Waste-To-Power: Assessment of Refuse-Derived Fuel use in a Gasification Plant in the Brazilian context

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In the past 10 years, Brazil's government has been investing in alternative sources to decrease the high dependence of the electricity grid on hydropower plants, mainly due to a constant decrease in pluviometry levels. A promising fuel in the context of the circular economy is refuse-derived fuel (RDF), which is the combustible fraction of Municipal Solid Wastes. It has high calorific power, low levels of hazardous components, and is a more homogeneous material. Moreover, RDF is an abundant, secure source of fuel with a market price nearly independent of external currencies. As gasification is a common Waste-To-Power (WTP) technology used worldwide, this work evaluated the electricity generation by this technology on a small scale (200 kW), using air as a gasifying agent and gas turbines, and according to Brazilian legal requirements regarding the composition of RDF. The process was simulated in Aspen Plus v8.6 for an RDF with an LHV of 15.9 MJ/kg. Sensitivity analysis on key operational parameters showed that for the representative composition of RDF in Brazil, an ER between 0.1-0.3 would be suitable for a gasification process, resulting in a net electrical efficiency of 22-27%.

1. Introduction

In 2019, about 80% of the Brazilian grid was composed of renewable sources, having hydropower plants supplying over 65% of the internal demand. The high dependency on this source altogether with seasonality and the linear decrease in precipitation levels in the past 10 years led the country to increase generation by thermopower plants (ONS, 2021). In these cases, the associated costs are also increased due to costs related to the raw material (mainly fossil fuels) as well as the low energy efficiency from generation to transmission (Filippo Filho, 2018).

A promising feedstock that may help overcome the use of fossil fuels is refuse-derived fuel (RDF). It consists of a high-value combustible solid fraction of Municipal Solid Wastes (MSW) without inert and recyclable materials (Mehdi et al., 2020) and is suitable for gasification to produce gas fuels for power generation.

However, for RDF to be used as gasification fuel in the State of São Paulo in Brazil, legislation (legal resolution n.047, SIMA, enacted in 2020) determines that the lower heating value (LHV) of RDF has to exceed 9.6 MJ/kg and the gasifier has to operate at temperatures equal or higher than 750 °C. As such, the legal requirements prompted us to investigate, via Aspen Plus simulation, the net electrical efficiency of a waste-to-power plant considering the air gasification of an average composition of RDF in Brazil.

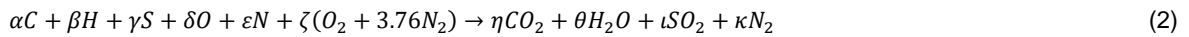## 2. Refuse-Derived Fuel Composition and Simulation

Since the compositions of municipal solid waste and its derivate RDF depend on cultural and socioeconomic factors, this investigation is based on the composition of RDF reported by previous studies that considered the Brazilian context (Násner et al., 2017; Marques et al., 2021). The average composition used to describe this non-conventional component in Aspen Plus v8.6 is presented in Table 1. The LHV (kJ/kg) was estimated using Mendeliev's Estimation (Equation 1), which requires only the ultimate analysis percentages on a wet basis (Cortez et al., 2008).

Peng-Robinson's Equation of State was selected to calculate the thermodynamic properties of the gasification components (Santiago et al., 2020), and the thermodynamic properties of steam were calculated by the IAPWS-95 method. As for the non-conventional components, HCOALGEN and DCOALIGT were employed to calculate both enthalpy and density, allowing adding the proximate and ultimate analysis of RDF in the simulation environment. More assumptions regarding the simulation are described below:

- The process is at steady state conditions.
- All chemical reactions reach the thermodynamic equilibrium.
- Air (21% O_2 and 79% N_2, mol fraction) is used as a gasification agent.
- No temperature gradients are considered within the reactors, nor are heat losses through the walls.
- No intermediate products are considered; no information about the chemical reactions is given, but the final compounds (i.e., H_2, O_2, CO, CO_2, H_2S) are considered.
- Ashes are input as a non-conventional component.
- "Char" is represented by graphitic carbon.

A stoichiometric reaction (Equation 2) was used to determine the minimum amount of agent to fully oxidize the RDF. The equivalent ratio ("ER", Equation 3) was adopted as a parameter to better visualize the effects of operating below or above stoichiometric conditions, in which $\dot{m}_a$ and $\dot{m}_{RDF}$ are the mass flowrates of air and RDF, respectively. The subindex "stoic" accounts for the stoichiometric conditions.

$$LHV = 339C^w + 1030H^w - 109(O^w - S^w) - 24 \times Moisture^w \tag{1}$$

$$\alpha C + \beta H + \gamma S + \delta O + \varepsilon N + \zeta(O_2 + 3.76N_2) \to \eta CO_2 + \theta H_2O + \iota SO_2 + \kappa N_2 \tag{2}$$

$$ER = \frac{\left(\frac{\dot{m}_a}{\dot{m}_{RDF}}\right)}{\left(\frac{\dot{m}_a}{\dot{m}_{RDF}}\right)_{stoic}} \tag{3}$$

Table 1: Proximate and ultimate analysis (dry basis, %) of RDF.

Parameter	Násner et al. (2017)	Marques et al. (2021)	This work
Proximate Analysis (%)			
Fixed Carbon	26.30	16.70	26.30
Volatiles	67.60	72.58	70.09
Moisture	12.00	8.29	10.15
Ashes	6.00	2.43	3.61
Ultimate Analysis (%)			
Carbon	49.40	44.91	47.16
Hydrogen	6.50	6.45	6.48
Nitrogen	1.50	1.70	1.60
Sulphur	0.30	2.12	0.70
Oxygen	36.10	44.82	40.45
Heating Value			
LHV (MJ/kg)	15.20	15.36 [a]	15.93 [a]

[a]Estimated by equation 1.

Figure 1 shows the process scheme developed in Aspen Plus v8.6. A mass flow of 200 kg/h of RDF was simulated as a non-conventional stream entering an "RStoic" reactor, simulating a drying process and removing 90% of the water content from the RDF. The dried mass then enters the Yield block to simulate a pyrolysis step, operating at 500 ºC and 1 bar. This block is essentially decomposing the RDF into known components, such as H_2, O_2, N_2, and H_2O based on a known yield distribution.

Volatile compounds are used in the RGibbs reactor in which thermodynamic equilibrium is reached by minimizing the Gibbs free energy. A more detailed description of the chemical reactions expected to occur when gasifying solid waste is described by Arena (2012). The gasification step initially operates at 750 °C, 1 bar, and the gasification agent mass flow is initially 250 kg/h. The resulting stream goes into a cyclone to remove the ashes and is cooled to 25 °C, allowing the removal of water and other residues (H_2S) before entering the compressor (dry syngas).

To generate electricity, a Brayton cycle was implemented simulating a Capstone C200 microturbine taking as reference the efficiencies reported by Santiago et al. (2022) and Henao et al. (2022) (Table 2). According to the authors, the C200 is suitable to operate with landfill gases, producer gases, natural gas, and others. Although its maximum nominal power is 200 kW, the simulation considered a full decompression, lowering the outlet combustor pressure to 1 bar, to fully evaluate the RDF's capacity to generate power regardless of economic constraints.

The combustion chamber was set to operate adiabatically at 4 bar and simulated in an "RStoic" reactor, to which a second air stream ("AIR-2") is fed at 810 kg/h – enough to produce a minimum amount of O_2 content in the outlet stream of the combustion chamber. The air stream exchanges heat with the exhaust gas in a heat exchanger set to operate at a minimum temperature approach of 10 °C.

The energy generation efficiency (η) of the power plant was calculated by equation 4 according to Galeno et al. (2011). The efficiency accounts for the difference between the power generated by the turbine (kW) minus the power consumed at the compressors (kW), divided by the mass flowrate of RDF (kg/s) and its LHV (kJ/kg). In addition, the cold gas efficiency ("CGE") was calculated as the ratio between the chemical energy of syngas and the chemical energy of RDF (equation 5) (Salman and Omer, 2020).

Table 2: Techincal parameters of the C200 microturbine

Parameter	Value[a]
Compression Ratio	4.0
Compressor efficiency	79.0%
Turbine efficiency	82.5%
Generator efficiency	93.8%

[a]obtained from Santiago et al. (2022) and Henao et al. (2022).

$$\eta \ (\%) = \frac{W_{turbine} - W_{compressors}}{m_{RDF} \times LHV_{RDF}} \tag{4}$$

$$CGE \ (\%) = \left[\frac{LHV_{syngas}}{LHV_{RDF}}\right] \times 100 \tag{5}$$
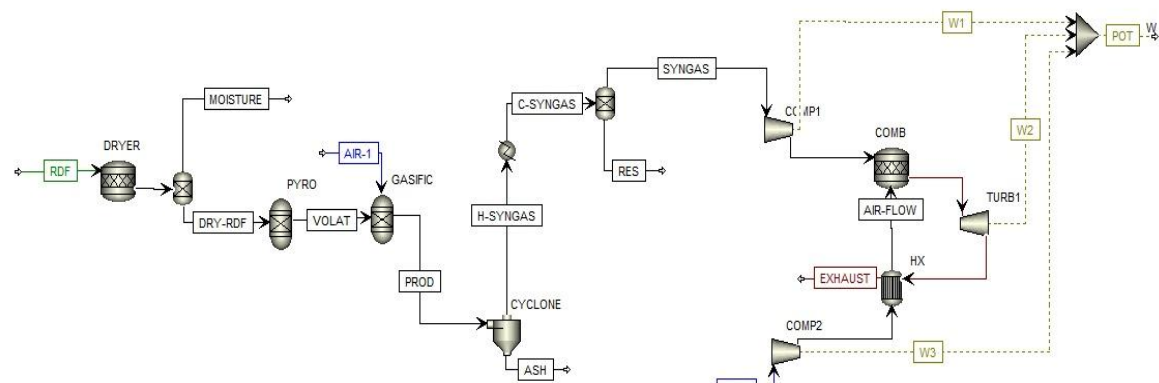

Figure 1: Power plant simulated in Aspen Plus v8.6.

3. Results

To set the gasification temperature, we assessed its effect on both syngas composition and LHV (Figure 2). By varying the temperature between 550 and 1100 °C, the LHV increased by approximately 4 MJ/kg in the interval between 550 and 750 °C and then leveled off. Thus, the gasifier was set to operate at 750 °C, which is the lowest temperature allowed by Brazilian legislation.

Next, we assessed the effect of the air equivalent ratio (ER) on the dry, cold syngas composition at 750°C (Figure 3). As the mass flowrate of the gasifier agent approximates stoichiometric conditions (ER = 1 or 5.91 kg of air/kg of RDF), the mole fraction of CO decreases as the mole fraction of CO_2 increases, as expected.

Meanwhile, the N_2 mol fraction increases given that it is not consumed (inert component). As a result, both the ER and the Cold Gas Efficiency (CGE) show a decrease in their profile (Figure 4).
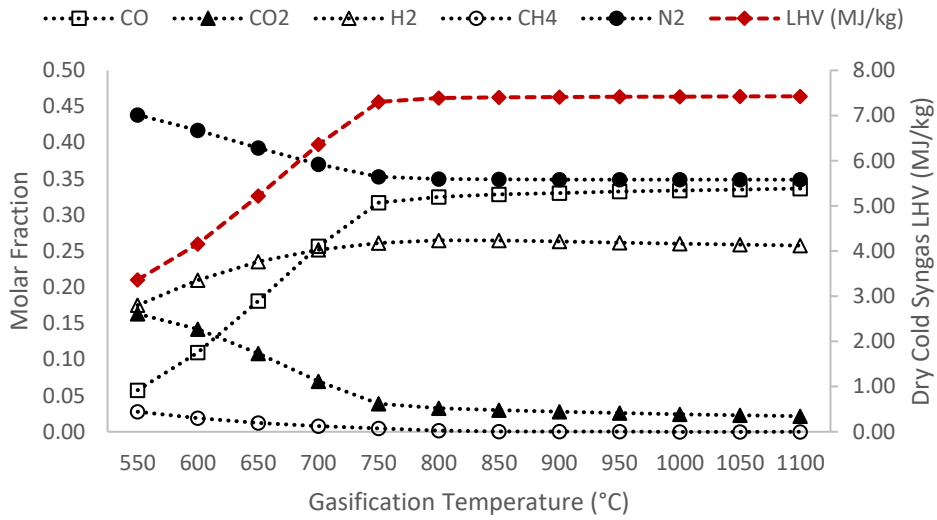

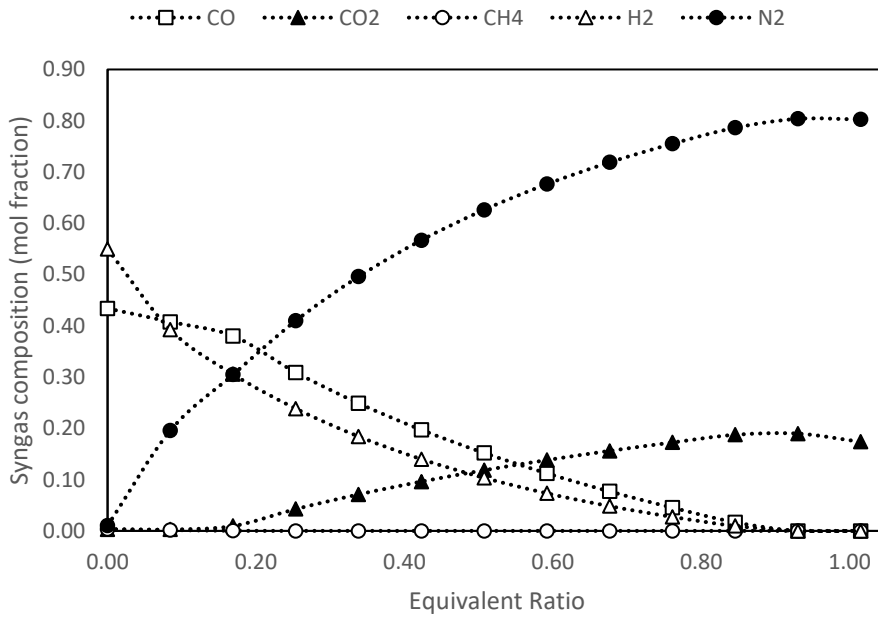*Figure 2: Influence of gasification temperature on syngas LHV and composition.*

Figure 3: Influence of equivalent ratio on syngas composition.

Consequently, the net electrical efficiency decreases (Figure 5) given that higher values of ER (i) increase the concentration of N_2 in the syngas and (ii) decrease the concentration of combustion gases such as H_2 and CH_4. The electrical efficiency is maximized by ER values between 0.1 and 0.3, reaching values between 25-29%, which are expected for gas turbines and similar to values reported by Arena (2012).
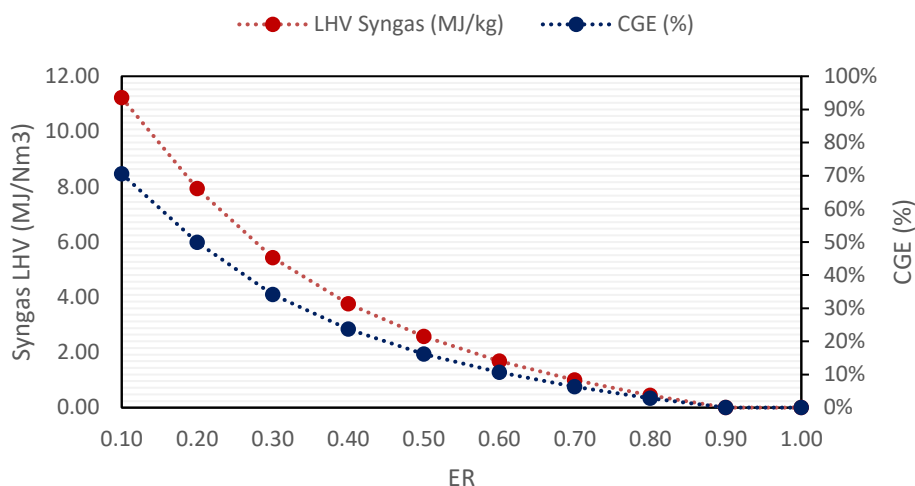
Figure 4: Influence of equivalent ratio on the syngas LHV and cold-gas efficiency.
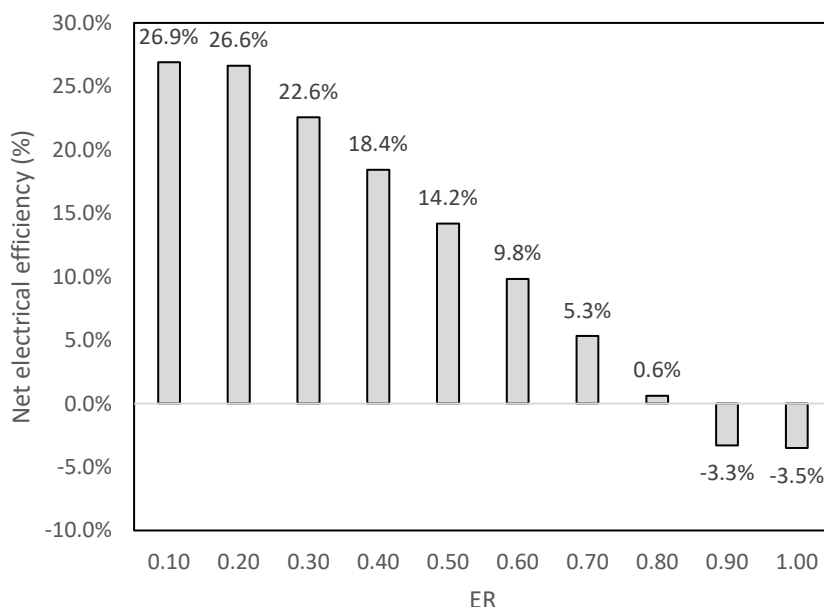

Figure 5: Net electrical efficiency of the power plant as a function of the equivalent ratio.

4. Conclusions

This study evaluated the use of RDF as a feedstock to generate power in a small-scale plant, considering the main parameters regulated by Brazilian legislation. This study showed the importance of operating the gasification of RDF at temperatures ≥750 °C, as determined by a Brazilian regulation, to produce syngas with satisfactory energy content. Moreover, by using air as a gasification agent at an equivalent ratio in the range 0.1-0.3, the electrical efficiency was between 27-22% and similar to values found in previous studies on the gasification of RDF.

Nomenclature

LHV – Lower Heating Value, MJ/kg
C^w – Carbon percentage, wet basis   Moisture^w – Moisture content, wet basis
H^w – Hydrogen percentage, wet basis m_a– air flowrate, kg/h
O^w – Oxygen percentage, wet basis m_{RDF} – RDF flowrate, kg/h
S^w – Sulfur percentage, wet basis   ER – Equivalent Ratio

$W_{turbine}$– Gross work produced by turbines, kW

η– Net electrical efficiency, %

$W_{compressors}$ – Gross work produced by compressors, kW

LHV_{RDF} – Lower Heating Value of RDF, kJ/kg

Acknowledgments

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