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HYDROGEN-RICH SYNGAS PRODUCTION: AN CHP INTEGRATED SYSTEM WITH STEAM GENERATOR HEAT EXCHANGER AND GAS TURBINE FOR HYDROGEN PRODUCTION
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Abstract. *The use of hydrogen as source of energy clean it is being much discussed to mitigate carbon emissions, following this way, the present work indicates the steam gasification process as a route for hydrogen production, considering a circular economy of waste by doing gasification of RDF (Refuse-Derived Fuel). To understand the real conditions of hydrogen production by gasification proposed the integrated a gasification reactor witch a CHP plant (Combined Heat Power), making possible the generation of super-heated steam for the process with the addition of the production of electrical power in low CO2 emission. Therefore, the maximization of hydrogen in RDF gasification was investigated and parameters as process temperature, amount of steam an injected oxygen, showed great relevance in increasing the percentage of hydrogen contained in Syngas.*

Keywords: *Solar Gasification, Hydrogen, RDF, Circular Economy, CHP Plant*

1. INTRODUCTION

1.1 Hydrogen

The National Energy Plan 2050, prepared by the Ministry of Mines and Energy of Brazil in 2020, is a strategy that aims to decarbonize the Brazilian economy by reducing greenhouse gas emissions from the energy sector. This plan identifies hydrogen as a key element to achieve a cleaner energy matrix, as it can be produced from renewable sources. At the moment the main source of hydrogen it is non-renewable, and involves the methane gas reforming process through catalysts. Different of the methane the water is a renewable source and also rich in hydrogen, the use of this source in gasification promotes the enrichment of the percentual of hydrogen in the synthesis gas.

Gasification is a thermochemical process that transforms carbonaceous raw materials into syngas. This gas can be used as a clean fuel in industrial processes, converted into chemicals or used to generate electricity, offering a more sustainable and versatile alternative to fossil fuels. Other sub-processes, such as the pyrolysis process, partial oxidation of the raw material, water reduction, among others, are involved in gasification (Verissimo, 2014), the latter two described respectively by eq.1 and eq.2.

$$\text{Oxidação parcial: } 1C + \frac{1}{2}O_2 \rightarrow CO;\ \ \Delta H = -111MJ.kmol^{-1} \qquad \text{eq.1}$$

$$\text{Gás-Vapor: } 1C + 1H_2O \rightarrow 1CO + 1H_2, \Delta H = 131MJ.kmol^{-1} \qquad \text{eq.2}$$

Partial oxidation is a stage in which a reaction takes place between oxygen and the carbonaceous raw material, promoting the formation of carbon monoxide and releasing the heat that sustains the gasification process (BOLOY, 2010; Puig-Arnavat et al., 2010). In the reaction of eq.2, water vapor (H2O) reacts with carbon (C) present in the raw material, generated in the formation of hydrogen (H2) and carbon monoxide (CO). This steam reduction step is crucial in gasification, as hydrogen and carbon monoxide are the main components of the synthesis gas produced.

The first readily accessible reports of research on the use of solar flux in gasification reactors occurred through experimental means Gregg et al. (1980); Taylor et al. (1983). With the need for cleaner and carbon-free processes, new research was conducted. Kodama et al. (2008) propelled an internally circulating fluidized bed reactor into a downward-flowing bed, promising for industrial-scale solar coal gasification. Already (Piatkowski & Steinfeld, 2011) developed a gasification model for solar irradiation conditions, and an efficiency of 89.4% was achieved in the solar-chemical conversion for industrial sludge gasification. This present study uses chemical equilibrium to analyze RDF gasification with process heat provided by solar radiation and provides operating conditions of a CHP plant for power generation and hydrogen-rich Syngas. It also clarifies the increase in efficiency and percentages of Syngas in gasification with solar radiation, highlighting the importance of gasification in the energy transition to renewable energy sources.

1.2 Circular economy

In order to promote sustainability and minimize the environmental impact caused by solid urban waste, the adoption of sustainable approaches, such as the circular economy, should be encouraged by innovative policies. Circular economy is a sustainable model that proposes to minimize waste and consumption of finite natural resources. Unlike the traditional linear model, which follows the "take, make, use and discard" pattern, the circular economy seeks to close the loop, keeping materials in use for as long as possible through reuse, recovery, recycling and regeneration, promoting the idea that waste from one process can become resources for another.

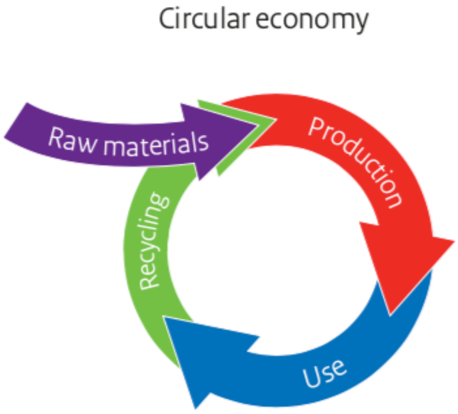

Figure 1: Circular economy diagram (RICHARD DIXON, 2021).

Gasification can be installed in this scenario as a waste-to-energy technology, using urban solid waste as carbonaceous raw material for the process, requiring a pre-treatment that converts the waste into an RDF. The adoption of RDF in the steam gasification process can, in addition to enabling the mitigation of greenhouse gas emissions, promote the reintroduction of waste in the production chain, reducing the exploitation of natural resources, specifically biomass.

2. MATERIALS

2.1 RDF

RDF was used to feed the gasification reactor, as similar to biomass it has good percentages of carbon needed in the gasification process, but it is not necessary to degrade the environment to obtain the input. The RDF used has ultimate analysis characterized by Phyllis, 2004 and is described in Table 1.

Table 1: RDF data used (Phyllis, 2004).

Proximate Analysis (%)	Wet	Dry
Moisture Content	5,20	-
Ash Content	7,37	7,77
Volatile Matter	79,87	84,25
Fixed Carbon	7,57	7,98
Ultimate Analysis (%)		
C	52,49	55,37
H	10,83	11,42
O	23,42	24,70
N	0,28	0,30
S	0,01	0,01
HHV (MJ/kg)	26,19	30,87

2.2 Gasification integrated into a CHP plant

If the analysis conditions are not real, there is no reason in investigating parameters that contribute to the increase in the percentage of hydrogen. Therefore, it is proposed the elaboration of a CHP plant with integrated gasification in a way that makes it possible to analyze the gasification in conditions possible to reach in practice, even limits in the recovery of heat for steam generation from the flue gases coming from a gas turbine. The proposed plant is illustrated in Figure 2 containing a pressurized gasification reactor, a gas turbine of model M1A-17 of the AMA Energy and a steam generating heat recovery boiler.

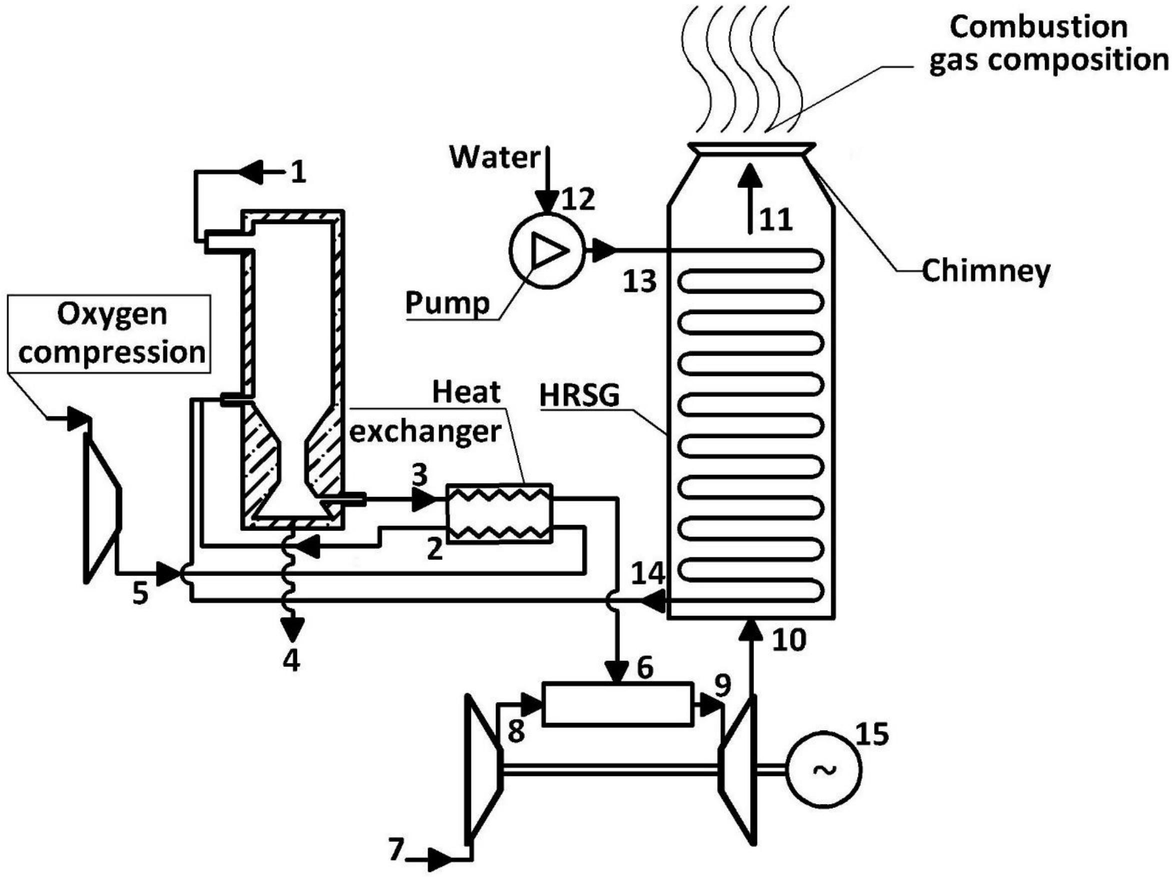

Figure 2:Proposal for a gasification reactor integrated into the CHP plant.

Still in Figure 2, the carbonaceous material to be gasified by the reactor is fed at point 1 followed by the gasifying agent's oxygen and water vapor, point 2 and 14 respectively. Point 3 is the output of synthesis gas from the reactor and the input of a heat exchanger responsible for increasing the oxygen temperature at the reactor inlet. After giving up heat to oxygen, the synthesis gas enters the combustion chamber at point 6 with a higher specific mass and at the combustion pressure, the combustion chamber is fed with compressed atmospheric air between points 7 and 8, combustion takes place and flue gases are expanded in the turbine between points 9 and 10. The heat contained in the flue gases is recovered by the boiler between points 10 and 11 to generate steam, the boiler is fed with pressurized water just above the gasifier pressure between points 12 and 13.

3. METHOD

All the operating conditions of the gasification integrated in the CHP plant are obtained from numerical simulation carried out in the EES Software (Klein & Nellis, 2012). The gasification process is analyzed using a chemical equilibrium numerical model described and validated by Silva et al., 2020. The gas turbine is simulated using the Brayton thermodynamic cycle and the heat recovery boiler is dimensioned using the NUT efficiency method, both modeling described by J. C. SILVA, 2022.

In the gasification simulations, the flow of RDF fed into the reactor is permanently set at 50 kg/h, as well as the efficiency of converting carbon into gas, which is 98%, and the heat losses involved in the reactor, which are 10%. The ratio between oxygen and RDF is Φ=3[-] or Φ=infinity [-], the latter considering that there is no oxygen supply, using only water vapor as gasifying agent.

For the functioning gas turbine set to the following parameters: isentropic efficiency of 90% for the turbine, 85% for the compressor, a compression ratio of 6[-] in the compressor, and a pressure loss of 0.015 bar in the combustion chamber. More details are in Table 2 and Table 3. Using the operating conditions described, the influence of the gasifying agent steam on the process temperature and on the calorific value of the synthesis gas was analyzed. For this, the oxygen and RDF ratio was kept constant at Φ=3[-] which provided a flow of 31.57 kg/h of oxygen in the process. The steam mass was increased according to eq.3, where $\dot{m}_{Steam}$ is the steam flow that participates in the gasification process according to a percentage x of the mass flow rate $\dot{m}_{RDF}$ of RDF. The result can be seen in Figure 3 and Figure 4.

$$\dot{m}_{Steam} = x * \dot{m}_{RDF} \quad \text{eq.3}$$

Another analysis was performed by keeping the gasification process temperature constant at 1154 K, which allowed using only steam as the gasifying agent. The amount of injected steam was also kept constant, while the participation of injected oxygen in the process was gradually reduced to levels close to zero, which could not be reset due to code limitations such as divisions by zero. The process heat needed to maintain the set temperature in the analysis can be supplied from external sources. The results are shown in Figure 5.

4. RESULTS

4.1 CHP Plant

The integration of a gasification plant with a CHP (Combined Heat and Power) plant allows the generation of energy and heat recovery for steam generation, which is used here as a gasifying agent. The Figure 2 illustrates the plant proposed by this study, the points of thermodynamic states are specified according to Table 2. In this operating condition, 99 MW was generated, the maximum amount of steam generated by the boiler is close to 304 kg/h, the composition of the synthesis gas obtained is 50,04 % for H2; 32,74 % for CO; 15,42 % for CO2; 1,81 % for CH4; where the efficiency of the cold gas is of 76,26 % and the lower calorific value of 13,223 MJ/kg. And the composition of the combustion gases of the gas turbine when leaving the boiler is 51,84 % of H2O and 48,15 % of CO2.

Table 2: CHP plant operating data.

Point	Substance	Pressure (**Bar**)	Temperature (**K**)	Flow rate mass (**kg/h**)	Enthalpy - Δh (**kJ/kg**)	Power Generated (**MWh**)
1	Input of RDF	-	300	50	-111733	-
2	Input of Oxygen	7,9645	807,8	31,57	503,9	-
3	Synthesis gas	6,1	1154,1	92,03	-63368	-
4	Output of Ash	-	-	1,82	-	-
5	Oxygen	8	513	31,57	203,5	-
6	Syngas	6,0645	346,2	92,03	1343	-
7	Air	1,0365	300	1380,6	300,4	-
8	Air	6,212	497	1380,6	500,3	-
9	Fuel gas	6,2	1255	1472,4	-9,087	-
10	Fuel gas	1,0365	845,4	1472,4	-9,868	-
11	Fuel gas	1,01325	829,5	1472,4	-9,897	-
12	Water	1,0365	300	12	112,7	-
13	Water	7,98	300	12	113,3	-
14	Input of Steam	7,965	807	12	3555	-
15	Electricity	-	-	-	62,45	99,09

The function of the heat recovery boiler in the proposed CHP plant in this study is to utilize the residual heat from exhaust gases to generate steam for the gasification process. However, for this to be achieved effectively, a well-designed heat exchanger is required. To optimize the operation of the boiler, the Pinch Point analysis was employed, which is crucial when designing heat recovery boilers. It allows for the evaluation of the thermal efficiency of the system while respecting the second law of thermodynamics. The Pinch Point analysis involves determining the minimum feasible temperature difference between the exhaust gases and the feedwater. This temperature difference, known as the "Pinch Point" (ΔT_PP), plays a key role in maximizing the heat transfer between the fluids. When designing the heat exchanger, it is essential to ensure that the Pinch Point is low enough to allow for efficient heat transfer, but not too low. A very low Pinch Point can cause overheating in the walls of the heat exchanger, significantly increase its size, and raise project costs. The Pinch Point analysis in this study indicates that the required temperature difference to meet the steam production required for gasification is ΔT_PP = 388.8 K, which enables a maximum mass flow rate of feedwater steam of $\dot{m}_{Steam}$ = 12 kg/h. A ΔT_PP below this temperature difference leads to excess steam generation. Table 3 presents the operating characteristics and dimensions of the boiler.

Table 3: Operation data and dimension of the heat recovery boiler.

Variable	Value
Inlet gas temperature	845,4 K
Outlet gas temperature	829,5 K
Inlet water temperature	300 K
Outlet water temperature	807 K
Average CP of flue gases	1680 (J/kg)K
Average CP of Water	3351 (J/kg)K
Operating Pressure	8 bar
Δ Pressure	0,1013 bar
Combustion Gas Flow	0,409 kg/s
Water Flux	0,0033 kg/s
Total Heat Transferred	10,96 kW
super heater	0,1863 m²
Evaporator heat	0,18544 m²
Economizer heat	0,04331 m²

4.2 Gasification

When making the increment of steam injected into the reactor, it is observed in Figure 3 the linear drop in the temperature of the gasification process, followed by a reduction in the conversion of the steam participating in the process into hydrogen. This reduction in temperature and in the $^{H_2}/_{H_2O}$ ratio is due to the chemical reactions represented by eq.2, which are extremely endothermic and the increase in the percentage of steam, even when injected in a superheated state, requires greater energy for these reactions to occur, resulting in the temperature reduction. The lower calorific value reduction of the gas LHV_{gas} shown in Figure 4 also occurs due to the need for more energy for more steam injected into the process, as indicate by Babu & Sheth, 2006.

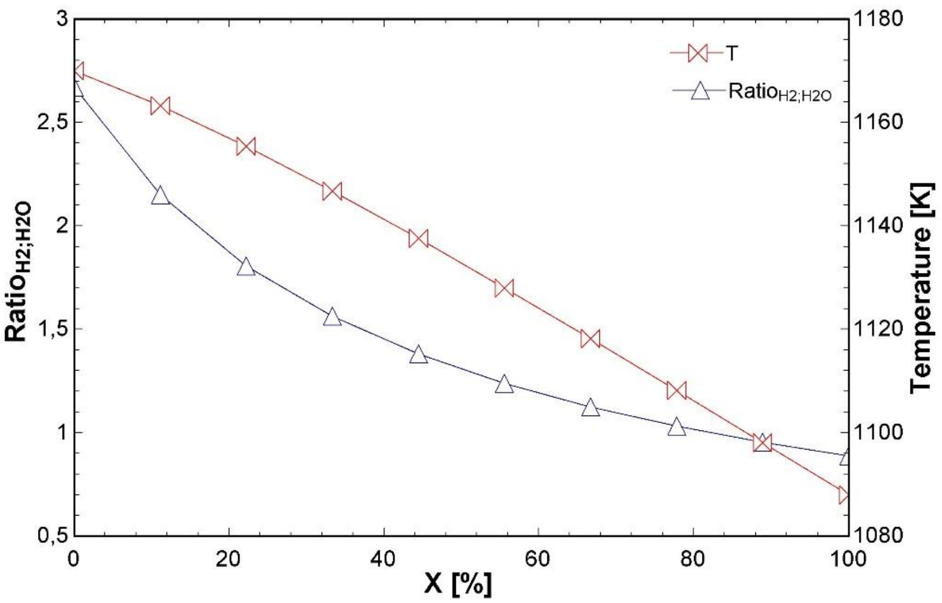

Figure 3: Variation of temperature and in the conversion of H2O to H2 in function of the percentage of steam injected in the gasification process.

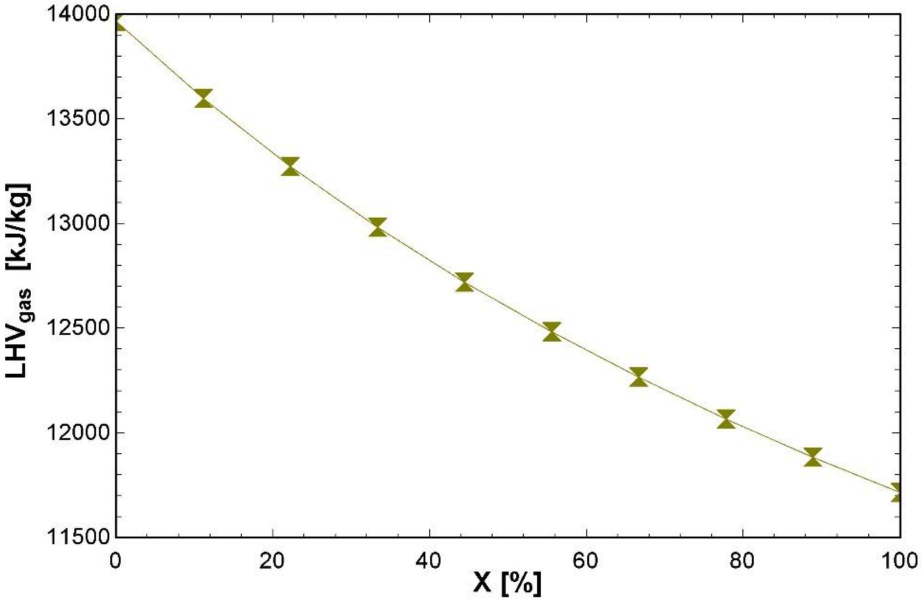

Figure 4: Variation of the lower calorific value of the synthesis gas as a function of the percentage of water vapor injected in the gasification process.

The result of the second numerical experiment brings something very interesting shown in Fig xx. Because by decreasing the amount of oxygen injected, the conversion ratio of water into hydrogen increases, followed by a considerable increase in the lower calorific value of the synthesis gas. This is a very advantageous point for gasification processes that use external energy sources such as solar. The answer to the increase in the amount of hydrogen contained in the gas is when we realize that the reduction of oxygen injected in the process promotes the growth of the number of free carbon molecules. Having more carbon available, the greater will be the occurrence of reactions of eq.2 since the temperature is kept high by external energy sources, causing the displacement of oxygen from water to carbon, forming CO and leaving free H2.

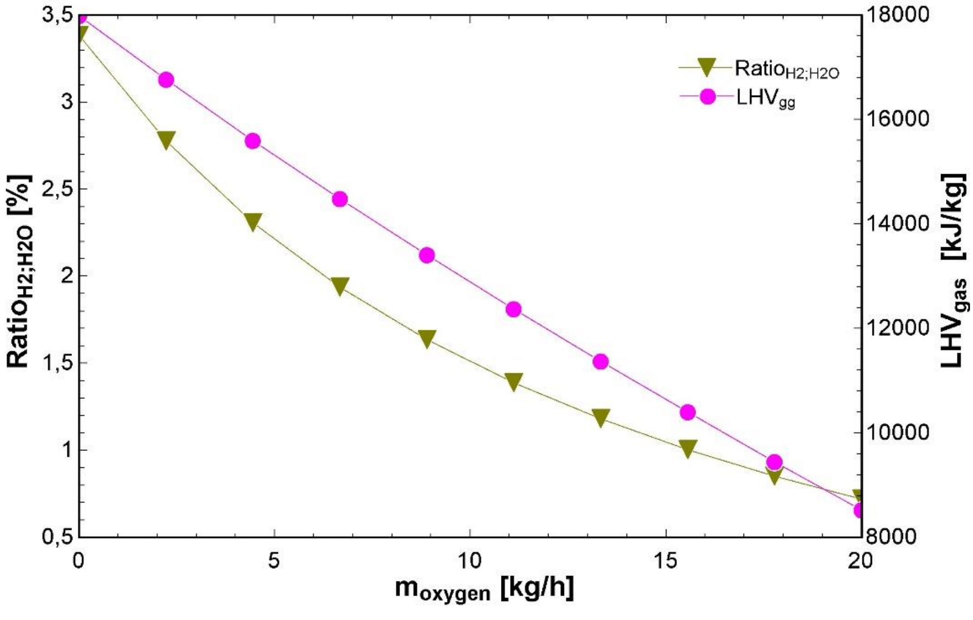

Figure 5: Variation of the lower calorific value of the synthesis gas and conversion of H2O in H2 as a function of the mass of oxygen injected in the gasification process.

5. CONCLUSIONS

It became clear that the gasification process is extremely endothermic and that even providing heat for the process, the injection of pure oxygen has the disadvantage of occupying space that can be used to displace the O2 molecule from water to carbon leaving H2 free. In this sense, further investigations into the use of external energy sources such as solar in the process of gasification with water vapor can bring higher percentages of hydrogen in the synthesis gas. As the synthesis gas obtained from the gasification process can be rich in hydrogen, the emissions resulting from its burning have a higher H2O content, which makes this technology attractive for cleaner and less polluting energy solutions, in line with international commitments, such as the Paris Agreement and the UN Sustainable Development Goals. In addition to the previously mentioned environmental and economic benefits, the gasification of solid urban waste can also contribute to the recovery of degraded areas by reducing the amount of waste sent to landfills, which can extend the useful life of these landfills and reduce the need for expansion area for waste disposal. Therefore, it positively impacts urban solid waste management, promoting the opening of doors to the practice of circular economy, replacing in the production chain what would be discarded and contributing with the more efficient use of natural resources.

6. REFERENCES

Babu, B. V., & Sheth, P. N. (2006). Modeling and simulation of reduction zone of downdraft biomass gasifier: Effect of char reactivity factor. *Energy Conversion and Management*, *47*(15–16), 2602–2611. https://doi.org/10.1016/j.enconman.2005.10.032

BOLOY. (2010). *SIMULAÇÃO COMPUTACIONAL DE GASEIFICAÇÃO DE MADEIRA DE PEQUENO PORTE EMPREGANDO UM GASEIFICADOR DOWNDRAFT*.

Gregg, D. W., Taylor, R. W., Campbell, J. H., Taylor, J. R., & Cotton, A. (1980). *SOLAR GASIFICATION OF COAL, ACTIVATED CARBON, COKE AND COAL AND BIOMASS MIXTURESt* (Vol. 25).

J. C. SILVA. (2022). *MODELO NUMÉRICO PARA ANÁLISE DE GASEIFICAÇÃO INTEGRADA A CICLO COMBINADO PARA RECUPERAÇÃO DA ENERGIA DE RESÍDUOS SÓLIDOS URBANOS*. https://repositorio.unb.br/handle/10482/43668

Klein, S., & Nellis, G. (2012). *Mastering EES*. http://fchart.com

Kodama, T., Enomoto, S. I., Hatamachi, T., & Gokon, N. (2008). Application of an internally circulating fluidized bed for windowed solar chemical reactor with direct irradiation of reacting particles. *Journal of Solar Energy Engineering, Transactions of the ASME*, *130*(1), 0145041–0145044. https://doi.org/10.1115/1.2807213

Phyllis. (2004). *RDF-2766:phyllis.nl/Biomass/View/2766*.

Piatkowski, N., & Steinfeld, A. (2011). Solar gasification of carbonaceous waste feedstocks in a packed-bed reactor-Dynamic modeling and experimental validation. *AIChE Journal*, *57*(12), 3522–3533. https://doi.org/10.1002/aic.12545

Puig-Arnavat, M., Bruno, J. C., & Coronas, A. (2010). Review and analysis of biomass gasification models. In *Renewable and Sustainable Energy Reviews* (Vol. 14, Issue 9, pp. 2841–2851). https://doi.org/10.1016/j.rser.2010.07.030

RICHARD DIXON. (2021). *Making sense of waste*. Https://Foe.Scot/Making-Sense-of-Waste/.

Silva, J. C., Veras, G., & Brasil, A. C. (2020). *SIMULATION TOOLS FOR THE ASSESSMENT OF ADVANCED THERMAL TREATMENT OF MSW-GASIFICATION CODE*. https://www.researchgate.net/publication/364960402

Taylor, R. W., Berjoan, R., & Coutures, P. (1983). SOLAR GASIFICATION OF CARBONACEOUS MATERIALS. In *Solar Energy* (Vol. 30, Issue 6).

Verissimo. (2014). *ESTUDO COMPUTACIONAL DA GASEIFICAÇÃO DE BAGAÇO DE CANA-DE-AÇÚCAR EM UM REATOR DE LEITO FLUIDIZADO*.

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