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EXERGETIC ANALYSIS OF BIOMASS TORREFACTION AND GASIFICATION FOR POWER GENERATION IN INTERNAL COMBUSTION ENGINES

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Abstract. *The present work shows the exergetic analysis of the valorization of biomass using thermochemical processing for power generation in an IC engine. The producer gas compositions were predicted using a stoichiometric thermochemical equilibrium model and then simulated in an IC engine using ANSYS CHEMKIN PRO®. The compositions were predicted for bamboo, sugar cane bagasse, and rice husk for two different experimental torrefaction temperatures of 250 °C and 300 °C. Results indicated a positive influence of torrefaction in the gasification, making a producer gas more suitable to be used in internal combustion engines. The exergetic analysis of torrefaction was done both for each individual conversion process and for the system as a whole. The results showed that for the torrefaction of 300 °C the torrefier is the main source of exergy destruction due to the mass loss on the feedstock, while at 250 °C the gasifier is the main source of exergy destruction due to the thermochemical conversion. The overall exergetic efficiency increased for the three analyzed feedstocks for the torrefaction at the temperature of 300 °C. For the case of torrefaction at 250 °C, only bamboo benefited on the overall exergetic efficiency.*

Keywords*: Torrefaction, Gasification, Internal Combustion Engine, Energy Generation*

1. INTRODUCTION

Biomass is naturally grown around the world and has the potential to be one of the key resources that might be used by humanity to achieve the goal of a long-lasting energy production. However, the conversion efficiency of biomass in large scales is affected by factors such as its low energy density, hygroscopic and heterogeneous nature. For these reasons, its conversion requires pretreatment stages to achieve higher efficiencies.

Biomass can be separated into two categories, lignocellulosic or non-lignocellulosic. Non-lignocellulosic usually are used for nutritional purposes and are not considered in this study. The lignocellulosic are the non-starch and fibrous part of the plants that can't be digested by humans. They are usually agricultural waste composed mainly of organic compounds (Basu, 2013). Lignocellulosic biomasses are mainly composed of cellulose, hemicellulose and lignin, which are organic fibers that can be used to produce heat, electricity and other biofuels using appropriate conversion technologies. Detailed information about each kind of these fibers can be found in the work developed by Nhuchhen et al. (2014). Pyrolysis, gasification and direct combustion are the most common thermochemical processes that can be used in order to convert biomass into useful energy.

Gasification is the thermochemical process that happens with low air/fuel ratio and high residence time in order to convert a carbonaceous feedstock into a combustible gas mainly composed by hydrogen, carbon monoxide, carbon dioxide, and water, usually referred as syngas. If the gasifying agent used is air, there is significant presence of nitrogen and the product gas is called producer gas (Fiore, Magi, & Viggiano, 2020). The conversion temperature ranges between 700 to 1100 °C, depending on the type of gasifier and the reactants used. There are two main types of gasifiers, one is called fixed bed gasifier and the other is called fluidized bed gasifier, the designation of fluidized or fixed bed is related to the motion of the reactor bed (Arena, 2012).

Three main factors define the producer gas composition: the fuel composition, the type of gasifier used and the gasifying agent of this process. If high heating values are desired (10 to 40 MJ/Nm³), the gasifying agent needs to be pure oxygen, water vapor or carbon dioxide. Air gasifiers with agricultural biomass typically generate producer gas with low heating values (~5 MJ/Nm³) and compositions of 15~20% of H_2 15~20% of CO, 0-2% of CH_4, 10~15% of CO_2, 40~55% N_2 and traces of $O_2 \wedge C_xH_y$. The composition of the producer gas is not constant during the gasifier operation, for this reason, it is common to see published works with producer gas blended with other fuels in order to improve the combustion stability (Yaliwal & Banapurmath, 2021).

The producer gas from low gasification temperatures (700 °C) tends to have a higher heating value than those from processes that have higher temperature (1100 ºC) because the energy required to increase the process temperature comes from the oxidation of the fuel; On the other hand, increasing the temperature greatly increases the reaction rate and cracking of tars (Molino, Chianese, & Musmarra, 2016). For this reason, fixed bed gasifiers usually have low gasification temperatures and are indicated in the case of small and medium size processes while fluidized bed gasifiers have higher temperatures and are more feasible at large scales (Basu, 2013).

Most gasifiers operate in the range where the conversion to power in internal combustion (IC) engines is more cost effective than gas-turbines and steam turbines (Jradi & Riffat, 2014). The presence of tar, particles and the high temperature of the gas requires filtering and cooling of the producer to provide an adequate durability of the engine components (Martínez, Mahkamov, Andrade, & Silva Lora, 2012). Experimental results of internal combustion engines working with artificial producer gas can be found at (Muñoz, Moreno, Morea-Roy, Ruiz, & Arauzo, 2000; Silva, Lacava, Daniel, & Boggio, 2017), or using real producer gas (Rinaldini et al., 2017; Shah, Srinivasan, To, & Columbus, 2010; Vakalis, 2018; Wang, Yoshikawa, & Namioka, 2007).

Although raw biomass may be a good feedstock be used in a gasifier, it is necessary to be prepared to be properly gasified. The preparation is usually related to drying and cracking/chopping the biomass into pieces with homogeneous size. The moisture of the biomass is highly related to the process efficiency and drying it naturally usually decreases the content down to a minimum of 10%. The presence of moisture is unwanted in gasifiers because water take away a significant portion of the useful energy generated by the oxidation. For this reason, methodologies that decrease the moisture content as a pre-treatment are important to increase gasifying systems efficiency. Drying, leeching and torrefaction are largely studied as pretreatment processes.

Torrefaction is the thermochemical process where biomass is heated in the absence of oxygen to temperatures from 200 to 300 °C. This process may be used as a pre-treatment to others in order to improve the feedstock characteristics. The enhancements are related to removing the volatiles and cracking part of the feedstock fibers. After torrefaction, the feedstock usually has darker color and becomes more suitable to be crushed into smaller pieces. This happens because this pre-treatment process breaks portions of the fibers and rearranges them into finer structures. The biomass also loses part of its weight and increases its energy density, which makes it more suitable for transportation. For combustion and gasification processes, torrefaction improves the feedstock characteristics by decreasing the moisture content of the biomass and increasing C/O ratios (Prins, Ptasinski, & Janssen, 2006). The optimal temperature and residence time of the process depends on the type of biomass used and the types of fibers that compose the material. Unlike other processes, torrefaction needs a very slow heating in order to keep most of the solid products in the fuel (Kiel, 2005). Without catalysts, hemicellulose degradation starts at 200 °C, lignin at 250 °C and cellulose at 275 °C. At temperatures above 300 °C, thermal cracking of cellulose happens at a fast rate, which leads to tar formation and extensive devolatilization of cellulose and lignin, mitigating the torrefaction performance. That is why the upper limit of torrefaction temperature is 300 °C (Basu, 2013). The residence time of the process also depends on the particle's distribution and temperature of the reactor, and it is usually in the range of a couple of minutes to two hours.

The first law analysis is the conventional way of investigating whether the conversion process is efficient or not. However, the energy analysis cannot specify the quality degradation of energy in each process. In terms of power generation, the exergetic analysis usually is more efficient because it allows the evaluation of what are the most important sources of irreversibility and losses and thus, understand which systems are extracting useful work when it comes into equilibrium with its environment (Moran & Shapiro, 2006). Considering a first law analysis, it is known that torrefier-gasifier systems improve the conversion of biomass and will yield a gas with higher heating value (Lu et al., 2021; Machin et al., 2021; Prins et al., 2006). However, when it comes to exergetic evaluation of integrated systems, there are not many reports about the combined torrefaction-gasification process (Manatura, Lu, Wu, & Hsu, 2017) and no reports about the exergetic evaluation of integrated torrefier-gasifier-engine systems were found. Within this context, this work addresses an exergetic analysis of the integrated system torrefier-gasifier-engine to predict what is the influence of the torrefier-gasifier system in terms of quality of energy.

2. METHODOLOGY

The considered thermochemical process after torrefaction is gasification in a fixed bed downdraft gasifier. The dry biomass is considered to be fed into the torrefier, the torrefied biomass enters the gasifier, where the gasification happens at 800 °C. The producer gas leaves the gasifier at the same temperature and is used to heat up the torrefier. After exchanging heat in the torrefier, the producer gas is cooled and filtered, which makes it suitable to be fed in the IC engine at the ambient temperature.

The torrefied biomasses were taken from the experimental data of Chen et al. (Chen, Du, Tsai, & Wang, 2012) for bamboo, rice husk and sugarcane bagasse for the residence time of 60 minutes and temperatures of 250 and 300 °C. Figure 1. shows the schematics of the analyzed process. The producer gas composition is predicted using a thermodynamic equilibrium model derived from the methodology proposed by Zainal et al. (Zainal, Ali, Lean, & Seetharamu, 2001) for the three feedstocks with different torrefaction severity. The producer gas for combustion with air was simulated in an IC engine using the software ANSYS CHEMKIN PRO®.

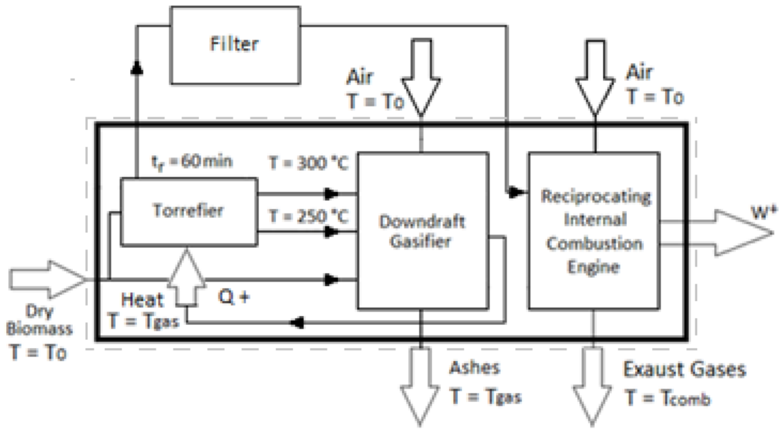

Figure 1. Schematics of the analyzed process

2.1. Prediction of syngas composition

There are two common methodologies to predict the syngas composition, namely, the stoichiometric method (Mendiburu, Carvalho, & Coronado, 2014) and the non-stoichiometric method (Mendiburu, Carvalho, Zanzi, Coronado, & Silveira, 2014). Both cases consider the composition of the feedstock and the producer gas to be in equilibrium and at permanent operation. For the prediction, only the most relevant chemical reactions involved in the process are considered to complement the mass and energy balances. In the case of this work, the stoichiometric method developed by Zainal (2001) was used with a consideration that part of the feedstock available energy would be lost on the ashes heating. The ashes were considered to be inert in the gasification reaction. The conservation of mass and energy are considered with the methanation and water shift reactions. This prediction method tends to have a higher hydrogen and lower carbon monoxide content in the producer gas composition (Melgar, Pérez, Laget, & Horillo, 2007), however, it does not change considerably in terms of energy available on the generated gas.

The thermodynamic properties of the syngas components were taken from the NASA GLENN coefficients (Mcbride, Zehe, & Gordon, 2002). The ashes composition and its thermodynamic properties were taken from Vassilev et al. (2010). The system of non-linear equations was solved in MATLAB using the Newton – Raphson method. To validate the model, the predictions were compared with the results of Zainal et al. (2001). Wood was the considered feedstock for comparison. The prediction error of the composition of the HHV of the yield gas was 4.60%, indicating that the methodology was a good reference to predict the working parameters and yield gas composition of a downdraft gasifier.

2.2. Simulation of combustion in the IC engine

The chemical reaction software (ANSYS CHEMKIN 17®) is a software widely used to simulate the pathways of chemical reactions. In this software, it is necessary to predetermine the thermodynamic data and consider kinetics mechanisms of the involved reactants and input the process parameters. In the current study, the improved mechanism developed by Curran et al. (1998), namely, n-heptane, was chosen because it covers a wide range of possible conditions pertinent to internal combustion engines (up to 40 bar). It covers 1550 species and 6000 reactions pathways for the saturated and non-saturated linear hydrocarbons up to C_7. The sub-mechanism $C_o - C_4$ from this version was used by Keromnes et al. (2013) to study the syngas combustion at elevated pressures and found good fitting between predictions and experimental data.

The considered engine is a single cylinder research engine with optical access coupled with PFI injection, which is the engine present in the laboratory of the authors. This setup was chosen because these results can be later compared with experimental investigation. The considered conditions of the engine are shown in Table 1, where CAD stands for crank angle degrees.

Table 1. Engine specifications

Component	Value
Total volume	530 cm³
Rotation	900 rpm
Bore	82 mm
Stroke	90 mm
Initial pressure	1 atm
Compression Ratio	8.8:1
Valves	4 (2 adm, 2 exaust)
Connecting Rod	144 mm
Stoichiometric Ratio	1.0

Chemkin-Pro software has three pre-determined modules that characterize the reactions in internal combustion engines, which considers the combustion chamber as a 0-D reactor. The used module was the Spark Ignition Zonal Model (SIZM), which is an intermediate approach between the 3-D CFD and simpler approaches to modeling the combustion phenomena. This module allows to a faster CFD simulation having the combustion reaction up to an acceptable degree of certainty. It consider the mass and energy transfer between predetermined zones inside the cylinder at the three stages of compression, combustion and expansion (Ansys, 2016). The rate of heat release, start of the spark and pressure parameters were considered from the experimental data developed in the same engine configuration (Boggio et al., 2018).

2.3. Exergetic analysis of the system

Moran & Shapiro (2006) define exergy as being a property of a state where the maximum theoretical work is obtained as it interacts with the environment until equilibrium, the ambient reference was established at 298K and 1 atm. The efficiencies related to the process control volume are shown in Table 2.

Table 2. Efficiencies related to the process

	Exergetic efficiency (η_{ex})
Torrefier	$\dfrac{b_{conv,fuel}}{b_{fuel} + Q_{ad}\left(1 - \dfrac{T_o}{T_{gas}}\right)}$
Gasifier	$\dfrac{b_{i,gas}}{b_{conv,fuel}}$
Engine	$\dfrac{W^+}{b_{i,gas}}$
Whole Process	$\dfrac{W^+}{b_{fuel}}$

where $W^+$is the net work of the system and b_{fuel} is the exergy of the raw feedstock; $b_{i,gas}$ is the exergy of the producer gas and $b_{conv,fuel}$ is the exergy from the torrefied feedstock.

The raw feedstock exergy was considered to be purely chemical. For the cases where torrefaction occurs, it was considered the feedstock to be delivered at the torrefaction temperature to the gasifier. The producer gas was considered to be at 25 °C and 1 atm when delivered to the engine.

2.4. Estimating the heat required from the producer gas to heat the torrefier

In order to achieve the torrefaction temperature, the maximum heat necessary is approximately 553.3 kJ/kg at 300 °C and 425.9 kJ/kg at 250 °C (Dupont, Chiriac, Gauthier, & Toche, 2014). For the energy available in the producer gas, the enthalpies are taken from Moran and Shapiro's (2006) properties tables between the gasification temperature and the torrefaction temperature. The increase in mass due to the addition of oxidant is also necessarily accounted. The heat available in the producer gas at 800 °C is given by

$$Q_{avail} = \sum y_i h_{i,T=800°C} - \sum y_i h_{i,T=T_{torrefaction}} = \frac{\dot{m}_{gas} - \dot{m}_{ashes}}{\dot{m}_{feed}} \sum y_i \left(h_{i,in} - h_{i,out}\right) \quad (1)$$

Where y_i is the number of mols and h_i is the enthalpy; The case of rice rusk torrefied at 300 °C yielded the producer gas with the minimum available heat, which is 1208 kJ/kg. Considering that only 553 kJ/kg are necessary to heat the biomass, no external source of heat is necessary for the torrefaction to occur.

2.5. Estimating the thermodynamic properties of the feedstock

The considered feedstocks are mainly composed by carbon, hydrogen and oxygen; with the presence small portions of nitrogen and traces of sulfur. The specific chemical exergy on molar basis is given by (Shieh & Fan, 1982):

$$\bar{b}_{ch} = 4.184 \cdot M_{comb} \cdot (8177.89[C] + 5.25[N] + 27892.63[H] + 4364[S] - 3173[O] + 0.15[O] \cdot (7837.6[C] + 33888.889[H] \quad (2)$$

where [C], [N], [H], [S] and [O] are the mass fraction of the chemical compound.

2.6. Estimating the thermodynamic properties of the producer gas

The chemical exergy of the producer gas can be estimated using the following equation (Pal, 2019):

$$\bar{b}_{ch,i} = \bar{h} - T_o\bar{s} - \sum\mu_{o,i}y_i = h_o - T_o s_o - \sum\mu_o y_i \quad (3)$$

where μ_o is the chemical potential at the unrestricted dead state, h_o is the enthalpy at the reference state, s_0 is the reference entropy and T_o is the reference temperature. For the case of this study, the reference values of chemical exergy are taken from Moran and Shapiro (2006).

2.7. Estimating the destroyed exergy in each process

The destroyed exergy related to each sub-system is shown in Table 3 (Moran & Shapiro, 2006).

Table 3. Efficiencies related to the process equipment

	Destroyed exergy (b_d)
Torrefier	$B_{raw,feed} + Q_i\left(1 - \frac{2 \cdot 298}{1073 + T_{torr}}\right) - B_{torref}$
Gasifier	$B_{producer,gas,hot} - B_{feed}$
Engine	$B_{producergas,cold} - W$
Whole Process	$\sum b_d$

3. RESULTS AND ANALYSIS

3.1. Valorization of the feedstocks in the torrefier

The influence of the torrefaction for the feedstock thermodynamic characteristics are in Table 4. When considering the feedstocks before and after torrefaction, the process has proven to be the best for bamboo, where the chemical exergy destroyed was 6,5% of the total exergy at 250 °C and 1,5% at 300 °C. This means that the weight loss is almost proportional to the increase in the heating value for this feedstock. For this case, the best torrefaction temperature is 300 °C.

For the case of rice husk, the exergy destroyed was 9,8% at 250 °C and 21,5% at 300 °C, which means that the weight loss was higher than the increase in torrefaction temperature for the two torrefaction temperatures considered. The temperature of 250 °C has shown to be the best option for the case of storing and transporting it.

For bagasse, there was virtually no difference between the chemical exergy before and after for the two torrefaction temperatures considering the mass loss. Since the temperature of the process is given by the hot producer gas, the valorization of bagasse could be done both at 250 and 300 °C without losing a considerable amount of exergy during the process.

Table 4. Estimated parameters of the feedstock

Material	Treatment	Composition	$M_{comb}\left[\frac{kg}{kmol}\right]$	$\bar{b}_{ch,estimated}\left(\frac{kJ}{kmol}\right)$	$\bar{b}_{ch,estimated}\left(\frac{kJ}{kg}\right)$	$\bar{b}_{ch,estimated}\left(\frac{kJ}{kJ_{raw}}\right)$
Bamboo	Raw	$CH_{1,3914}N_{0,1283}O_{0,6798}$	24,6711	455040	18444	1
	Torrefied (250 °C)	$CH_{1,1771}N_{0,1103}O_{0,4759}$	21,2089	469880	22155	0.9341
	Torrefied (300 ºC)	$CH_{0,8229}N_{0,0207}O_{0,2545}$	17,2516	468080	27133	0.9862
Rice Husk	Raw	$CH_{1,1972}N_{0,1797}O_{0,7270}$	27,6498	418420	15133	1
	Torrefied (250 °C)	$CH_{1,1563}N_{0,1748}O_{0,5220}$	24,9740	455210	18227	0.9073
	Torrefied (300 ºC)	$CH_{0,7117}N_{0,1082}O_{0,2384}$	21,6333	454310	21001	0.7841
Bagasse	Raw	$CH_{1,2109}N_{0,1294}O_{0,7133}$	25,8732	424410	16403	1
	Torrefied (250 °C)	$CH_{1,1244}N_{0,1244}O_{0,4856}$	22,6244	460070	20335	0.7904
	Torrefied (300 ºC)	$CH_{0,7885}N_{0,0512}O_{0,2071}$	18,2955	480077	25731	0.7845

3.2. Yield Gas Composition

Table 5 shows that torrefaction has a positive influence in the gasification process. For bamboo and bagasse, the heating value and the yield gas increased with more torrefaction. However, for rice husk, the HHV of the yield gas increased for torrefaction at 250 °C and decreased for torrefaction at 300 °C. This occurred because bamboo and bagasse have higher content of cellulose than rice husk (Nhuchhen et al., 2014), so the torrefaction temperature which fits best the rice is lower.

The torrefaction of the feedstock also decreased the predicted CO_2 content of the producer gas. Although it seems unlikely that a producer gas will have less than 1% of carbon dioxide in its composition, the composition is shown in dry basis, so at the conversion of the fuel hydrogen to water was more efficient than to CO_2.

Table 5. Yield gas parameters at 800 °C

Material	Treatment	Equivalence Ratio	Gas Yield (Nm³/kg)	Gas Yield $(kmol/kmo\ l_{fuel})$	CO [%]	H2 [%]	CO2 [%]	CH4 [%]	N2 [%]	HHV [kJ/Nm³]
Bamboo	Raw	0.33	2,412	2,657	25.80	20.03	9.15	0.52	44.50	5486.49
	Torrefied (250 °C)	0.34	2.915	2,760	29.28	18.13	5.31	0.43	46.85	5998.08
	Torrefied (300 ºC)	0.35	3.560	2,742	34.03	14.61	1.08	0.28	50.00	6241.29
Rice Husk	Raw	0.35	2.037	2,514	25.00	18.35	11.34	0.42	44.89	5260.70
	Torrefied (250 °C)	0.33	2.366	2,638	29.83	18.15	6.15	0.42	45.45	6037.59
	Torrefied (300 ºC)	0.37	2.895	2,796	33.40	12.69	1.61	0.21	52.09	5885.14
Bagasse	Raw	0.34	2.175	2,512	26.11	18.65	10.45	0.44	44.35	5470.98
	Torrefied (250 °C)	0.34	2.721	2,748	29.77	17.41	5.34	0.39	47.09	5962.18
	Torrefied (300 ºC)	0.35	3.421	2,794	34.67	13.97	0.16	0.26	50.94	6255.38

The hydrogen content decreased steeply for all three cases. This happened for two reasons, first because the moisture is reduced, and second because the higher heating value of the fuel enabled for a better conversion of hydrogen into water instead of carbon-to-carbon monoxide.

The torrefied bamboo gasification results are similar to the prediction results found by Kuo et al. (2014). Their work did not find many differences between the heating values of the gas, but found differences in the yield gas volumes. This difference occurred because the prediction model from this work considered that all carbon was converted, while their predictions considered different values of carbon conversion ratios.

Experimental results for torrefied rice husk in a fixed bed gasifier were not find in the literature, but the predictions found for raw rice husk were very similar to the ones found by Yoon et al. (2012). In their case, they used raw rice in a downdraft gasifier, which yield a syngas with $12\%H_2, 16\%CO, 10\%CO_2 \wedge 2,5\%CH_4$. The prediction model found higher contents of carbon monoxide and hydrogen in its composition, but just traces of methane. There are two conditions that influence that difference, one is that Yoon et al. (Yoon et al., 2012) did experiments at lower temperatures (600~800 °C), which tends to increase the production of $H_2 \wedge CH_4$ and decrease the production of CO. Another factor is that the prediction model accounted to the full conversion of carbon, which increases the heating value of the yield gas. The same validation can be applied to torrefied rice husk (250 ºC) when compared to the results found by Manatura et al. (2017) in a fluidized bed gasifier. Manatura et al. (2017) also found that the highest exergy efficiency of the gasification process happens for torrefaction at 250°C for the equivalence ratio of 0.3.

The prediction results for raw bagasse were very close to the ones found by Pellegrini and Oliveira Jr. (Pellegrini & De Oliveira, 2005). In their work, for the equivalence ratio of 0.35, the syngas composition was $25\%CO, 18\%H_2, 8\%CO_2, 44\%N_2$ and traces of methane. For torrefied bagasse, no experimental results were found in the literature, However, there is a simulation study conducted by Anukam et al. (2017), who found similar benefits to the ones presented in Table 5, but the composition of the yield gas was very different because they did simulations at higher temperatures, and thus, yield a gas with higher content of N_2 and CO_2, and lower contents of $H_2 \wedge CO$.

. Table 6. shows the estimated exergetic properties of the syngas. The first two columns refer to the chemical and physical exergy specific for the syngas components, while the third refers to the exergy considering the sum of both. As show in Table 5 the gas yield was between 2.51 and 2.80 Nm³/kg of fuel entering the gasifier. For this reason, it is necessary to make a correction between the specific physical exergy of the gas and the real exergy generated per kmol of pretreated fuel entering the gasifier, which is shown in column 4. Columns 5 and 6 refer to the exergy lost before and after the gasifier, not considering the weight loss due to torrefaction. It is noted that the process loses 17 to 23 % of the energy entering the gasifier when considering the physical exergy of the fuel, while it loses 25 to 31 % when not considering the temperature gain. The last two columns refer to the chemical exergy per kJ of raw fuel entering the process. This column considers the weight loss due to torrefaction according to the weight loss in torrefaction. The process of torrefaction and gasification together withdraws around 40% of the initial chemical exergy.

Since the physical exergy is considered to be used in the torrefier and it is cooled before entering the engine, only the chemical exergy is considered to be useful for the engine. In column 1, it seems that the best case for rice husk is torrefaction at 250 °C because it leads to a gas with higher exergy content. However, torrefaction at 300 °C leads to more gas being produced in the gasifier, so in column 7, when considering the energy of the raw feed entering the process and the cold gas, it is possible to notice which case is the best for the feedstocks considered.

For bamboo, torrefaction at 300 °C increased the useful exergy of the untreated feedstock from 71 to 74%, leading to an efficiency increase of 3%. For the case of rice husk and bagasse, the torrefaction loses the exergy yield in the syngas. At this point, if the yield gas is to be burned in a combustor, the torrefaction would only be important for the case of bamboo. However, it is important to notice that in column 3 the torrefaction at 300 °C leads to a syngas with a higher heating value for the three cases. The fuel with a higher heating value usually leads to higher efficiencies in engines, so it is still important to see the performance of the engine before getting into any conclusion of which case is the best for the three feedstocks considered.

Table 6. Yield gas thermodynamic properties, gasification at 800 °C

		1	2	3	4	5	6	7	8
Material	Treatment	$\overline{b}_{ch,mix}$ [kJ/kmol]	$\overline{b}_{ph,mix}$ [kJ/kmol]	$\overline{b}_{mix}$ [kJ/kmol]	$\overline{b}_{ch,mix}$ $[kJ/kmo\,l_{fuel}]$	$\overline{b}_{ch,mix}$ $[kJ/k\,J_{fuel}]$	$\overline{b}_{mix}$ $[kJ/k\,J_{fuel}]$	$\overline{b}_{ch,mix}$ $[kJ/k\,J_{raw}]$	$\overline{b}_{mix}$ $[kJ/k\,J_{raw}]$
Bamboo	Raw	121560	13571	135135	322985	0,7100	0,7896	0,7100	0,7896
	Torrefied (250 °C)	125340	13234	138575	345938	0,7362	0,8140	0,6877	0,7603
	Torrefied (300 ºC)	128390	12823	141212	352045	0,7521	0,8272	0,7417	0,8158
Rice Husk	Raw	114980	13680	128660	289060	0,6908	0,7730	0,6908	0,7730
	Torrefied (250 °C)	126930	13297	140223	334841	0,7356	0,8126	0,6674	0,7373
	Torrefied (300 ºC)	121690	12807	134498	340245	0,7489	0,8278	0,5873	0,6490
Bagasse	Raw	118730	13625	132360	298250	0,7027	0,7834	0,7027	0,7834
	Torrefied (250 °C)	124680	13215	137893	342621	0,7447	0,8236	0,5886	0,6510
	Torrefied (300 ºC)	128410	12738	141153	358777	0,7632	0,8390	0,5988	0,6582

3.3. Engine performance

The producer gases of Table 5 were simulated by Chemkin using the engine parameters of Table 1. The results are shown in Table 7, which does not consider the mass loss due to the torrefaction.

The indicated work varied between 0.2309 to 0.2411 kJ, being the highest for the bagasse that was torrefied at 300 °C. The IMEP was between 4.738 to 5.073 bar. These results are very similar to the experimental results of Boggio et al. (2018), where they found an IMEP of 4.6 for a syngas with LHV 20% higher. The torque varied between 17.92 and 19.19 N.m. Despite torrefied bagasse having the highest indicated power, the lowest specific fuel consumption and efficiency happened for the rice husk torrefied at 300 °C.

The torrefaction at 250 °C increased the thermal efficiency by only 1.5% for bamboo and bagasse, while it did not have any positive influences for rice husk. The torrefaction at 300 °C increased the engine performance by 6~7 % in all cases, which represents a gain of at least 50% in efficiency when compared to the combustion of syngas yield by the raw feedstock.

For the engine power, when not considering the mass loss, the 300 °C torrefaction showed to be the best option for the three feedstocks, where it increases around 0,100 kW of useful energy for the three scenarios analyzed.

Table 7. Engine Performance using the n-heptane mechanism

Feedstock	Treatment	Indicated Work (kJ)	Indicated Mean effective Pressure (bar)	Indicated Power 4-stroke (kW)	Torque (N.m)	Indicated Specific Fuel Consumption (g/kW-hr)	Indicated Thermal Efficiency (%)
Bamboo	Raw	0.2309	4.858	1.732	18.38	53.37	13.00
	Torrefied (250 °C)	0.2359	4.963	1.769	18.77	45.97	14.51
	Torrefied (300 ºC)	0.2406	5.061	1.804	19.14	34.97	18.73
Rice Husk	Raw	0.2252	4.738	1.689	17.92	50.75	14.98
	Torrefied (250 °C)	0.2365	4.975	1.774	18.82	45.46	14.58
	Torrefied (300 ºC)	0.2361	4.967	1.771	18.79	31.36	22.58
Bagasse	Raw	0.2284	4.806	1.713	18.18	50.23	14.50
	Torrefied (250 °C)	0.2355	4.955	1.766	18.74	44.01	15.36
	Torrefied (300 ºC)	0.2411	5.073	1.808	19.19	33.27	19.70

3.4. Exergetic balance of the process

With the results obtained from sections 4.1 to 4.3, it is possible to find the process efficiency accounting for the mass loss of the torrefaction and gasification. Table 8 shows the final results per equipment and also the overall exergetic efficiency of the process.

Table 8. Overall process efficiency and destroyed exergy per equipment

		Destroyed Exergy not considering the mass loss and mass flow of the gas yield ($kJ/k\,mol_{fuel,input}$)		Destroyed Exergy referenced to the raw feedstock, including the mass loss and mass flow of the yield gas ($kJ/k\,mol_{rawfeed}$)			Overall process
		1	2	3	4	5	Exergetic Efficiency
Feedstock	Treatment	Gasifier	Engine	Torrefier	Gasifier	Engine	%
Bamboo	Raw	319910	111800	-	319910	76551	9.23
	Torrefied (250 °C)	331310	115370	129900	226830	76226	9.97
	Torrefied (300 ºC)	326870	118220	170870	172590	85057	13.89
Rice Husk	Raw	289760	105460	-	289760	69910	10.34
	Torrefied (250 °C)	314990	116930	127250	202670	74715	9.73
	Torrefied (300 ºC)	319810	111710	210250	122210	61491	13.26
Bagasse	Raw	292050	109080	-	292050	73781	10.18
	Torrefied (250 °C)	322180	114720	178800	155430	63432	9.04

	Torrefied (300 ºC)	328920	118220	233350	93939	66705	11.80

Table 8 is divided in 2 sections, one where the destroyed exergy estimation does not consider the mass loss in the process and the other where the mass loss and the mass flow of the gas yield are considered.

Columns 1 and 2 are the results found if one chooses to put the control volume in the gasifier alone and the engine alone, not considering what happened before, meaning that these are the results in reference of each of these subsystems.

For the gasifier and for the engine, the destroyed exergy rises with the torrefaction when not considering the mass loss because the torrefaction makes a fuel with higher energy density, thus, there is more exergy able to be destroyed.

However, when considering the mass loss and the process itself, it is noted at columns 4 and 5 that the torrefier absorbs a huge part of the exergy from the raw feedstock and the mass loss is important enough to decrease the amount of exergy destroyed both in the gasifier and the engine.

When comparing the overall process with the mass loss, some inferences can be done. The torrefaction at of bamboo at 300 °C increased the process efficiency from 9.23 to 13.89%, increasing the energy conversion efficiency in approximately 50%, meaning that, for energy generation, the torrefier would be very necessary to increase the process efficiency.

Torrefaction of rice husk had the best efficiency also at 300 °C, increasing the efficiency from 10.34 to 13.26 %. The energy conversion efficiency was lower than for bamboo, and increased by 28%. It is important to notice that torrefaction at 250 °C actually decreased the efficiency of the process, meaning that the torrefier must have a very strict control in temperature to always keep it near 300 °C.

For bagasse, torrefaction at 300 °C increased the exergetic efficiency from 10,18 to 11,80 %, increasing the overall exergetic efficiency by 16%. The bagasse has shown to be the case where torrefaction led to a lower improvement.

In the case of raw feedstocks, the destroyed exergy is the highest in the gasifier due to the thermochemical conversion, which in this case, the products of gasification have a higher entropy. In the three analyzed cases the engine represented around 24% of the total exergy destroyed.

For the torrefaction at 250 °C and 300 °C, part of the exergy was destroyed in the torrefier due to the mass loss and part was destroyed in the chemical conversion between the raw and torrefied feedstock, most of the exergy was destroyed in the mass loss. In the column 5 of table 8 it is worth mentioning that the destroyed exergy in the engine relative to the raw feedstock did not vary more than 10% from the average in all the analyzed cases.

4. CONCLUSION

An exergetic analysis of the torrefier-gasifier-engine system was done. Torrefaction of feedstocks for gasification proved to be an excellent way to improve combustion of the producer gas in internal combustion engines. The exergetic analysis showed that for the torrefaction of 300 °C the torrefier is the main source of exergy destruction due to the mass loss in the process, while at 250 °C the gasifier is the main source of exergy destruction. The engine is in all cases the source that destroys the least exergy, because it is receiving gases whose combustion has a lower degree of irreversibility and it is actually converting part of the exergy into useful work. The overall exergetic efficiency increased for the three analyzed feedstocks for the torrefaction at the temperature of 300 °C. For the case of torrefaction at 250 °C, only bamboo benefited on the overall exergetic efficiency.

For the air blown gasifier considered at 800 °C, the destroyed exergy was lower for the cases with torrefied feedstocks, meaning that more useful energy from the feedstock could reach the engine. For the engine, the increase in efficiency was 25% for torrefaction at 250 °C and above 40% for the torrefaction at 300 °C. This efficiency could be improved more by increasing the compression ratio of the engine. The indicated power was increased by approximately 0,100 kW and the mechanical efficiency of the engine increased at least 15% by the presence of torrefaction. The authors intend to do further experimental studies to collaborate with the theoretical analysis done in this study.

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6. REFERENCES

Ansys, C. P. (2016). ANSYS Chemkin Tutorials Manual. *Design*, 1–274.

Anukam, A., Mamphweli, S., Okoh, O., & Reddy, P. (2017). Influence of torrefaction on the conversion efficiency of the gasification process of sugarcane bagasse. *Bioengineering*, *4*(1). https://doi.org/10.3390/bioengineering4010022

Arena, U. (2012). Process and technological aspects of municipal solid waste gasification. A review. *Waste Management*, *32*(4), 625–639. https://doi.org/10.1016/j.wasman.2011.09.025

Basu, P. (2013). *Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory* (2nd ed.). New York: Elsevier.

Boggio, S. D. M., Lacava, P., Silva, M., Merola, S. S., Irimescu, A., & Curto-Risso, P. (2018). *Effect of Air-Fuel Ratio on Syngas Combustion in an Optically Accessible Spark Ignition Engine*. https://doi.org/10.26678/abcm.cobem2017.cob17-0706

Chen, W. H., Du, S. W., Tsai, C. H., & Wang, Z. Y. (2012). Torrefied biomasses in a drop tube furnace to evaluate their utility in blast furnaces. *Bioresource Technology*, *111*, 433–438. https://doi.org/10.1016/j.biortech.2012.01.163

Curran, H. J., Gaffuri, P., Pitz, W. J., & Westbrook, C. K. (1998). A comprehensive modeling study of n-heptane oxidation. *Combustion and Flame*, *114*(1–2), 149–177. https://doi.org/10.1016/S0010-2180(97)00282-4

Dupont, C., Chiriac, R., Gauthier, G., & Toche, F. (2014). Heat capacity measurements of various biomass types and pyrolysis residues. *Fuel*, *115*, 644–651. https://doi.org/10.1016/j.fuel.2013.07.086

Fiore, M., Magi, V., & Viggiano, A. (2020). Internal combustion engines powered by syngas: A review. *Applied Energy*, *276*(March), 115415. https://doi.org/10.1016/j.apenergy.2020.115415

Jradi, M., & Riffat, S. (2014). Tri-generation systems : Energy policies , prime movers , cooling technologies , con fi gurations and operation strategies. *Renewable and Sustainable Energy Reviews*, *32*, 396–415. https://doi.org/10.1016/j.rser.2014.01.039

Kéromnès, A., Metcalfe, W. K., Heufer, K. A., Donohoe, N., Das, A. K., Sung, C. J., … Curran, H. J. (2013). An experimental and detailed chemical kinetic modeling study of hydrogen and syngas mixture oxidation at elevated pressures. *Combustion and Flame*, *160*(6), 995–1011. https://doi.org/10.1016/j.combustflame.2013.01.001

Kiel, J. H. A. (2005). *Torrefaction for biomass upgrading*. (October), 17–21.

Kuo, P. C., Wu, W., & Chen, W. H. (2014). Gasification performances of raw and torrefied biomass in a downdraft fixed bed gasifier using thermodynamic analysis. *Fuel*, *117*(PARTB), 1231–1241. https://doi.org/10.1016/j.fuel.2013.07.125

Lu, H., Gong, Y., Areeprasert, C., Ding, L., Guo, Q., Chen, W. H., & Yu, G. (2021). Integration of Biomass Torrefaction and Gasification based on Biomass Classification: A Review. *Energy Technology*, *9*(5), 1–20. https://doi.org/10.1002/ente.202001108

Machin, E. B., Pedroso, D. T., Machín, A. B., Acosta, D. G., Silva dos Santos, M. I., Solferini de Carvalho, F., … de Carvalho Júnior, J. A. (2021). Biomass integrated gasification-gas turbine combined cycle (BIG/GTCC) implementation in the Brazilian sugarcane industry: Economic and environmental appraisal. *Renewable Energy*, *172*, 529–540. https://doi.org/10.1016/j.renene.2021.03.074

Manatura, K., Lu, J. H., Wu, K. T., & Hsu, H. Te. (2017). Exergy analysis on torrefied rice husk pellet in fluidized bed gasification. *Applied Thermal Engineering*, *111*, 1016–1024. https://doi.org/10.1016/j.applthermaleng.2016.09.135

Martínez, J. D., Mahkamov, K., Andrade, R. V., & Silva Lora, E. E. (2012). Syngas production in downdraft biomass gasifiers and its application using internal combustion engines. *Renewable Energy*, *38*(1), 1–9. https://doi.org/10.1016/j.renene.2011.07.035

Mcbride, B. J., Zehe, M. J., & Gordon, S. (2002). *NASA Glenn Coefficients for Calculating Thermodynamic Properties of Individual Species*. (September).

Melgar, A., Pérez, J. F., Laget, H., & Horillo, A. (2007). Thermochemical equilibrium modelling of a gasifying process. *Energy Conversion and Management*, *48*(1), 59–67. https://doi.org/10.1016/j.enconman.2006.05.004

Mendiburu, A. Z., Carvalho, J. A., & Coronado, C. J. R. (2014). Thermochemical equilibrium modeling of biomass downdraft gasifier: Stoichiometric models. *Energy*, *66*, 189–201. https://doi.org/10.1016/j.energy.2013.11.022

Mendiburu, A. Z., Carvalho, J. a., Zanzi, R., Coronado, C. R., & Silveira, J. L. (2014). Thermochemical equilibrium modeling of a biomass downdraft gasifier: Constrained and unconstrained non-stoichiometric models. *Energy*, *71*, 624–637. https://doi.org/10.1016/j.energy.2014.05.010

Molino, A., Chianese, S., & Musmarra, D. (2016). Biomass gasification technology: The state of the art overview. *Journal of Energy Chemistry*, *25*(1), 10–25. https://doi.org/10.1016/j.jechem.2015.11.005

Moran, M. M., & Shapiro, H. N. (2006). Fundamentals of Engineering Thermodynamics. In *Fundamentals of Engineering Thermodynamics* (5th editio). WILEY. https://doi.org/10.1201/9780367816087

Muñoz, M., Moreno, F., Morea-Roy, J., Ruiz, J., & Arauzo, J. (2000). Low heating value gas on spark ignition engines. *Biomass and Bioenergy*, *18*(5), 431–439. https://doi.org/10.1016/S0961-9534(99)00101-4

Nhuchhen, D., Basu, P., & Acharya, B. (2014). A Comprehensive Review on Biomass Torrefaction. *International Journal of Renewable Energy & Biofuels*, *2014*, 1–56. https://doi.org/10.5171/2014.506376

Pal, R. (2019). *Chemical exergy of ideal and non-ideal gas mixtures and liquid solutions with applications*. https://doi.org/10.1177/0306419017749581

Pellegrini, L. F., & De Oliveira, S. (2005). Exergy analysis of sugarcane bagasse gasification. *ECOS 2005 - Proceedings of the 18th International Conference on Efficiency, Cost, Optimization, Simulation, and Environmental Impact of Energy Systems*, *32*, 393–400. https://doi.org/10.1016/j.energy.2006.07.028

Prins, M. J., Ptasinski, K. J., & Janssen, F. J. J. G. (2006). *More efficient biomass gasification via torrefaction*. *31*, 3458–3470. https://doi.org/10.1016/j.energy.2006.03.008

Rinaldini, C. A., Allesina, G., Pedrazzi, S., Mattarelli, E., Savioli, T., Morselli, N., … Tartarini, P. (2017). Experimental investigation on a Common Rail Diesel engine partially fuelled by syngas Dual Fuel operation. *Energy Conversion and Management*, *138*, 526–537. https://doi.org/10.1016/j.enconman.2017.02.034

Shah, A., Srinivasan, R., To, S. D. F., & Columbus, E. P. (2010). Bioresource Technology Performance and emissions of a spark-ignited engine driven generator on biomass based syngas. *Bioresource Technology*, *101*(12), 4656–4661. https://doi.org/10.1016/j.biortech.2010.01.049

Shieh, J. H., & Fan, L. T. (1982). Estimation of energy (enthalpy) and exergy (availability) contents in structurally complicated materials. *Energy Sources*, *6*(1–2), 1–46. https://doi.org/10.1080/00908318208946020

Silva, M. F., Lacava, P., Daniel, S., & Boggio, M. (2017). *Cobem-2017-0699 Characterization of Flame Development in the First Cycles of Operation in a Direct Injection Spark Ignition Engine Fueled With Anhydrous Ethanol*.

Vakalis, S. (2018). *Modeling the emissions of a dual fuel engine coupled with a biomass gasifier — supplementing the Wiebe function*. 35866–35873.

Vassilev, S. V., Baxter, D., Andersen, L. K., & Vassileva, C. G. (2010). An overview of the chemical composition of biomass. *Fuel*, *89*(5), 913–933. https://doi.org/10.1016/j.fuel.2009.10.022

Wang, Y., Yoshikawa, K., & Namioka, T. (2007). *Performance optimization of two-staged gasification system for woody biomass*. *88*, 243–250. https://doi.org/10.1016/j.fuproc.2006.10.002

Yaliwal, V. S., & Banapurmath, N. R. (2021). Combustion and emission characteristics of a compression ignition engine operated on dual fuel mode using renewable and sustainable fuel combinations. *SN Applied Sciences*, *3*(1), 1–15. https://doi.org/10.1007/s42452-020-03987-2

Yoon, S. J., Son, Y. Il, Kim, Y. K., & Lee, J. G. (2012). Gasification and power generation characteristics of rice husk and rice husk pellet using a downdraft fixed-bed gasifier. *Renewable Energy*, *42*, 163–167. https://doi.org/10.1016/j.renene.2011.08.028

Zainal, Z. A., Ali, R., Lean, C. H., & Seetharamu, K. N. (2001). Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. *Energy Conversion and Management*, *42*, 1499–1515.

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