a thermodynamic simulation method. Indeed, after the validation of both woody biomass and citrus peel gasification models, the analysis of the co-gasification process has been developed employing a simulation model. The variation in terms of syngas composition, efficiency and yields of the process has been evaluated at different wood mass fraction (from 0.1 to 0.4 wt/wt) in the mix of wood/citrus peel biomass blend at 750°C, ER=0.3 and S/B = 0.5. The central element in the simulation flowsheet is the ideal Gibbs reactor, which makes use of different approach temperature in the single feedstock simulation. Two different model's configurations have been considered. The main differences consisted of the use of one or two Gibbs reactors. In the first case, the approach temperature was weighted according to the concentration of the two feedstocks, showing negligible differences compared with the other configuration with two independent Gibbs reactors at different temperatures approach. The results of the simulation model showed that both syngas yield and gasification efficiency showed slight variations as the woody fraction increases. In particular, the Cold Gas Efficiency (CGE) is around the values 0.59- 0.60 at the wood mass fraction that were investigated, while the syngas yield varies from 2.3 to 2.4 Nm^3/kg, respectively. The LHV of syngas increases as the wood fraction increases, varying from 4.35 MJ/Nm^3 (0.1 wood mass fraction) to 4.54 MJ/Nm^3 (0.4 woody mass fraction). In conclusion, the results allow determining the influence of mixing biomasses with different reactivity, in terms of conversion and thermal efficiency, in a gasification reactor operated at a moderate temperature, as well as the impacts on a possible gasification-CHP system.

INTRODUCTION

The growing need to reduce the environmental impact worldwide promotes a continuous development of processes and technologies aimed at a reduction of pollutant emissions. This has involved in the last years in research efforts in the field of energy efficiency [1], electrical and thermal energy storage [2,3] and the production of renewable energy

74th ATI National Congress
AIP Conf. Proc. 2191, 020082-1–020082-10; https://doi.org/10.1063/1.5138815
Published by AIP Publishing. 978-0-7354-1938-4/$30.00

vectors [4]. Among these, the production effective cleaner fuels is one of the main challenge. In prospective, attaining of such a goal would represent a milestone towards the exploitation of natural and renewable sources like biomass instead of oil as feedstock for fuel production [5]. Among renewable energy solutions, gasification is a flexible and reliable technology that converts, at high temperature (700–1000 °C) in the presence of an oxidant agent (air, steam, O_2 or CO_2), a solid carbonaceous feedstock (such as: biomass, coal, plastic, etc…) into a gaseous fuel (syngas) [6,7]. Syngas can be adopted for heating and power generation purposes [8-10], nevertheless the syngas composition depends on several factors such as reactor type, flow rate and characteristics of feedstocks [11], residence time, pressure and temperature of reactor and oxidant agent type adopted. In this context, bubbling fluidized bed reactors (BFB) present high potential for biomass gasification due to their optimum gas/solid contact, temperature control and flexibility in feedstock [12,13].

Agro-food waste (i.e. orange and citrus residues) represent a potential feedstock for energy application with its production of about 2 million tons gathered each year in different European countries [14-16]. Hence, conversion of citrus peels to bio-oil and/or chemicals by pyrolysis process was often proposed [16-21]; nevertheless, the high content of pectin species in these residues was predicted to lead at high concentrations of methanol and lower aromatics that affect bio-oil, mainly in terms of oxygenated content [19,20]. Authors recently explored the potential valorization of citrus peel residues through air-steam gasification process (at 750 °C, 1 bar) in order to produce hydrogen rich syngas operating both in fixed and fluidized bed reactor [21,22]. Experimental data revealed a maximum cold gas efficiency rate of 64%, at 850°C; S/B = 0.5 (wt/wt); and an H_2 yield of 0.65 $Nm^3/kg_{biomass}$ at 750°C and S/B = 1.25 (wt/wt) [23]. Further studies assessed the feasibility to use the amounts of citrus peels produced by a real juice company to supply a combined heat and power (CHP) system integrated with the juice factory production process. Results showed that, the integration of the gasification-CHP system into the juice industrial cycle could supply about 88% of the factory's demand [24]. However, the seasonal availability of the citrus residues resulted to be a critical factor affecting the syngas production during the year. A possible solution to this issue would be the mixing two or more biomass materials, available in the same area.

Although co-gasification of coal with different biomasses have been studied extensively [25,26], few works investigated the co-gasification of one biomass with the other in details. Among these, Sulaiman et al. [27] examined the co-gasification of wood chips and coconut waste in a downdraft gasifier and, in particular, co-gasification of biomass having different agglomeration tendency was explored. It has been reported that the agglomeration potential of the biomass reduces with the presence of calcium in biomass ash [28]. Thus, the co-gasification of blended fuel is expected to reduce agglomeration effectively. Kaewpanha et al. [29] studied co-gasified seaweed/Japanese cedar and reported the catalytic effects of alkali and alkaline earth metals on co-gasification. Alkali and alkaline earth metals improve gas yield, particularly in terms of the H_2 content. Aigner et al. [30] studied the effect of temperature on tar elements and quantity of tar produced during the steam co-gasification of wood pellets and wood/straw pellets. It was reported that the type of biomass blend has no significant effect on tar production compared to the temperature of gasification. He et al. [31] performed co-gasification of wood/straw, wood/miscanthus, and miscanthus/straw in order to identify the potential substitution of wood. H_2, CO, CH_4, and LHV increase as the miscanthus proportion increases in the blend, while the gas yield has no significant effect. In addition, a small quantity of $Ca(OH)_2$ in the blend improves syngas composition, LHV, gas yield, cold gas efficiency and carbon conversion efficiency. In another study, Pinto et al. [32] co-gasified rice husk and rice straw to minimize the associated problem of ash agglomeration and seasonal availability of feedstock. Saw and Pang [33] described interaction between lignite and wood, in a co-gasification experiment in a bubbling fluidized bed. Different ratios of each component were tested, the optimum blend consisting of 40% lignite and 60% pine sawdust. Producer gas yield and composition depicted non-linear correlations, tar yield and concentration being reduced with increasing lignite fractions. Given this, the co-gasification of biomass and several different types of wastes often revealed synergetic effect, as the final products showed enhanced properties when compared to each of the fuels by themselves. The most evident explanations rely on the interactions of molecules during pyrolysis and on the hydrogen transfer from waste polymers to biomass derivatives [32]. Hence, this kind of mixed-fuels can help to solve problems related to the unsteady accessibility of biomass and its unfixed composition, enhancing its utilization and rationalization. Nevertheless, the diversity found in the properties of the new combined fuel, its blending ratio and possible interactive effects during co-gasification are still a matter open of research. In this context, the main goals of this paper is to investigate the effect of blending ratio on syngas composition and performance of co-gasification of blended feedstock of wood (white pine) and citrus peels. This investigation is carried out by means of a simulation model of the gasification process, with the aim of assessing its validity with a blended feedstock. The model validation has been carried out in a bench-scale fluidized bed reactor.

Furthermore, the effects of the mixed biomass used as feedstock on the performance of an integrated gasification process with a combined heat and power unit (CHP), with an electrical output of 612 kW, are also evaluated in order to assess the gasification-CHP system efficiency at different feedstock blend mix.

Nomenclature

Abbreviations and symbols		Subscripts	
CGE	Cold Gas Efficiency	syn	Related to syngas
HHV	Higher Heating Value [MJ/kg]	biom	Related biomass
LHV	Lower Heating Value [MJ/kg]	db	Related to dry basis
S/B	Steam to Biomass mass ratio	*st*	Related to steam (gasification agent)
CHP	Combined Heat and Power	air	Related to air (gasification agent)
H_2GE	Hydrogen Gasification Efficiency	el	Related to electricity
H	Heat stream [kWh]	th	Related to thermal energy
η	efficiency	gas_th	Related to the thermal performance of the gasifier
TA	Temperature Approach [°C]	gas+CHP	Related to the system of gasifier coupled with the CHP unit
BFB	Bubbling Fluidized Bed	wet15%	Related to 15% of moisture content
$\dot{m}$	Mass flow rate [kg/h]		

MATERIALS AND METHODS

Simulation Model

The simulation of the gasification system was performed by modeling the different thermochemical phases that occur during the conversion of solid biomass into gas. The model was developed by means of ASPEN Plus simulation software. Indeed, in the biomass gasification process it is possible to identify four main steps of conversion: drying, pyrolysis, gasification and combustion (which can be split in oxidation and reduction reactions). Biomass is not a pure component, therefore, is included in the model as a Non-conventional component, which is mainly described by ultimate and proximate analysis. The approach used to simulate the gasification process needs experimental data of the pyrolysis steps in order to determine the yield of char, gas and tar of this step. The detailed description of the simulation model made by the authors is described in previously scientific paper [21]. After the Pyrolysis unit, the elements composing the solid, the liquid, and the gas products of pyrolysis, are directed to the block that represents the gasification and combustion phases of the whole gasification process, which is indicated hereinafter as gasification block. This is described by an ideal Gibbs reactor block (RGibbs block) where the reactions with the gasifying agents (steam and air) take place. This block is based on the minimization of Gibbs free energy, though the gasification and combustion phases are not at equilibrium conditions, involving large deviations between experimental and simulated data. Hence, a restricted chemical equilibrium method is applied in order to compensate these differences using a Temperature Approach (TA). The two independent simulation model of citrus peel and wood were validated in range of steam to biomass ratios in a previous work [34]. The authors found out that a single TA of the Gibbs reactor for each biomass considered can be used in the steam to biomass range 0.5-1.2. Nevertheless, the optimal TA is biomass specific, being -190°C and -170°C for citrus peel and wood respectively. In this work, a simulation model of the co-gasification process is developed. In particular, a feedstock blend of citrus and wood is used instead of a single biomass. In this case, the steps of the gasification process that are prior to the gasification reactor (i.e. drying and pyrolysis decomposition) are the same for both biomasses in the feedstock blend. Hence these steps are conducted separately and are grouped inside two Hierarchy blocks, as described in Figure 1, in order to improve the graphic display of the model. The streams outbound from the Hierarchy blocks are then conveyed into a common Gibbs reactor

(GASMIX), set at 750°C and S/B=0.5. The mass flow of the single biomasses varies according to the blend ratios. In particular, the wood mass ratio varied from 0.1 to 0.4, while the complement is citrus peel. Hence, inputs of this ideal thermodynamic reactor are the gasification agents (i.e. air and steam), and the outputs of the pyrolysis steps of the two feedstocks. Since a common Gibbs reactor is used for modeling the gasification step, the actual TA is obtained by weighing the TA of the two biomasses proportionally to the respective blend mass fractions. The output of the GASMIX block is a wet syngas at 750°C, which is cooled to 650°C in order to take into account the heat losses, which are modeled with a cooler (HEATLOS block). The sensible heat of wet syngas at 650°C is used to produce steam used as gasification agent at 220°C and 2 bar. The syngas stream leaves the heat exchanger for the steam production with an energy content high enough for heating the air necessary as a gasifying agent at 200°C. Heated the gasification agents, they are mixed before entering into the gasification reactor. Since in this work the syngas cleaning section is not investigated, the lower temperature limit of syngas cooling for heat recovery is set to 200°C in order to avoid tar condensation before the syngas cleaning section. Indeed, some syngas cleaning technologies could not involve the possibility of heat recovery. Hence, the further temperature reduction of syngas is modeled by two heat exchangers. The first (HEATREC) allow recovering heat for a potential user, while the second (SYNTREAT) models the temperature reduction to room conditions after the syngas cleaning steps, followed by a flash separator that splits water from the syngas stream. The simulation model of wood/citrus co-gasification is experimentally validated in a bench scale fluidized bed reactor. The validation is necessary to determine whether a single weighed temperature approach (i.e. a single Gibbs reactor) can or cannot describe the co-gasification behavior of the two biomasses that have been investigated. The experimental procedure and set-up are described in the following section.

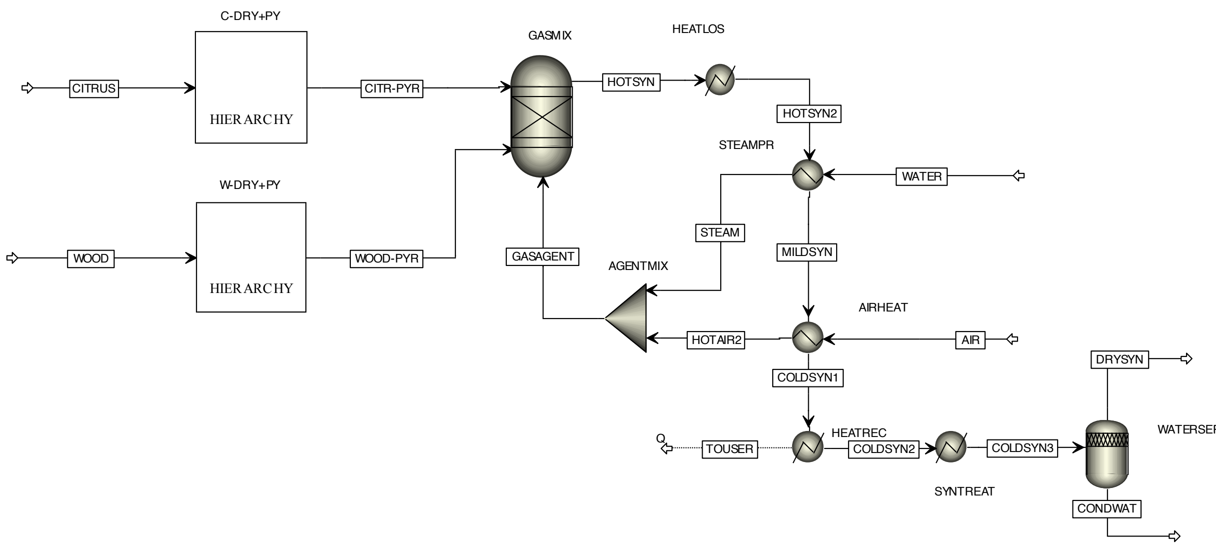

FIGURE 1. Flowsheet of the co-gasification simulation model

After the model validation, a sensitivity analysis is carried out by varying the wood mass ratio in the feedstock blend in order to assess its impact on the biomass conversion yield and energy efficiencies.

In particular, syngas yield, cold gas efficiency (CGE), gasification thermal efficiency ($\eta_{gas_{th}}$) and hydrogen energy efficiency (H_2GE) are considered as the main outputs of the sensitivity analysis. The cold gas efficiency express the capacity of the system to transform the chemical energy of the feedstock into the chemical energy of syngas. The gasification thermal efficiency, instead, includes the heat recoverable from syngas cooling (H_{syn}), with a ΔT of 450°C, to which the required energy heating the gasification agents must be removed (i.e. steam production at 220°C (H_{st}) and heating air from room temperature to 200°C (H_{air})). The energy losses of the system, including energy contained in non-converted char and tar, as well as the thermal losses, can be deduced from the complement of $\eta_{gas_{th}}$. Since a possible application of syngas utilization is hydrogen production, the H_2GE was indeed evaluated. It indicates the maximum theoretical efficiency in converting the chemical energy of biomass in the chemical energy of hydrogen. CGE, $\eta_{gas_{th}}$, and H_2GE are formally expressed in Eq. 1, 2 and 3 respectively.

$$CGE = \frac{LHV_{syn}\,\dot{m}_{syn}}{\dot{m}_{db}\cdot LHV_{biom}} \tag{1}$$

$$\eta_{gas\_th} = \frac{LHV_{syn}\,\dot{m}_{syn}+H_{syn}-H_{air}-H_{st}}{\dot{m}_{db}\cdot LHV_{biom}} \tag{2}$$

$$H_2GE = \frac{LHV_{H2}\,\dot{m}_{H2}}{\dot{m}_{db}\cdot LHV_{biom}} \tag{3}$$

$$\eta_{gas+\mathrm{CHP}} = CGE\cdot(\eta_{th}+\eta_{el}) \tag{4}$$

In the above equations, the lower heating values (LHV) of biomass and syngas and their mass flow rates ($\dot{m}$), are referred on a dry basis. In addition, the potential efficiency of a gasification-CHP system can been calculated multiplying the CGE by the sum of electrical and thermal efficiencies (Eq.4) of a CHP system based on an internal combustion generator fed by syngas operated at full load [23].

Experimental set-up

Gasification experiments were carried out at 750°C and atmospheric pressure in a bench-scale bubbling fluidized bed (BFB) reactor (i.d. 27 mm, H=475 mm). Figure 2 reports a description of the BFB plant, elsewhere described [21].

FIGURE 2. BFB bench-scale gasifier

The produced syngas was analyzed by a Pollution Vega micro-GC and the stream gas composition was determine as the average point of ten measurements. Gasification tests were performed at equivalent ratio (ER) equal to 0.3 and with steam to biomass ratio of 0.5 wt/wt. The air amount needed for the gasification process was calculated considering both the ultimate-proximate analysis (Table 1) and the amount of biomass fed (citrus peel and wood). Before each test all biomasses were shredded and sieved into a size range of 0.4<d<1 mm, successively, the resulted samples has been dried and conserved in an electric oven at 80°C.

TABLE 1. Ultimate and proximate analysis of Wood and Citrus Peel

Ultimate Analysis [%wt_{db}]					
	C	H	N	S	O[a]
Wood	52.7	5.9	0.5	1.4	38.5
Citrus peel	43.0	6.3	1.3	0.1	40.8

	Proximate Analysis [%wt_{db}]				HHV_{db}*	LHV_{db}*
	Moisture	VM	FC	Ash	[MJ/kg]	[MJ/kg]
Wood	7.6	74.2	17.4	0.8	21.54	20.51
Citrus peel	8.0	71.9	19.6	8.5	18.0	16.66

a. by difference; *HHV = 0.3491C + 1.1783H + 0.1005S – 0.1034O – 0.015N – 0.0211A [21]

RESULTS AND DISCUSSIONS

Gasification tests of citrus peel and wood mixtures were performed with different wood fraction ratio (0.1-0.4 wood/citrus peel), thus results were used to validate the model.

Figure 3 depicts the comparison between experimental syngas compositions (vol%) with simulation data. In particular, a good agreement of data confirms the goodness of the model that was verified for all mix ratios.

The H_2 yield is almost constant for all samples, however, a maximum value was observed with the 0.2 ratio blend (23.2 vol%). CO yields were undergone at a slight increase at higher blend ratios. Indeed, the highest CO yield was obtained from 0.4 mix ratio (8.5 vol%) that was nearly 2% higher than that obtained with 0.1 blend ratio (6.5 vol%). The CO_2 composition reported only a small decrease as the wood fraction increased (from 21.3 vol% to 20.6 vol%). While the CH_4 content in the syngas remained below 1.3%. This would suggest that the mix ratio did not reveal a significant effect on syngas composition; as observed by other authors about the effect of blending biomass ratio on co-gasification for syngas production [27,34].

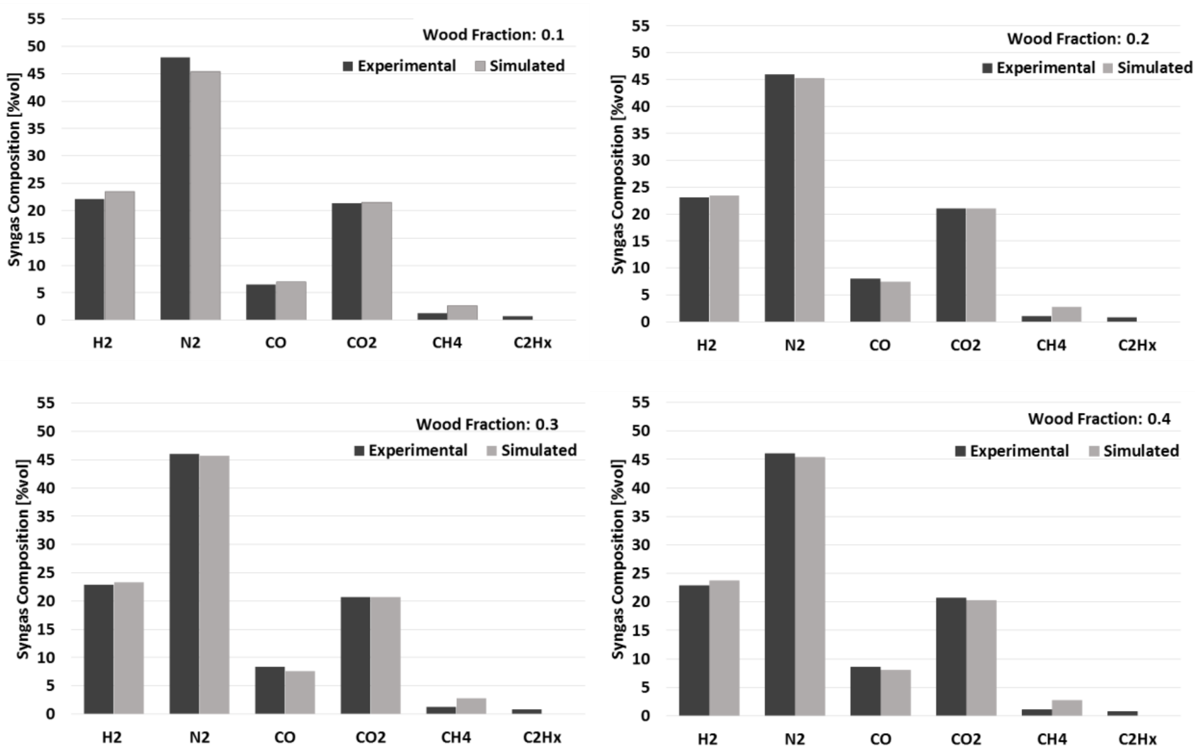

FIGURE 3. Simulation model validation by syngas composition at different wood mass fraction (0.1, 0.2, 0.3, and 0.4). Black columns experimental data, grey columns simulated data.

Figure 4 shows the sensitivity analysis of syngas yield (dashed line) and syngas lower heating value (solid line) when the wood mass fraction is varied in the range 0.1-0.4. The syngas yield, which expresses the normal volume of dry syngas produced per mass unit of dry biomass, increases slightly from 2.3 to 2.4 Nm^3/kg_{dbiom}, when the wood fraction is varied from 0.1 to 0.4. Hence, the syngas yield variation can be considered constant with a good approximation. Despite the slight increase of nitrogen concentration in the syngas stream, the constant values of syngas yield is due to increasing amount of air used as oxidant in the reactor when the wood fraction increases. This fact is due to the higher airflow rate that is needed to reach the same ER value when more wood is added. Indeed, higher carbon content in the feedstock requires higher oxygen demand. As regards the syngas LHV, it varies from 4.35 to 4.54 MJ/Nm^3 at wood mass fraction of 0.1 and 0.4, respectively. At the investigated conditions, the presence of wood in the feedstock blend positively affects the syngas heating values, which is consistent with the increase of the carbon monoxide concentration.

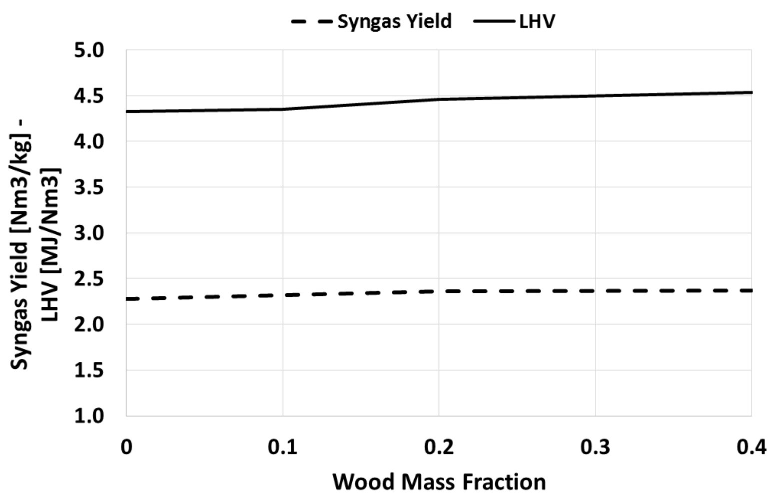

FIGURE 4. Sensitivity analysis of syngas heating values and syngas yield at 750°C and S/B=0.5

The combination of LHV and syngas yield leads to the CGE, as described in Eq. 1 and showed in Figure 5 along with $\eta_{gas_{th}}$ and H_2GE. Despite the slight increase of syngas yield and LHV with the wood mass fraction, the CGE can be considered constant, since it ranges between 0.59 and 0.60, due to the higher LHV of the wood compared to the citrus peel. Indeed, the higher wood fraction increases the energy input when the feedstock mass flow is constant. The $\eta_{gas_{th}}$curve has the same shape of CGE and values that are slightly higher than CGE. The $\eta_{gas_{th}}$ reflects the capacity of converting the input biomass chemical energy into syngas chemical energy and heat. In this study, the mix of syngas and steam is cooled from 650 to 200°C and the sensible heat is recovered. However, the recovered heat is used for steam production and for heating the air used as gasification agent. The very close values of $\eta_{gas_{th}}$and CGE underline that most of the recovered heat is used for heating the gasification agents. However, from the simulation model it has been determined that the net heat recovery from the syngas cooling section (i.e., obtained by subtracting the heat for air and water heating from the heat of syngas cooling) is positive. In particular, the net recovered heat varies from 0.48 to 0.49 MJ/kg_{dbiom}, explaining the very small difference between CGE and $\eta_{gas_{th}}$. These results show that the addition of wood in the air-steam gasification process of citrus peel has negligible effects on the CGE, while the heat recovery section does not contributes substantially to the global gasification efficiency at the investigated process conditions. The slight downward trend of H_2GE, shown in Figure 5, from 0.34 to 0.33 is due to the increased energy content of the input feedstock as the wood fraction increases and to the decreasing the hydrogen energy efficiency.

Assuming to use the syngas produced by the gasification plant through a CHP production system, the combined heat and power efficiency variation for the gasification-CHP system ($\eta_{gas+CHP}$ in Eq. 4) is evaluated and its trend is showed in Figure 5. In this work, an electricity production system, based on internal combustion engine developed for syngas utilization by Jenbacher, with 612 kW of maximum electrical power output is selected. Of course, the shape of $\eta_{gas+CHP}$ is the same of CGE, since the assumption of a constant engine electrical and thermal efficiencies has been considered in this work, which are 0.372 and 0.443 respectively. It is possible to observe that $\eta_{gas+CHP}$ can be considered constant around the value of 0.49. This value is obtained by the sum of electrical and thermal efficiencies of the combined gasification and CHP system, which are 0.22 and 0.27 respectively. The low value of electrical efficiency is the result of the relatively low temperature investigated in this work (750°C) and the significant amount of steam introduced into the reactor. Indeed, the use of a moderate temperature for the gasification process favors CO2 content in the syngas lowering the LHV. While high steam flow rates contribute to higher hydrogen and carbon dioxide formation from the water-gas shift reaction to the detriment of carbon monoxide.

From these results, it is possible to determine that the biomass feeding for the proposed gasification-CHP system is about 612 kg/h on dry basis (720 kg/h of feedstock with 15% of moisture), for an electrical power output of 612 kW at full load. The biomass feeding rate can be considered constant in the investigated wood fraction range, as it is for the $\eta_{gas+CHP}$ in Figure 5.

With regard to the specific case of citrus peel as feedstock the drying step is the most energy intensive one of the entire process [23], since this residue needs to be dried in order to reduce the moisture content from about 66% to 20% or lower. Considering the case of 15% of final moisture content in citrus peel, about 1.31 kWh/$kg_{wet15\%}$ are needed, taking into account a drying efficiency of 84% [23]. Hence, the addition in the feedstock of a biomass that has a lower original moisture content can improve the global efficiency of the combined gasification-CHP system. For instance, if wood is provided with 40% of moisture content, the heat need for 1 kg of feedstock with 15% of moisture content varies from 1.22 kWh/$kg_{wet15\%}$ to 0.96 kWh/$kg_{wet15\%}$ at 10% and 40% of wood mass content in the feedstock blend, respectively.

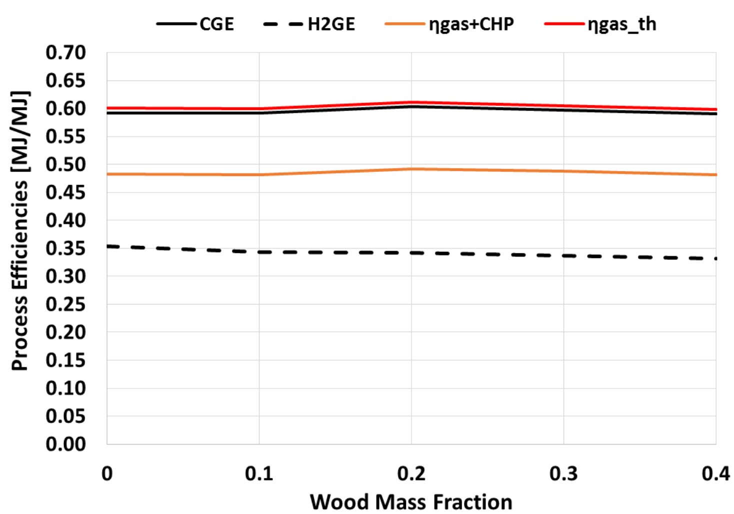

FIGURE 5. Sensitivity analysis of cold gas efficiency (CGE), gasification thermal efficiency (η_{gas_th}), hydrogen gas efficiency (H_2GE) and electrical efficiency (EE) for gasification coupled with a CHP unit (reciprocating engine, efficiency 37.5%)

CONCLUSIONS

In this work, the effects of biomass blends on the performance of air-steam gasification plant and the efficiencies of an integrated gasification-CHP system for decentralized power production were investigated. In particular, the feedstock considered was a mix of citrus peel and wood, with wood mass fraction in the range of 10% - 40%. The study was developed through a simulative and experimental approach on a laboratory scale under air-steam gasification conditions at 750°C and S/B=0.5. The main outcomes of the study can be summarized as follow:

- a preliminary study on the simulation model of wood/citrus peel mix gasification process showed that, in the investigated process conditions, two GIBBS ideal reactors using two different temperature approach gives the same results of a single GIBBS reactor with a temperature approach weighted on mass fraction of the single biomass present in the mix;
- the model validation of the mathematical model, made by experimental tests in a bench scale bubbling fluidized bed reactor, shows a good agreement between experimental and simulated data in all biomass mix used in terms of syngas composition;
- as far as the syngas composition a slight increase in the CO concentration and a slight decrease in CO2 concentration can be observed as the wood fraction in the mix increases. While there is no changes in the amount of hydrogen and methane in the syngas composition depending on wood mass fraction in the feedstock;
- the syngas LHV slightly increases with the wood fraction (from 4.35 to 4.54 MJ/Nm^3), due to the higher carbon monoxide concentration, while the syngas yield was almost constant, around 2.3-2.4 Nm^3/kg;
- the cold gas efficiency was about 60% and its variation were negligible when the wood mass fraction was varied at the investigated conditions;
- in terms of gasification-CHP system efficiency, if the syngas produced by the gasification plant is used for combined heat and power production (CHP), the overall efficiency follows the same trend of CGE (almost constant) achieving about 49% of the feedstock energy input;
- at the investigated conditions, woody biomass can be blended with citrus peel for mitigating the problems related to the seasonal features of citrus and heat requirement for drying the feedstock. This mixing makes it possible not to substantially compromise the performance of the gasification system and that of a possibly connected CHP unit.

REFERENCES

1. D. D'Agostino, D. Parker, Energy 149, 814-829 (2018).
2. Lai C.S, Jia, Y, Lai L.L, Xu Z, McCulloch M.D, Wong K.P. Renew Sustain Energy Rev, 78, 439-451 (2017).
3. E. Piperopoulos, E. Mastronardo, M. Fazio, M. Lanza, S. Galvagno, C. Milone, Applied Energy, 215, 512-522 (2018).
4. C. Gutiérrez-Antonio, F.I. Gómez-Castro, J.A. de Lira-Flores, S. Hernández, Renewable and Sustainable Energy Reviews, 79, 709-729, (2017).
5. W. Gądek, M. Mlonka-Mędrala, M. Prestipino, P. Evangelopoulos, S. Kalisz, W. Yang, E3S Web Conf, 10, (2016).
6. J. Schneider, C. Grubea, A. Herrmanna, S. Rönsch, Fuel Processing Technology 152, 72-82 (2016).
7. A. Demirbas, Energy Conversion Managment 49, 2106-2116 (2008).
8. P.S. Nigam, A. Singh, Progress Energy Combustion Science 37, 52-68 (2011).
9. D.H. Lee, C.P. Hung, International Journal of Hydrogen Energy 37, 17753-17765 (2012).
10. P. Adams, T. Bridgwater, A. Lea-Langton, A. Ross, I. Watson, "Biomass Conversion Technologies", in Greenhouse Gas Balance of Bioenergy System, edited by Patricia Thornley and Paul Adams (elsevier, 2018), pp. 107-139.
11. M. Prestipino, A. Galvagno, O. Karlström, A. Brink, Energy, 161, 1055-1063 (2018).
12. A. Molino, S. Chianese, D. Musmarra, Journal of Energy Chemistry 25, 10-25 (2016).
13. I.L. Motta, N. Toscano Miranda, R. Maciel Filho, M.R. Wolf Maciel, Renewable Sustainable Energy Review 94, 998-1023 (2018).
14. M. Prestipino, V. Chiodo, S. Maisano, G. Zafarana, F. Urbani, A. Galvagno, International Journal of Hydrogen Energy 42, 26816-26827 (2017).
15. V. Negro, B. Ruggeri, D. Fino, D. Tonini, Resources Conservation and Recycling 127, 148-158 (2017).
16. M. Volpe, D. Panno, R. Volpe, A. Messineo, Journal of Analytical Applied Pyrolysis 115, 66-76 (2015).
17. R. Miranda, D. Bustos-Martinez, C. S. Blanco, M.H. Gutiérrez Villarreal, M.E. R. Cantu, Journal of Analytical Applied Pyrolysis 86, 245-251 (2009).
18. Y.M. Kima, J. Jae, H.W. Lee, T.U. Han, H. Lee, S.H. Park, et al., Energy Conversion and Management, 125, 277-289 (2016).

19. B.S. Kim, Y.M. Kim, J. Jae, C. Watanabe, S. Kim, S.C. Jung, et al., Bioresource Technology 194, 312-319 (2015).
20. L. Aguiar, F. Marquez-Montesinos, A. Gonzalo, J.L. Sanchez, J. Arauzo, Journal of Analytical Applied Pyrolysis 83, 124-130 (2008).
21. M. Prestipino, V. Chiodo, S. Maisano, G. Zafarana, F. Urbani, A. Galvagno, International Journal of Hydrogen Energy 42, 26816-2682 (2017).
22. V. Chiodo, F. Urbani, G. Zafarana, M. Prestipino, A. Galvagno, S. Maisano, International Journal of Hydrogen Energy 42, 28048-28055(2017).
23. A. Galvagno, M. Prestipino, S. Maisano, F. Urbani, V. Chiodo, Energy Conversion and Management 193, 74-85 (2019).
24. J.S. Brar, K. Singh, J. Wang, S. Kumar, International Journal of Forestry Research 2012, 1-10 (2012).
25. L.Q. Wang, Z.S. Chen, Applied Thermal Engineering 59, 278-282 (2013).
26. M. Sharma, S. Attanoor, S. Dasappa, Fuel Processing Technology 138, 435-444 (2015).
27. S.A. Sulaiman, R. Roslan, M. Inayat, M. Yasin Naz, Journal of Energy Institute 9, 779-785 (2018).
28. V. Mettanant, P. Basu, J. Butler, The Canadian Journal of Chemical Engineering 87, 656-684 (2009).
29. M. Kaewpanha, G. Guan, X. Hao, Z. Wang, Y. Kasai, K. Kusakabe, et al., Fuel Processing Technology 120,106-112 (2014).
30. B. Buragohain, P. Mahanta, VS. Moholkar, International Journal of Energy and Environment 2, 551-78 (2011).
31. L. He, G. Kati, G. Matthias, Journal of Agricultural Science and Technology 2, 1109-1118 (2012)
32. A. Ramos, E. Monteiro, V. Silva, A. Rouboa, Renewable and Sustainable Energy Reviews 81, 380–398 (2018).
33. WL. Saw, S. Pang, Fuel 112, 117–24 (2013).
34. A. Galvagno, M. Prestipino, V. Chiodo, S. Maisano, S. Brusca, R. Lanzafame, Energy Procedia, 126:485-492 (2017).